PABLO MIRANDA GUIMARÃES

TWO ESSAYS ABOUT AGRICULTURE PRODUCTION IN THE BRAZILIAN CERRADO

Tese apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Economia Aplicada, para obtenção do título de *Doctor Scientiae*.

Orientador: Marcelo José Braga

Coorientadores: Lylian Estela Fulginiti
Glauco Rodrigues Carvalho

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Assentimento:

Pablo

Pablo Miranda Guimarães
Autor

Marcelo

Marcelo José Braga
Orientador

Este trabalho é dedicado à minha esposa, à minha filha e ao meu vô Tatão

(Promessa feita, promessa cumprida Vô!)

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“Maria passa na frente e vai abrindo estradas e caminhos”.

RESUMO

GUIMARÃES, Pablo Miranda, D.Sc., Universidade Federal de Viçosa, dezembro de 2021. **Two essays about agriculture production in the Brazilian Cerrado**. Orientador: Marcelo José Braga. Coorientadores: Lilyan Estela Fulginiti e Glauco Rodrigues Carvalho.

O Cerrado é conhecido como o celeiro do mundo, e dois elementos caracterizam sua ocupação desde o final dos anos 1960: Adoção de tecnologias e ondas de expansão de sua fronteira produtiva. Essa dinâmica vem se estabelecendo juntamente ao apelo das questões ambientais no processo produtivo do bioma. No primeiro trabalho, buscou-se analisar os efeitos da adoção da biotecnologia das sementes geneticamente modificadas das lavouras do Cerrado. A área colhida com a biotecnologia GM no bioma teve uma expansão superior a 20 vezes, entre os anos de 2006 e 2017. Ganhos de produtividade, diminuição de custos, realocação de insumos e ganhos ambientais são algumas das consequências da dinâmica agrícola produtiva gerada pela adoção da tecnologia. Utilizando a técnica de fronteira estocástica, observou-se, entre os dois últimos censos agropecuários, que a elevação em ponto percentual da área colhida com sementes GM expandiu a produção agropecuária em 0,364%. Regiões de produção mais consolidada do Cerrado, como no Centro-Oeste, tiveram um maior ganho de eficiência técnica. Quando observada as diferenças de produtividade entre as regiões agrícolas mais consolidas e o MATOPIBA, os resultados mostraram um maior ganho de produtividade na nova fronteira agrícola. O segundo trabalho, se desenvolveu no debate a respeito de intensificação de produção agropecuária e a necessidade da diminuição dos avanços de desmatamento e redução de emissão de gases de efeito estufa. Utilizando uma função *Output Distance Function* com a implementação de um technological changing variable, o trabalho estimou o valor de conversão de um hectare de pastagem degradada em pastagem boa plantada. Essa conversão foi baseada nas produtividades locais, com objetivo de estabelecer um indicador de ganhos, capacitando produtores, agentes públicos e privados quanto aos ganhos de recuperação de áreas, gerando benefícios ambientais.

Palavras-chave: Produtividade. Cerrado. Tecnologia. Eficiência. Mitigação de impactos ambientais.

ABSTRACT

GUIMARÃES, Pablo Miranda, D.Sc., Universidade Federal de Viçosa, December, 2021. **Two essays about agriculture production in the Brazilian Cerrado**. Adviser: Marcelo José Braga. Co-advisers: Lilyan Estela Fulginiti and Glauco Rodrigues Carvalho.

Brazilian Cerrado, often characterized as the world's breadbasket, has manifested two key elements in its agricultural sector since the late 1960s: The implementation of new production technologies and expansion waves of the production frontier. Nowadays, although well established, these two factors present an environmental dilemma; however, they can also be a possible solution to this problem. Our first essay analyzes the effects of adopting biotechnology by genetically modified seeds on Cerrado crops. The harvested area with GM biotechnology in the Cerrado increased more than 20 times between 2006 and 2017. By stochastic frontier methodology, it was observed that GM seeds expanded Cerrado's agricultural production in 0.364%. Consolidated production areas on the Cerrado, such as the Midwestern states, had greater gains in technical efficiency. However, the last Brazilian agricultural frontier, Cerrado's MATOPIBA, showed greater gains in productivity than the consolidated agricultural regions. The second paper examines the intensification of agricultural production, which can reduce deforestation and greenhouse gas emissions. Using an output distance function with a technological changing variable, were estimate the marginal gains of converting one hectare of degraded pasture into good and planted pasture. This conversion was based on local productivity, considering local conditions and methods of production. It aims to establish an indicator of gains, thus enabling producers, the public and private agents to evaluate the benefits to production and the environment of pasture recovery.

Keywords: Cerrado. Productivity. Technology. Efficiency. Environmental mitigation.

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1 Introduction

> *”The sertão describes itself: it is where the grazing lands have no fences; where you can keep going ten, fifteen leagues without coming upon a single house (...) The Urucúia rises in the mountains to the west. But today, on its banks, you find everything: huge ranches bordering rich lowlands, the flood plains; farms that stretch from woods to woods; thick trees in virgin forests - some are still standing. The surrounding lands are the Gerais. This gerais are endless. Anyway, the gentleman knows how it is: each one believes what he likes: hog, pig, or swine, as you opine. The sertão is everywhere”(Guimarães Rosa, 1963)*

Comprising almost a quarter of Brazil’s territory, the Cerrado Biome is the Sertão described by João Guimarães Rosa in his major work, with all its environmental, cultural, and economic relevance to Brazil.

This biodiversity hot spot, the cradle of three of the biggest watersheds in South America (Amazônica/Tocantins, São Francisco, and Prata), is located in the central region of Brazil. In addition to the environmental importance it’s animal and vegetable species, the Cerrado is prominent in Brazil’s and the world’s agriculture.

A vast Savannah, the Cerrado biome, with its regional variation, raises essential social, economic, and technological issues. Its patterns of spatial and temporal occupation, public investments, macroeconomics, and market inducements have been modeled in their economic, social and environmental aspects (MUELLER; MARTHA Jr.., 2008).

All of these characteristics reflect the advances made in the production of food, whether as commodities for export, or provision for national food security, as well as in the development of environmentally sustainable agriculture and preservation of biodiversity (MUELLER; MARTHA Jr.., 2008; CHADDAD, 2016; BOLFE; SANO; CAMPOS, 2020).

Of these advances, two stand out in relation to social and productive dynamics: The waves of occupation and innovations and technologies affecting production.

Brazil’s investment in agricultural R&D increased in the 1960s and continues today. These efforts developed new areas and technology in the agricultural sector, expanding production and increasing productivity. Consequently, Brazil has achieved food security, the price of food has decreased, and lowered the share of the household of income spent on food (CAMPOS, 2010; RADA; BUCCOLA, 2012; CHADDAD, 2016).

Prior to the 1960s, the basis of Cerrado’s economy was subsistence agriculture (rice, cassava, beans, and others) and extensive livestock production. A wave of new settlers was stimulated by the reallocation of Brazil’s capital to the country’s center and by the policies and development programs and infrastructure investments in the 1960s and 1970s (GOEDERT; WAGNER; BARCELLOS, 2008; GIUSTINA, 2013).

Drawn to the region by political and economic incentives to develop the agricultural area of the region, such as rural credit and minimum price policies, new settlers also took advantage of technical assistance, low land prices, and favorable climatic conditions. The new occupants expanded agricultural production and changed the dynamics of the biome (REZENDE; HELFAND; REZENDE, 2003; CATTELAN; DALL’AGNOL, 2018; SILVA, 2018; CONTINI et al., 2020).

Research and Development (R&D) by universities and the Brazilian Agricultural Research Corporation (EMBRAPA) also spurred change in the biome. Research and introduction of new technologies, such as seeds suitable for the region and methods of correcting the region’s acid soil supported the development of Cerrado (BRAGAGNOLO; SPOLADOR; BARROS, 2010).

The second main impetus for the development of the Cerrado began in the the second half of the 1980’s, reaching its peak after the country’s macroeconomic reforms of 1990’s (CHADDAD, 2016). The government’s involvement in agriculture decreased, but the private sector’s increased, a radical reversal of the previous of the interventionist strategy and trade barriers (CHADDAD; JANK, 2006; MUELLER, 2008).

Even with decreases of public participation in agriculture, the remodeling of the rural credit system at the beginning of the 1990’s produced an increase in the number of machines for crop procution by FINAME and MODERFROTA programs (BRANDÃO; REZENDE; MARQUES, 2006). In 1994, the BM&F developed financial instruments (as Rural Product Ballot) that helped the producers to minimize risk and predict revenues (CAMPOS, 2010).

Technological development and their concomitant productive evolution spread in the 1990s to southeastern Goiás State, the central region of Mato Grosso State, and induced migration to western Bahia state (ARAÚJO et al., 2019). Just like in Cerrado’s first occupation wave, in the second one, the landscape and the low cost of land helped spur this expansion into a new frontier (REZENDE; HELFAND; REZENDE, 2003; LINS; PINAZZA, 2004).

The adoption of new technologies in Brazilian agriculture has facilitated the transformation of underused natural resources into productive resources. Brazil’s practice of permitting the implementation of technologies on the borders of science has led to productivity gains and cost reductions.

The innovative technologies and practices now used the Cerrado include: the use of inoculated bacteria as nitrogen fixers (NOGUEIRA; HUNGRIA, 2013); the implementation of the agroclimatic zoning; the integration of crop and livestock production; the widespread adoption of no-till practices (DROS, 2004; CATTELAN; DALL'AGNOL, 2018). And the introduction of selected forage plant cultivars in livestock production (MARTHA Jr.; VILELA, 2002).

The newest advances in practices and processes as precision agriculture, real-time analysis, and, above all, the adoption of transgenic seeds that aid weed and insect control, have been introduced and are being consolidated as mainstream practices.

Biotechnology has provided tolerance of plagues, crops with a shorter life cycle, making possible more than one harvest crop in a year, and better adaption of hybrid seeds to the environment. All of which have helped increase productivity and yield.

In the Cerrado biome, Genetic Modified (GM) seeds produced more than 60% of Brazilian maize, almost 99% of its cotton, and 57% of its soybean in 2017 (IBGE, 2017b).

While waves of new people and innovative production processes have led to gains in agricultural production in the Cerrado, these developments are also seen as antagonistic to the environmental (BRANDÃO; REZENDE; MARQUES, 2006). New agricultural areas were established by converting native land to cropland and pasture was expanded by deforestation, both of these practices now occurring in MATOPIBA (TRIGUEIRO; NABOUT; TESSAROLO, 2020). This itinerant agriculture, together with the search for new areas of greater productivity, has also left a trail of low-yielding pastures and other areas of low productivity (BRANDÃO; REZENDE; MARQUES, 2006).

1.1 Problem and importance

Agriculture production is confronted by the impacts of economic activity on the environment. The rapid process of conversion of land uses has deforestation driven by agricultural uses. Once the land becomes degraded, areas of virgin forest and Savannah is cleared to be used, mainly, for livestock production. Additionally, deforestation, greenhouse gas (GHG) emissions and land competition among cultures are also negative consequences from the bad managed agricultural production (SILVA et al., 2015).

The consequences of environmental problems, such as climate change, biodiversity losses, degradation of land, water shortages, and extreme weather events, can affect agriculture negatively. They may cause lower harvested yields, higher yield variability, and a reduction in suitable areas for traditional crops (OLESEN; BINDI, 2002). The optimization of inputs, investments in technology, better crops, livestock production processes, and intensification and efficiency in existing production systems can help achieve equilibrium between environmental problems and supply the increasing demand for food.

As a prominent player in agricultural production, Brazil is involved with several issues related to it. The transformation of Brazilian agriculture has been most pronounced in Brazil's Savannah (ECONOMIST, 2010). The Cerrado (figure 1) is the most threatened tropical savanna in the world, the second largest biome of Brazil, and occupies almost 24% of its area. A distinguish agricultural relevance, the biome was responsible for 24.9% of Brazil's total GVP and 37.1% of the national agricultural GVP, in 2017 (IBGE, 2017c). Additionally, 47.1% of Brazil's cattle herd, 70% of its temporary cropland, and 87% of its grains production (IBGE, 2017b).

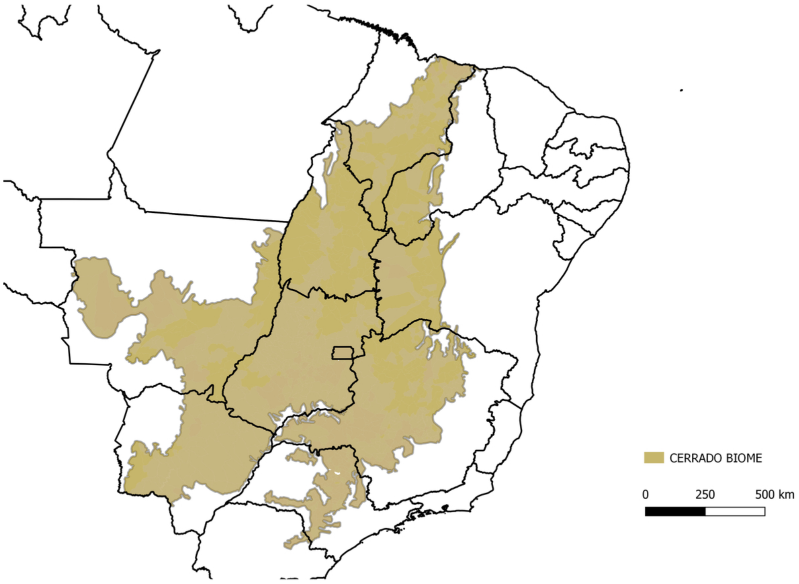

Figure 1 – Brazilian Cerrado

Source: Own elaboration based on EMBRAPA's criteria

The implementation of technologies is an important part of the occupation process, and the major part of crops from the Brazilian savanna are planted with transgenic seeds.

Nevertheless, all of this thriving agricultural economy was based on disorderly occupation, with its consequent social, economic, and environmental damages. The rate of land-use intensification in Brazil has created pressure to convert additional land to grown crops (BARRETTO et al., 2013), leading to deforestation and GHG emission. In particular, between 2000 and 2017, 23.9% of natural habitat of the Cerrado was vanished Grande, Aguiar e Machado (2020), while just the beef production in the biome will be responsible to 9% of Brazilian CO_2 emission (equivalent to 2.6 Gt $CO_2\ equivalent$) from 2010 to 2030 (SILVA et al., 2015).

Even as environmental issues have grown, the Cerrado has introduced innovative agricultural processes aimed at improving sustainability and productivity of agricultural land, including sustainable intensification of pastures, incorporation of low-carbon agricultural practices, expansion, and adoption of other sustainable practices, and support for traditional agricultural products (DICKIE et al., 2016). Several themes are extremely relevant to the development of the biome: conservation and use of biodiversity; use and conservation of soil; agricultural and forestry production; impacts of production systems and mitigation strategies; and biotechnology, transgenics, and biosafety (VICTORIA et al., 2020).

Velazco et al. (2019) point out that climate change and poor land use will cause great damage to Cerrado's environment by 2050 and 2080, even under optimistic conditions. This raises two important questions: How to keep increasing food production with limited land in a time of rising demand? How do optimize the inputs available in the biome, while minimizing the environmental consequences?

Crop development and biotechnology help address the first question. The first generation of GM seeds has increased productivity, while minimizing costs, allowing farmers to raise production and expand their welfare (LENCE; HAYES, 2005; KLÜMPER; QAIM, 2014). These results support discussion about the legalization of other crops/seeds, push the development of second and third-generation seeds, along with technologies to address nutritional issues, and measures to resist extreme environmental events, pushing the intensification of agriculture production.

The GM crops increase yields, minimize costs, and reduce the land and environmental footprint of agriculture (ZILBERMAN; HOLLAND; TRILNICK, 2018). Moreover, with production improvements, the technology supports the reduction of GHG emissions and, by improvement of yields, deforestation slowdown.

Margulis (2003) and Azevedo, Rodrigues e Silva (2021) explain, that deforestation is also consequence of livestock, particularly the low productivity activity. The low productivity is a consequence of degraded pasture and supports the expansion of the agricultural frontier, and has been happening in some areas of the newest Cerrado's frontier, MATOPIBA.

Despite the newest agricultural frontier shows a positive perspective, with the development of GM seed and techniques, consolidating gradually the agricultural development and supporting the economic dynamics (BOLFE et al., 2017), deforestation is a relevant element of discussion about an increment of production (ARAÚJO et al., 2019).

Although, agricultural efficiency can offer an optimum allocation of resources, inhibit externalities related to the overuse of inputs, support the slowdown of deforestation rate (AZEVEDO; RODRIGUES; SILVA, 2021).

Considering Cerrado's situation, this point meets the second question from Velazco et al. (2019) about the management of inputs and environmental minimization. This issue can be represented by the unique possibility to expand again Cerrado's agriculture frontier, the interior expansion of the frontier.

The opportunities in the biome's old frontier can be demonstrated in the amount of degraded pastures. Silva et al. (2017) claims that more than 50% of Brazilian livestock production is on degraded pasture. Being Cerrado the main producer of livestock, the analysis of pasture based on remote sensing indicates a high portion of pastures under some stage of degradation (24% under optimistic scenario and 60% in the most realist one (ANDRADE et al., 2016). This information based on the density of cattle herd per hectare tells that the amount of degraded pasture in Cerrado is around 43% (LAPIG/UFG, 2020). Even using subjective criteria about the personal perception of degradation, 52 million hectares of pastures were self-reported as degraded, or almost 7% of the total of pastures (IBGE, 2017a)

More than boosting the productivity based on the management of degraded pasture, the improvement of efficiency can reduce the deforestation rates (AZEVEDO; RODRIGUES; SILVA, 2021; FELTRAN-BARBIERI; FÉRES, 2021) and the restoration of pastures can mitigate the GHG emission (SILVA et al., 2015). The discussion and attention about the degraded pasture in Cerrado and its recovery is one action of Brazilian Intended Nationally Determined Contribution (INDC), part of the Paris Agreement (Observatório ABC, 2017a), and a relevant point of discussion at Glasgow's climate summit (COP26).

So the potential interior wave of expansion of Cerrado is a trade-off between revenues from the recovery area and the costs to recover it, with environmental consequences. The sizing of potential revenues from recovered areas can contribute to the discussion of credits addressed to conservation practices and/or recovery of degraded pastures.

Silva et al. (2017) analyze it by a cash flow framework, maximizing profit, including scenarios with or without environmental credit, a robust evaluation of the impact of recovery considering local productivity and including inputs and output can also support these discussions of environmental preservation, agricultural expansion, and also the expansion of wealth.

So, the contribution of this research is to develop indicators, measuring incentives for the adoption of pro-environmental production processes. The first essay incorporates into the economical literature the discussion of biotechnology agriculture production. The results can be a driver of debate about agricultural efficiency, food production, environmental issues, and the development of new GM technologies. Additionally, the review of productivity behavior in the newest agriculture frontier can support the policy maker in respect of MATOPIBA's development plan.

The second essay, by the output distance function, quantifies the transformation of degraded pasture, a low productivity input, into a pasture with better productivity. These results can reinforce the discussion of improvement of efficiency in agricultural production, especially in respect of environmental issues such as slowdown deforestation and diminishing the GHG emission. The local gains from pasture restorations can also support governmental guidelines, such as ABC Plan and its credit lines aimed at recovering pastures. Along with the discussion about rural credit, a debate on rural service assistance and other financial instruments favorable to the environmental issues.

1.2 Objectives

1.2.1 General Objective

Develop the effects of technological implementation in the agricultural process and the expansion of the productive frontier in the Cerrado. It aims to contribute to the discussions of market incentives mechanisms for policy formulation;

1.2.2 Specific Objectives

1. Verify the impact of GMOs on the agricultural production of the biome;
2. Measure the evolution of agricultural productivity in the MATOPIBA region;
3. Estimate the unbiased technical efficiency of municipalities from the Cerrado;
4. Estimate the transformation of degraded pasture into better quality pasture;
5. Determine the additional gross production value obtained from a marginal hectare of additional good-planted pasture.

2 GM technology over the agricultural productivity in Brazilian Cerrado

2.1 Introduction

Technical innovation and innovating firms in the modern agrifood sector have helped alleviate hunger and food insecurity around the world (GIANNAKAS, 2014). These innovations and advances are the results of investments in production and processing practices, new products, new locations for producing existing products, and new institutions for organizing supply chains (ZILBERMAN; LU; REARDON, 2019).

Advances in agricultural biotechnology, particularly the development of genetically modified crops, have become important in worldwide agricultural production. They expand output and make land use more efficient. They reduce tilling, which can lead to erosion. They minimize the use of toxic chemicals and the emission of greenhouse gas (BARROWS; SEXTON; ZILBERMAN, 2014; ZILBERMAN; HOLLAND; TRILNICK, 2018).

The benefits can be shared among innovators, farmers, and consumers. So, GM technology in agriculture can support societal welfare by increasing productivity and diminishing the environmental footprint.

In the last 20 years, similar advances have occurred in Brazilian agriculture. The confluence of market factors, agricultural dynamism, and environmental conditions has led Brazil to lead the position as a major player in the producer market of maize and soy. These developments generated economic, social, environmental, technological, and political impacts.

The development and consolidation of the Cerrado biome as a maize and soy-producing region can be characterized by three moments, occurring in different periods: the first, which is characterized by the wide availability of land, migration, and public policies; the second moment, with advances in mechanization and technological contributions; and finally, research, improvements of handling techniques and genetic advances that allowed the expansion of productivity.

Since legal permission was given in 2005 for the wide use of GM seeds, average yearly yields of the main GM crops in Brazil (maize and soybean) have increased by 4.93% and 2.63%, respectively. After the introduction of GM maize, many more farmers were able to plant two high-yield crops per year (CELERES, 2018). Now, Brazil is one of the prominent producers of GM crops in the world (AGROCONSULT, 2018; FIGUEIREDO et al., 2019) and the Cerrado biome is the main hot spot of agricultural GM cropland.

Jointly with the advances of biotechnology over Cerrado, a new area is getting distinction, the MATOPIBA region. The region formed by 337 municipalities from four Brazilian states has been expanding its participation in Brazilian agriculture, especially grains.

Investments in agricultural R&D in new technologies can drive the sector's productivity (ALSTON; BEDDOW; PARDEY, 2009). GM crops have become particularly important but have not been studied extensively in Brazil. The economical literature is mainly based on *Bt* cotton crops analysis with groups of farms classified by the GM adoption (QAIM; ZILBERMAN, 2003; CROST et al., 2007; FERNANDEZ-CORNEJO et al., 2014; KOUSER; QAIM, 2015). So, using a stochastic frontier, the present study explores and measures the effects on agricultural productivity of GM technology in the Cerrado, Brazil's main agricultural biome. Different from the literature, we inserted GM technology in the frontier as a shifter. This study also examines elements that impact the technical efficiency of agricultural production in the biome. We also measure the productivity evolution between the MATOPIBA region and other regions of the Cerrado.

An analysis of productivity in the Cerrado between 2006 and 2017 showed an increase in productivity in areas planted with GM crops. The study showed that successful implementation of GM technology in the Cerrado occurred faster than the implementation of new agricultural technology as described by Hayami e Ruttan (1970).

While education is the main element supporting the increase in the technical efficiency of production in the region, the adoption of GMO technology also provides a significant impact on production. An increase of 1 percentage point in the area planted with GMO seed resulted in a 0.3644% increase in Cerrado's agricultural productivity. Additionally, the study finds that productivity in the MATOPIBA region shows is higher than in other areas of Cerrado, as expected in new production areas.

This paper is divided into five additional parts. The first part is an explanation of GMOs and their relation to agricultural production. The second and third present a theoretical model and empirical model and data. The last two sections discuss the results and a conclusion.

2.2 GM technology in agriculture and the Brazilian Cerrado

The introduction of genetically modified organisms (GMO) into the food system is one of the most notable features of the increasingly industrialized agri-food marketing systems of numerous countries, both developed and developing, around the world (GIANNAKAS, 2014).

The evolution of the bioeconomy emphasizes new supply-chain structures, such as feedstock and biofuels, which have consistent backward and forward linkages. The adoption of agricultural GM technology in developing countries correlates with economic and social advantages, especially the increase in yields and cost reductions (QAIM; ZILBERMAN, 2003; CROST et al., 2007; KLÜMPER; QAIM, 2014). Biotechnology can improve the net return of land, by reducing labor during planting and crop management, saving resources and reducing the use of pesticides (FERNANDEZ-CORNEJO et al., 2014; ALMEIDA et al., 2017).

The predilection of Brazilian agriculture over the years to adopt new technologies and scientific advances has increased productivity and reduced costs. The spread of GM technology continues this evolution, particularly in the Cerrado, mainly in cotton, maize, and soybean crops (AGROCONSULT, 2018).

Brazil's Biosafety Law was adopted in 2005, but the impacts of GMO crops were felt earlier, since 2003, even without institutional stability for it [1]. Between 2003 and 2016, GM crops generated gains of US$ 19.8 billion, involving 300,000 properties (BRIEFS, 2017). Celeres (2018) also points out that the use of biotechnology in maize, soybean, and cotton crops, the main Brazilian GM crops, generated significant benefits, motivated cost reduction, and increased productivity.

The share of GM crops has been increasing since 2009, when, at least, one GM cultivar of each had received permission for planting. Agroconsult (2018) pointed out that 94% of cotton crops, 92.3% of soybean crops, 86.7% of maize winter crops, and 74.7% of maize summer crops were planted with GM crops in 2017.

In 2017, the Cerrado biome produced more than 60% of Brazil's maize, almost 99% of its cotton, and 57% of its soybeans (IBGE, 2017b). Between 2006 and 2017, the land cultivated with GM seeds in the whole of Cerrado was 19 times greater in 2017 than in 2006. In MATOPIBA the increase was 37-fold greater (IBGE, 2006; IBGE, 2017a).

While biotechnology was taking root in the Cerrado, the amount of land in the biome devoted to agriculture was also increasing particularly in its northwest region. Located in four states of Northeastern area of biome, as in figure 2.

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[1] Before 2005, some farmers imported GMO soybean seeds from Argentina and Paraguay and planted, especially, in Paraná and Mato Grosso do Sul state

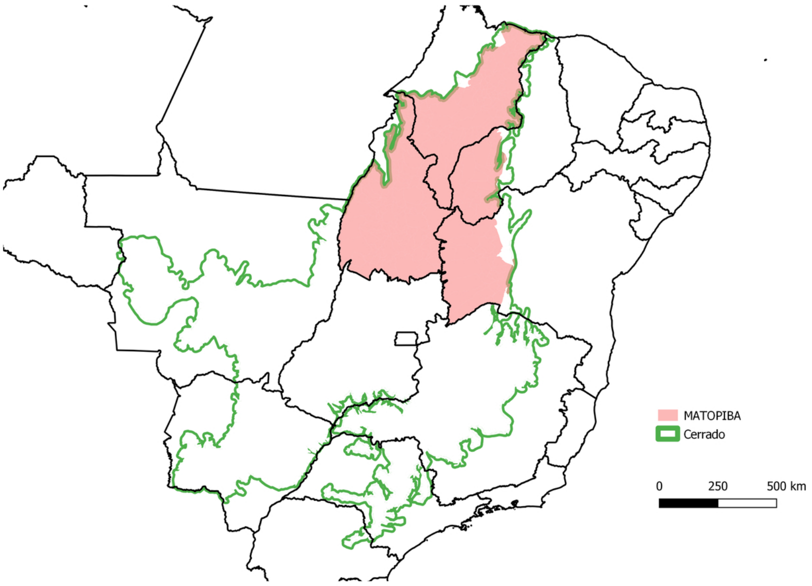

Figure 2 – Cerrado biome and MATOPIBA

Source: Own authors based on information from (BRASIL, 2015)

The Brazilian government's Agricultural and Livestock Development Plan for MATOPIBA (BRASIL, 2015) reflects the importance of the region, with its differentiated and dynamic growth and its outstanding agricultural results. This region, gradually, expanded its participation in Brazilian agriculture, especially in grains. Between 2006 and 2017, its production of maize more than tripled and almost doubled the soybean, two of the main GMO crops (IBGE, 2006; IBGE, 2017a).

Modern agriculture and biotechnology in heterogeneous region, principally in the Cerrado, have impacted the spatial and economic dynamics. These new agricultural processes, such as GM crops, have increased local income (MENDOLA, 2007; KASSIE; SHIFERAW; MURICHO, 2011), environmental benefits (BURACHIK, 2010; KOUSER; QAIM, 2015), have positively affected other sectors, such as industry and services (BUSTOS; CAPRETTINI; PONTICELLI, 2016).

2.3 Theoretical Framework

The production function is a mathematical form that is defined by the production input sets of a technology needed to produce the maximum output for an arbitrary input vector (SHEPHARD, 1970).

$$y = f(x) \tag{2.1}$$

An additional unit of any input can never decrease the level of output (monotonicity). The input set assumes the law of the diminishing marginal rate of technical substitution holds (CHAMBERS, 1988).

The modeling of production behavior assumes that all production activities occur on the frontier of the feasible production set. The analysis of efficiency relaxes this assumption and considers the possibility that the local agricultural production operates below the frontier due to technical inefficiency (KUMBHAKAR; WANG; HORNCASTLE, 2015).

Battese e Coelli (1995) specified a stochastic frontier adding the specification of technical inefficiency, as shown in equation 2.2:

$$y_{it} = f(X_{it}\beta)e^{v_{it}-u_{it}} \tag{2.2}$$

Here, X_{it} is one of the set input variables of the frontier of the i^{th} unit of analysis in time t; $v_{it} \sim i.i.d$, which is a random variation error term, capturing potential effects of measurement error and exogenous shocks; u_{it} is a non-negative random error term associated with effects related to technical inefficiency in production.

The stochastic frontier analysis is mainly directed toward the prediction of inefficiency effects. The most common output-oriented measure of this prediction is based on the ratio of observed output to the corresponding stochastic frontier output (COELLI et al., 2005). Therefore, the specification of inefficiency makes it possible to obtain a prediction of the Technical Efficiency (TE) of local agricultural production each year:

$$\begin{aligned} TE_{it} &= \frac{y_{it}}{y^*_{it}} \\ &= \frac{y_{it}}{e^{(x'\beta+v_{it})}} \\ &= \frac{e^{(x'\beta+v_{it})}E[e^{(-u_{it})}|e]}{e^{(x'\beta+v_{it})}} \\ &= E[e^{(-u_{it})}|\epsilon] \end{aligned} \tag{2.3}$$

According to equation 2.3, the measure of technical efficiency (TE) takes a value between 0 and 1. It indicates the output of the i^{th} (y_{it}) unit of analysis relative to the output that could be produced (y^*_{it}) if this unit were fully efficient using the same input vector.

Given that there is a possibility of inefficiency, technical inefficiency of production can be represented by:

$$u_{it} = \delta z_{u,it} + w_{u,it} \tag{2.4}$$

where $z_{u,it}$ is a $m\ x\ 1$ vector of explanatory variables associated with technical inefficiency; δ is a vector $(m\ x\ 1)$ of coefficients and $w_{u,it} \sim N(0, \sigma^2)$ are random errors. Here we are imposing a half-normal distribution of the technical inefficient error term, $u_{it} \sim N^{+}(0, \sigma_u^2)$.

In the half-normal model, when the heteroscedasticity of v_{it} is not controlled, the frontier function parameters (β) are estimated consistently, except for the intercept, which is inconsistent, and it also biases the estimation of technical efficiency. Additionally, when we disregard the heteroscedasticity of u_i, both technical efficiency and parameters (β) are biased (KUMBHAKAR; WANG; HORNCASTLE, 2015).

The parametrization of equation 2.4 is possible, so:

$$\sigma^2_{u,it} = e^{(z_{u,it}, w_u)} \tag{2.5a}$$

$$\sigma^2_{v,it} = e^{(z_{v,it}, w_v)} \tag{2.5b}$$

A simultaneous estimation of $\sigma^2_{u,it}$ and $\sigma^2_{v,it}$ avoid bias due to a model misspecification.

2.4 Data

The last two Brazilian Censuses (2006 and 2017) were chosen for the present analysis providing a pooled database from 1390 municipalities in 10 federal states.

The inclusion of municipalities in the Cerrado biome for this paper follows the specification of the Brazilian Agricultural Research Agency (EMBRAPA). A municipality is classified as belonging to the Cerrado biome if more than 50% of its area is in this biome.

The classification of MATOPIBA follows the definition of the strategic territorial intelligence group of EMBRAPA. Using this classification, 322 of all 337 municipalities of MATOPIBA are located in Cerrado.

Covered in this database is one output, four inputs, and eight variables that control for inefficiency. The descriptive statistics for the whole biome are shown in table 1.

We used as inputs in this analysis the number of workers (Labor [2]), the amount of agricultural area (Land), and the number of tractors (Capital). The GMO variable represents the share of harvest land planted with GMO seeds. The use of the variable

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[2] Family and non-family workers, older than 14 years old, including permanent, temporary and partner workers

harvest land planted with GMO is the only information available related to this technology in the agricultural censuses of Brazil in the respective years analyzed. This variable is a proxy to characterize the adoption of GM technology in Cerrado's crops.

To represent the outputs, we used the agricultural Gross Production Value (GPV). Due to the estimation method used, the revenue values (OUT; which is the same as GPV) from 2006 are normalized to the 2017 basis. To do this, we used an implicit price deflator Rada, Helfand e Magalhães (2019) based on the Internal Availability General Index Price (IGP-DI) as in Rada (2013). The variable t in the analyses indicates the year of the observation, with $t = 0$ for 2006 and $t = 1$ for 2017.

The majority of the data are available in the agricultural censuses at the municipality level. To create the Aridity Index (AI) for agricultural potential, we used the method proposed by Davis, Giuseppe e Zezza (2014), which is based on the mean annual precipitation and mean annual potential evapotranspiration. The higher the AI value, the wetter the location. The AI is an exogenous indicator displaying long-term conditions in a region.

$$AI_{i,t} = \frac{\overline{Precipitation_{i,t}}}{\overline{Potential\ Evapotranspiration_{i,t}}}$$

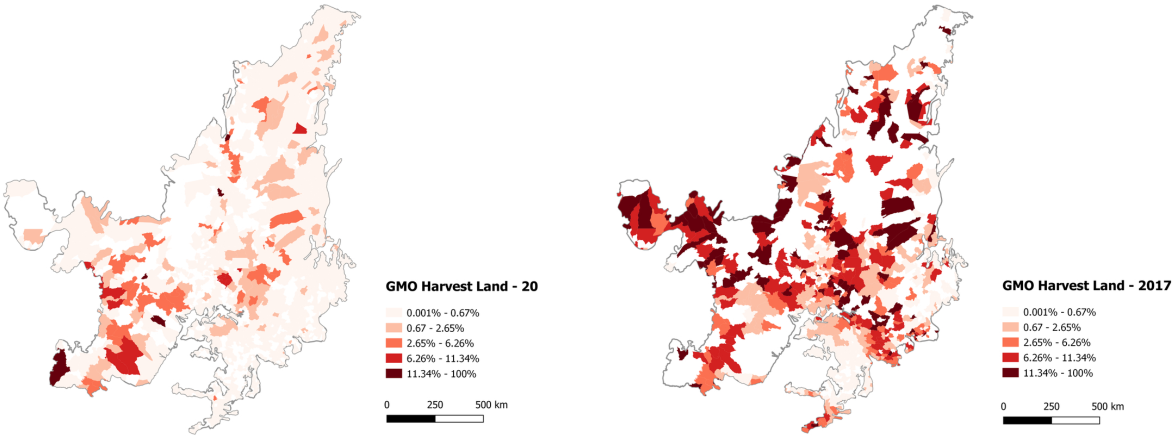
The database of precipitation and evapotranspiration used are of 2006 and 2016 from Sheffield, Goteti e Wood (2006) and Xavier, King e Scanlon (2016), respectively.

The descriptive statistics of Cerrado's output and inputs show that the total GPV increased 79.81%, and the deviation around the average also increased. This increase can be explained by the expansion of the maize and soybean crops across the biome between 2006 and 2017. At this time, maize and soybean production (tons) increased by 228.5% and 101.1%, respectively.

Among inputs, there was a notable increase in capital, with an average growth of almost 45%, while labor decreased by almost 28.18%. Rural credit incentives resulted in an increase in the use of tractors and trucks, which partly explains these input changes (BARICELO; VIAN, 2017).

The most significant impact on Cerrado's agricultural production in this period was the increase in the use of GMO seeds. While the total land in the biome harvested between 2006 and 2017 increased 83.60%, the amount planted with GMO seeds was 19 times greater. In a study of soybean crops in the US, GMO technology was shown to generate significant savings of labor (GARDNER; NEHRING; NELSON, 2009). Bustos, Caprettini e Ponticelli (2016) pointed out that the adoption of GMOs in Brazilian soybean crops showed similar results, which helps explain the decrease of labor in the Cerrado, where the soybean crops represented almost 50% of all agricultural land.

The adoption of GMO seeds in MATOPIBA and in the rest of Cerrado increased significantly between 2006 and 2017, as shown in figure 3. In 2006, the share of harvested crops planted with GMO seeds, in both, regions was 2.1% in MATOPIBA and 4.4% in the other regions of Cerrado. Eleven years later, on average, land planted with GMO seeds was, respectively, 43.8% and 47.6%.



((a)) 2006

((b)) 2017

Figure 3 – Share of harvested land planted with GMO seeds, per municipality

Source: Own elaboration from 2006 and 2017 Agricultural Census

For variables that support the control of heteroscedasticity of technical efficiency, we added the farm size variables, as described Helfand e Levine (2004), Helfand, Magalhães e Rada (2015), Helfand e Taylor (2020), which analyzed the efficiency and the TFP of farms by size. We are using the size classification by Helfand e Taylor (2020):

- Size 1: Small farms between 0 and 5 hectares, being defined as Small Farms;
- Size 2: Medium farms between 5 and 20 hectares, being classified as Medium Farms;
- Size 3: Medium farms between 20 and 100 hectares, being classified as Medium Farms;
- Size 4: Big farms between 100 and 500 hectares, being classified as Big Farms;
- Size 5: Big farms size has more than 500 hectares, being classified as Big Farms;

To support the control of heterocedasticity in the inefficiency term was added three other variables: *Cooperatives Association*, used as proxy of Social Capital (WOLLNI;

ZELLER, 2007; GEZAHEGN et al., 2019); *Schooling*, defined as years of study (BATTESE; COELLI, 1995) and *Aridity Index* (DAVIS; GIUSEPPE; ZEZZA, 2014), using evapotranspiration and precipation data.

Table 1 – Cerrado Descriptive Statistics, 2006 - 2017

		2006				**2017**			
	Unit	Mean	SD	Min	Max	Mean	SD	Min	Max
Output	$R\$$ 1000.00	87172.1	150804.2	233.8	1725491	156517.4	287622.9	286	3248127
Capital	$\#$ of Tractors	208.3	269.9	0	2424	302	384.2	0	3777
Land	Ha	112630.1	208973.2	351	5000952	119298.5	215239.8	31	5000982
Labor	$\#$ of Workers	3500.8	3732.8	59	33284	2514.0	2372.3	0	21812
GMO	%	0.0185	0.0604	0	1	0.1940	0.2593	0	.9530
Schooling	$\%$	0.0734	0.0763	0	0.6190	0.1313	0.0957	0	.5000
Social Capital	$\%$	0.3927	0.2396	0	0.9987	0.1389	0.1667	0	0.7987
Farm Size 1	%	0.0061	0.0121	0	0.1129	0.0099	0.0494	0	0.9934
Farm Size 2	%	0.0376	0.0427	0	0.3384	0.0381	0.0439	0	0.3864
Farm Size 3	%	0.1738	0.1252	0	0.8766	0.1665	0.1208	0	0.7098
Farm Size 4	%	0.2833	0.1450	0	0.8822	0.2494	0.1380	0	0.8499
Farm Size 5	%	0.3942	0.3036	0	0.9971	0.3345	0.2846	0	0.9949
Precipitation	mm	122.6	23.8	0	200	116.2	23.0	209.9	0
Evapotranspiration	mm	3.9	0.39	2.9	5.2	4.1	0.4	2.8	5.5

Source: Research Results

2.5 Empirical Model

A translog function form represents a twice continuously differentiable regional production function [3]. Its flexibility provides the benefit of eliminating arbitrary restrictions on substitution elasticities. Thus the technology can be represented as shown in equation 2.2:

$$\begin{aligned} Y_{i,t} =& \beta_0 + \sum_{k=1}^{4} \beta_k X_{i,k} + 0.5 \sum_{k=1}^{4} \sum_{j=1}^{4} \beta_{i,kj} X_{i,k} X_{i,j} + \alpha_0 t + \sum_{k=1}^{4} \alpha_{i,k} t X_{i,k} \\ &+ \mu_i \; M_i + \sum_{h=1}^{9} \gamma_i \; FS_i + v_i - u_i \end{aligned} \tag{2.6}$$

where β_0 is the state of technical knowledge; $Y_{i,t}$ is the natural logarithm of gross value of production of i_{th} municipality in time t; $X_k \; and \; X_j$ represent the natural logarithm production factors k, j (*Land*, *Labor*, *Capital* and *GMO*); M_i is a dummy variable for MATOPIBA and FS_i represents dummies for federal states.

We have imposed a half-normal distribution on the inefficient error term $[u \sim i.i.dN^{+}(0, \sigma_u)]$. The estimation of parameters for the maximum likelihood was accomplished using Stata 15 following the command *sfmodel* suggested by Kumbhakar, Wang e Horncastle (2015) [4].

All parameters are required to meet substitution elasticities and $\beta_{i,kj}$ coefficients greater than zero. Therefore, additional units of any input can never decrease the level of output, satisfying the monotonicity property (CHAMBERS, 1988).

The variable *FS* is defined as a dummy equal to 1 when the municipality belongs to a specific state of Cerrado, and 0 otherwise, The addition of this variable controls local and institutional heterogeneity.

The MATOPIBA dummy captures the impact of MATOPIBA on productivity. This dummy is 1 when the municipality is part of MATOPIBA, and 0 otherwise.

Differentiating equation 2.6 with respect to X_k captures the production elasticity/semi-elasticity related to these inputs:

$$\begin{aligned} s_k =& \frac{\partial y_i}{\partial x_{i,k}} \\ =& \beta_{i,k} + 0.5 \; \sum_{j=1}^{4} \beta_{i,jk} x_{i,j} + 0.5 \sum_{k=1}^{4} \alpha_{i,k} t \end{aligned} \tag{2.7}$$

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[3] (COELLI; PERELMAN, 1999; BRAVO-URETA et al., 2007) recommend that a translog function maybe prefered to a Cobb-Douglas function

[4] Because we are working with two years, the term $\frac{\alpha_2 t^2}{2}$ was suppressed in equation 2.6

To obtain the technical change between the two agricultural censuses, we differentiate equation 2.6 with respect to t:

$$\begin{aligned} TC_i = & \quad \frac{\partial y_i}{\partial t} \\ = & \quad \alpha_0 + 0.5 \ \textstyle\sum_{k=1}^{4} \alpha_{i,k} X_{i,k} \end{aligned} \tag{2.8}$$

The technical efficiency term (u_{it}) is defined by:

$$\begin{aligned} u_{i,t} \ &= \delta_0 \ + \ \delta_1 \ Schooling_{i,t} \ + \ \delta_2 \ SocialCapital_{i,t} \\ & + \ \delta_3 \ IA_{i,t} \ + \ \delta_4 \ Size \ 1_{i,t} \ + \ \delta_5 \ Size \ 2_{i,t} \ + \ \delta_6 \ Size \ 4_{i,t} \\ & + \ \delta_7 \ Size \ 5_{i,t} \ + w_{i,t} \end{aligned} \tag{2.9}$$

2.6 Results and Discussion

2.6.1 Production Elasticities

The stochastic frontier defined by equation 2.6 in a polled data structure was estimated for all municipalities of Cerrado with data available. Its relevant to point out that some potential bias selection due to endogeneity issues arising from the data structure. Table 3 in the Appendix shows the estimated parameters obtained by MLE with different assumptions (Model I, II, III, and IV). The differences among MLE models are due to the presence of FS dummies and the control of heteroscedasticity in the inefficiency term.

The central core of the stochastic frontier model is the specification of technical inefficiency, being necessary to test the existence of the one-sided error for the model. Using the LR test based on the log-likelihood values of the OLS and SF models, the null hypothesis of no technical inefficiency is broadly rejected. Model IV, an SF model with state dummies and exogenous inefficiency determinants, is the best model.

The Wald statistics show that the model fits well, rejecting the null hypothesis at 1% of joint insignificance of variables.

Table 2 demonstrated the coefficients of the stochastic frontier of the Cerrado as expected and the sum of input's elasticities ($s_{Capital}, s_{Labor} \ and \ s_{Land}$) shows a constant return to scale. Helfand, Magalhães e Rada (2015) and Morais (2019) found similar results in analysis with Brazilian whole country information.

Table 2 – Estimated Production Elasticities/Semi-Elasticity at the mean level for Cerrado

	Model I	Model II	Model III	Model IV
s_{Land}	0.073***	0.117***	0.119***	0.174***
	(0.0146)	(0.0173)	(0.0187)	(0.0214)
$s_{Capital}$	0.917***	0.804***	0.855***	0.774***
	(0.0151)	(0.0180)	(0.0194)	(0.0210)
s_{Labor}	0.060***	0.128***	0.065***	0.091***
	(0.0170)	(0.0202)	(0.0196)	(0.0217)
s_{GMO}	0.157	0.2513	0.300*	0.349**
	(0.1862)	(0.1783)	(0.1840)	(0.1760)
TC	0.161**	0.191***	0.151***	0.170***
	(0.0355)	(0.040)	(0.035)	(0.041)
FS	No	Yes	No	Yes
Inefficiency Control	No	No	Yes	Yes

$^{***}p < 0.01;^{**}p < 0.05;^{*}p < 0.1$

Source: Research Results

The positive and highly significant coefficients of Capital, Land, and Labor indicate that the value of output has increased more than inputs over the eleven-year period. The decrements in the number of workers and expansion of the number of tractors (as shown in the data section) correlate with these input elasticities.

Model IV shows that a labor increase of 10% will expand production, on average, 0.88%. A 10% expansion of capital produces almost eight times the expansion (7.74%), showing the relevance and impact of mechanization on Cerrado's agricultural production. The expansion of capital and its relevance in the agricultural production process is demonstrated by Gasques et al. (2012).

In the local landscape, which is broad and flat, large-scale crops, such as cotton, maize, and soybean are particular crops well suited to modern agricultural technology. In the Cerrado, 74.49% of total planted area in 2017 was devoted to these three crops (IBGE, 2017b)). Federal programs subsidized the purchase of modern equipment (Moderfrota, Moderagro, FINAME Agrícola, ...). These mechanical technologies, in conjunction with GMO technology, reduce the demand for labor in the agricultural sector, as described in Bustos, Caprettini e Ponticelli (2016).

In model IV, a 10% increase in land cultivated generated, on average, an increase of 1.76% in production. Is important to note that Cerrado's Agricultural GPV increased 79.81% between the two censuses, while land under cultivation increased just 6.07%. The relevance of this disparity is reflected in the changes in the price of agricultural land in Brazil, in all regions, which increased dramatically at all levels of productivity (low, medium, and high) (BACHA; STEGE; HARBS, 2016).

The Technical Change between 2006 and 2017 shows annual average productivity gains of 1.014% [5]. Thus, the most efficient producers in 2017 were able to produce almost 17% more than in 2006 without increased inputs. Helfand, Magalhães e Rada (2015) found a rate of technical change between 1985 and 2006 of 5% over all of Brazil and -2.81% in the Center-West of Brazil. Analyzing the same period of time Rada e Buccola (2012) and Rada (2013) got 4.54% for Brazil and 3.9% for Cerrado, respectively - a big range of difference in the literature.

In model IV, the GMO coefficient is represented by a semi-elasticity. A one percentage point increase in the planting of GMO seeds increases the output by 0.364%. This positive result conforms to a priori expectations, and correlates with several studies of the impact of GM technology on crops (QAIM; ZILBERMAN, 2003; ANDERSON; JACKSON; NIELSEN, 2005; BURACHIK, 2010; BAKHSH, 2017).

One aspect of the model's output results is problematic. The crop output is directly related to GM, the others contribute to the overall output figure, thereby inflating the perceived effect of GM as indicated by total output. Some alternatives were tried to address this problem, such as estimating the stochastic frontier using only information from temporary crops or family farming, although this re-sample was not possible because of the lack of some information, which could produce a jointness problem. The introduction of GM technology places also demands other technologies which can affect the technology contribution: more or different tractors, fertilizers, and irrigation equipment, may be needed.

GM's conspicuous role in production may have been pushed by the Brazilian Biosecurity Law, in 2005. Maize, soybeans, and cotton are the prevalent crops in the Cerrado, and also are the ones with the largest number of seed varieties. The consequence of the liberalization of GM seeds can be verified in the increase of the semi-elasticity of GMOs between 2006 and 2017, as shown in figure 4.

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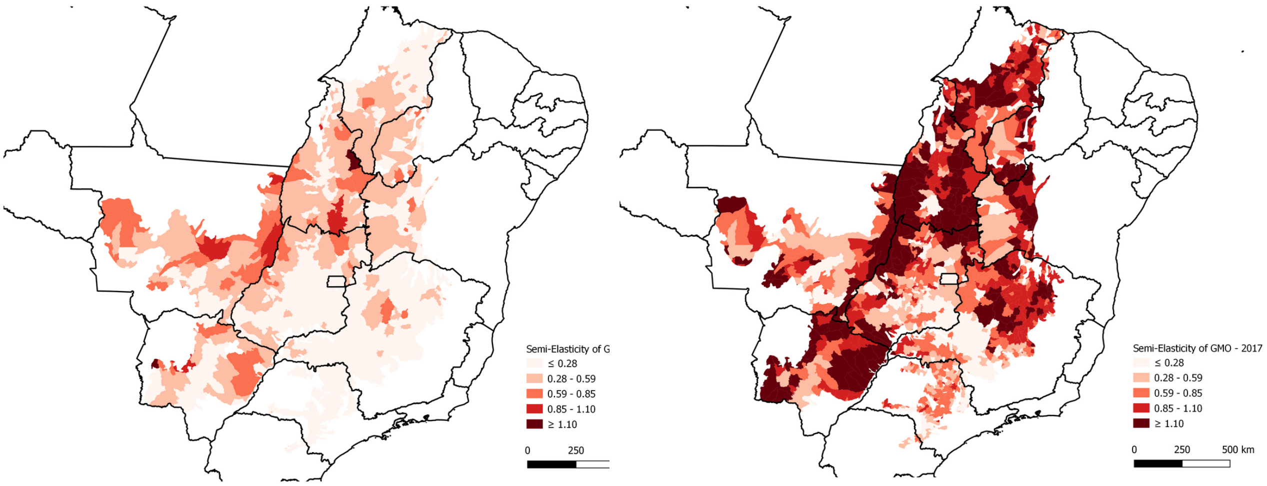
[5] $\sqrt[11]{1 + TC}$



((a)) 2006 ((b)) 2017

Figure 4 – Production Semi-Elasticity of GMO, per municipality

Source: Research Results

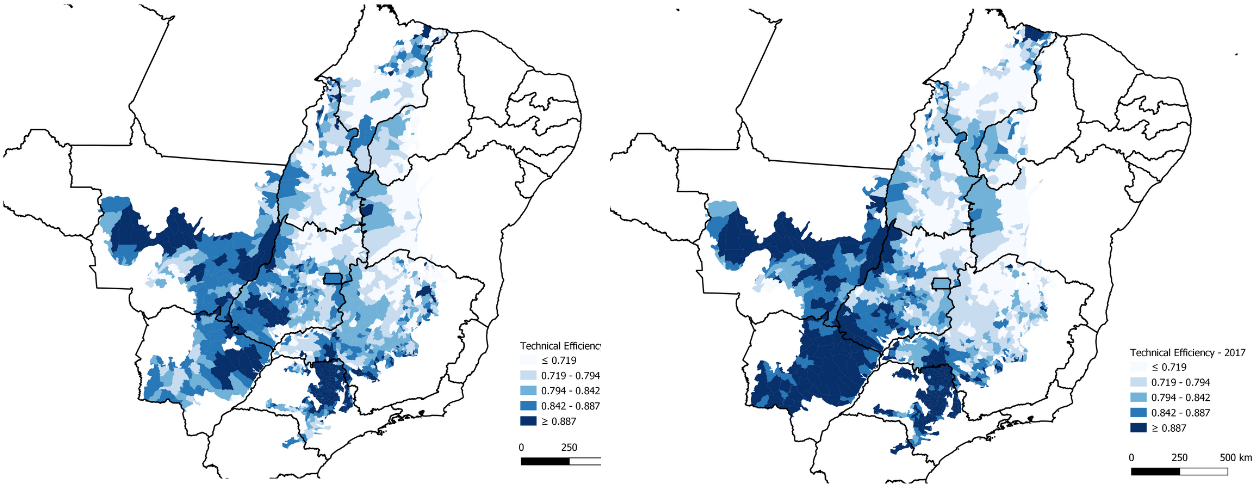
The accession of GMO is based on the indication that the way in which technology connects with other inputs, allows increasing production and saving inputs, supporting the decrease of the share of labor. So, the downshifted labor share and the increases in output per worker in the same period of time can be supported by Bustos, Caprettini e Ponticelli (2016) conclusion about GM technology is a labor-saving technical change.

The property of monotonicity, in which increased inputs lead to increased outputs, was violated in 799 observations of agricultural land in this study, 28.7% of the total observations. For labor, there 1091 violations (39.24%) and 11 for capital (0.3%).

2.6.2 Analysis of Technical Efficiency

When Technical Efficiency (TE), on average, is analyzed for all of the Cerrado, its value shows a small increase from 2006 to 2017, $TE_{2006} = 0.7964$ and $TE_{2017} = 0.7967$. Those coefficients show high technical efficiency in the Cerrado and a stable annual growth rate. Our results show positive rates while Rada (2013) research between 1985-2006 showed negative rates over time.

The differences between local growth rates of TE over the Cerrado biome are distinct and large. As shown in figure 5a, the greatest coefficients of TE in the Cerrado are located in the Center-West, São Paulo, and west of Minas Gerais, all regions with consolidated and a tradition of distinction in crops and livestock production, consistency with Bragagnolo, Spolador e Barros (2010).



((a)) 2006 ((b)) 2017

Figure 5 – Technical Efficiency rate, per municipality

Source: Research results

In 2017, the index of Technical Efficiency in the central and south regions of Cerrado maintains the same pattern as in 2006, but in greater magnitude.

While technical efficiency varies, the output of all states in the region has grown as a result of technological progress.

The results of heteroscedasticity control of technical inefficiency term, as demonstrated in equation 2.9, are shown in table 4 in Appendix.

Among all technical inefficiency controls estimated, only small farms (smaller than 5 ha) are not supported by the data. The total area of these farms was small in 2006 and decreased in 2017, so the absence of significance can be explained by the lack of variability of the share of the total cropland in the region.

The elevated heterogeneity across municipalities and farm size is reflected in the inefficiency control. Farms under 20 ha are not statistically significant for the analysis. Farms with more than 100 ha show greater inefficiency than those with 20 and 100 ha.

Our results differ from those in Helfand e Levine (2004). Their analysis of efficiency in farms from the Center-West of Brazil employed a data envelopment analysis to accommodate an output distance function. Their main result showed that efficiency behaved in a "U-shape"pattern. They found the highest level of inefficiency in farms between 100 and 2000 ha. Considering the average of farms from the category size 5 is 1138 ha and in 90% of Cerrado's municipalities have an average farm size of 2294 ha, our results are consistent with Helfand e Levine (2004), at least for the largest farms.

The other variables, Schooling and Social Capital, contribute positively to efficiency when compared with farms in other categories (lower level of education of the manager, for example). The effects of these variables are in line with the literature. The Aridity Index, as described by Davis, Giuseppe e Zezza (2014), significantly demonstrates that higher humidity increases technical efficiency.

Additionally, changes were also established in the inefficiency control elements. Both the exchange of Social Capital for the variable of Rural Technical Assistance and the inclusion of the interaction between schooling and Technical Change maintained the significance of the border elements.

2.6.3 The Dynamic of Production in MATOPIBA

The relevant proposal of this study is to analyze the relevance of productivity of the MATOPIBA region when compared with the other regions of Cerrado. The table 3 shows the μ coefficient is equal to 0.176, which means that the MATOPIBA region had a gain of productivity 17.6% bigger than the rest of Cerrado.

The expansion of the average land share of the region reflects the increment of its marginal productivity and impact on price. LIMA FILHO, Aguiar e Junior (2013) claim that land prices in Maranhão, Tocantins, Bahia, and Piauí, in 2010-2012, increased between 28.1% and 90%.

Even with the increment, the land price relative to other regions of the biome is lower and associated with the geographic position to export the production, making MATOPIBA a very attractive agricultural region, stimulating as well private investment (CHADDAD, 2016; MATTOS, 2019).

The advances of investments can be verified with the intensive use of capital and technology and large scale of production (BUAINAIN; GARCIA; FILHO, 2017). The increase in average semi-elasticity of GMO (figure 4), support this dynamic change of production between the two last agricultural censuses.

The emergence of corporate farms in Cerrado since the mid-2000s, especially in the newest agricultural frontier, which works with the basis: very large scale, professional management, and access to capital market - can express one of the productive changes of the region (CHADDAD, 2016).

The diversified pattern of production of MATOPIBA municipalities and, mainly, the recent agricultural occupation can be verified in the Technical Efficiency rate between 2006 and 2017. The value of the average technical efficiency is high (0.724 in 2006 and 0.704 in 2017), but lower than in the other regions of Cerrado. So it means that even the evolution of the productivity in some spots of the region turns explicit the inequality of production (BUAINAIN; GARCIA; FILHO, 2017).

The innovative practices adopted, as GM technologies, can also be positive productive spillovers over the region, not affecting only the main production region or just keeping inside of the farm's fence.

2.7 Conclusion

Innovation in the production system is considered when the resource allocation implies profitability, in turn affecting factors, especially in competitive markets. The measurement of genetic technology applied in agriculture is a relevant factor to support the comprehension of the technological change of the activity. The relationship between the technology and Cerrado's agricultural production was large between 2006 and 2017. The advance of 1 percentage point of harvested land planted with GMO seed increases, on average, the production by 0.364%.

Some regions, such as the North of Mato Grosso do Sul, and especially agricultural areas from Tocantins and Maranhão showed the highest results of the technological implementation. The advances over the Northeast of Cerrado can be verified in the average gains of productivity of MATOPIBA between 2006 and 2017.

So, the main idea of the paper about the greater productive dynamics in the new frontier, as well as the contribution of the new technology, could be observed in the present work.

For future works, it's possible to check the bias technical change developed by GM technology and also estimate a metafrontier between MATOPIBA and the rest of Cerrado. Another two future works can be the estimation of the distance function to achieve the direct impact of GMOs on crops. The last one tells about the possibility of the development of a quantity index, changing the gross production value, and avoiding some theoretical issues, as described by Malikov e Lien (2021).

Appendix - Chapter 2

Table 3 – Estimated coefficients from different models - SFA

$Y(GVP)$	Model I	Model II	Model III	Model IV
$Land$	0.550***	0.750***	0.718***	0.921***
	(0.159)	(0.162)	(0.164)	(0.168)
$Capital$	0.525***	0.164	0.482***	0.147
	(0.117)	(0.128)	(0.117)	(0.132)
$Labor$	-0.305**	-0.158	-0.336**	-0.167
	(0.144)	(0.146)	(0.147)	(0.155)
GMO	-3.999***	-2.902***	-3.218***	-2.364***
	(0.745)	(0.741)	(0.713)	(0.711)
t	0.534**	0.439*	0.369	0.304
	(0.257)	(0.252)	(0.256)	(0.254)
$Land^2$	-0.148***	-0.154***	-0.180***	-0.181***
	(0.0230)	(0.0234)	(0.0229)	(0.0238)
$Land * Labor$	0.0914***	0.0668***	0.125***	0.0956***
	(0.0182)	(0.0187)	(0.0175)	(0.0188)
$Land * Capital$	0.0797***	0.102***	0.0729***	0.0902***
	(0.0143)	(0.0150)	(0.0143)	(0.0156)
$Land * GMO$	0.545***	0.415***	0.476***	0.383***
	(0.0780)	(0.0780)	(0.0738)	(0.0739)
$Land * t$	0.0141	0.0290	0.0430	0.0592**
	(0.0301)	(0.0294)	(0.0300)	(0.0298)
$Labor^2$	0.0245	0.0234	-0.0224	-0.0260
	(0.0233)	(0.0233)	(0.0245)	(0.0247)
$Labor * Capital$	-0.163***	-0.133***	-0.143***	-0.112***
	(0.0125)	(0.0129)	(0.0128)	(0.0134)
$Labor * GMO$	-0.0894	-0.0940	-0.121	-0.133
	(0.111)	(0.108)	(0.109)	(0.107)
$Labor * t$	-0.0722**	-0.0795**	-0.0706**	-0.0887***
	(0.0331)	(0.0326)	(0.0338)	(0.0331)
$Capital^2$	0.169***	0.131***	0.140***	0.111***
	(0.0119)	(0.0132)	(0.0124)	(0.0136)
$Capital * GMO$	-0.339***	-0.205***	-0.261***	-0.161**
	(0.0753)	(0.0751)	(0.0758)	(0.0760)
$Capital * t$	-0.0242	-0.0234	-0.0487**	-0.0432*
	(0.0224)	(0.0220)	(0.0234)	(0.0234)
GMO^2	-1.209**	-1.395**	-1.239**	-1.435**
	(0.610)	(0.597)	(0.574)	(0.564)
$GMO * t$	1.262***	1.029***	1.113***	0.920***
	(0.304)	(0.299)	(0.295)	(0.290)
$MATOPIBA$	-0.0419	0.157**	-0.0337	0.176**
	(0.0327)	(0.0757)	(0.0366)	(0.0812)
$Constant$	4.691***	3.976***	4.074***	3.109***
	(0.856)	(0.868)	(0.799)	(0.814)
$States$	No	Yes	No	Yes
Log-Likelihood	-2526.43	-2456.37	-2410.20	-2349.29
Wald Test	13146.95	13977.21	997.90	9794.95
Prob > χ^2	0.0000	0.0000	0.0000	0.0000
Observations	2,753	2,753	2,753	2,753

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Source: Research Results

Table 4 – Estimated coefficients in respect of Inefficient Terms from different models-SFA

	Model I	Model II	Model III	Model IV
Inefficiency (U_{sigmas})				
$Size\ 1$			-1.831	-1.073
			(4.297)	(5.153)
$Size\ 2$			1.136	-4.626
			(2.750)	(3.487)
$Size\ 4$			5.917***	5.713***
			(0.880)	(0.922)
$Size\ 5$			2.084***	1.694***
			(0.587)	(0.604)
$Schooling$			-6.665***	-7.408***
			(1.882)	(2.307)
$Social\ Capital$			-1.587***	-1.573***
			(0.400)	(0.426)
$Aridity\ Index$			-0.107***	-0.110***
			(0.0147)	(0.0178)
$Constant$	-12.21	-12.31	-0.577	-0.194
	(439.9)	(463.3)	(0.582)	(0.637)
Inefficiency (V_{sigmas})				
$Size\ 1$			-3.273*	-3.420*
			(1.829)	(1.753)
$Size\ 2$			-1.145	-0.736
			(0.872)	(0.895)
$Size\ 4$			-2.026***	-1.989***
			(0.276)	(0.279)
$Size\ 5$			-0.668***	-0.717***
			(0.153)	(0.156)
$Schooling$			-0.110	-0.253
			(0.378)	(0.392)
$Social\ Capital$			0.224*	0.147
			(0.136)	(0.136)
$Aridity\ Index$			-0.00324	-0.00245
			(0.00582)	(0.00595)
$Constant$	-1.002***	-1.053***	-0.344*	-0.368*
	(0.0270)	(0.0270)	(0.202)	(0.206)
Observations	2,753	2,753	2,753	2,753

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Source: Research Results

3 The impact of pasture recovery in the agricultural GPV of Brazil's Cerrado

3.1 Introduction

The interweaving of global agriculture and the environment today raises concerns that are at the forefront of policy debates. Population growth, expansion of per capita income (especially in countries with a high-income elasticity of demand for food), and changing consumer habits have been the main drivers of demand for global agricultural commodities (GODFRAY et al., 2010; OECD/FAO, 2016).

To feed the world, agriculture has striven to boost productivity by increasing efficiency and the amount of land devoted to agriculture (FAO, 2017). However, the acceleration of productivity growth is hampered by the loss of biodiversity, pest diseases, and degradation of natural resources (FAO, 2017; FOLEY et al., 2011).

One of the main strategies to provide global food security is sustainable intensification, whereby technological improvements and specific management practices, increase agricultural yield without expanding agricultural area or causing significant negative environmental impacts (LAPOLA et al., 2014; DIAS et al., 2016).

Brazil and its Cerrado biome have been prominent in these agricultural considerations. In recent decades, the Brazilian Cerrado has become known as "one of the world‘s great breadbaskets" (ECONOMIST, 2010). Agricultural production in the Cerrado has also posed relevant environmental issues and these have not gained as much attention as those in other Brazilian biomes, like the Amazon and Atlantic forest (NEPSTAD et al., 2014; SCARANO; CEOTTO, 2015; GARCIA et al., 2017; SILVA; PERRIN; FULGINITI, 2019; SILVA et al., 2021).

The Cerrado developments in modern agriculture have contributed to local development and have expanded food production, but at the cost of a high conversion rate of native area (FILHO; COSTA, 2016; BOLFE; SANO; CAMPOS, 2020).

Sustainable intensification addresses this problem by recovering degraded pasture, allowing the continued increase in food and energy production without expanding into native areas, thus maintaining environmental equilibrium and also reducing CO_2 emission (FILHO; RIBERA; HORRIDGE, 2015; STRASSBURG et al., 2014). Assad et al. (2020) points out that transforming degraded pasture will raise production on that pasture. It seems directly when the degraded pasture offer low productivity (FELTRAN-

BARBIERI; FÉRES, 2021).

The transformation of degraded pasture to well-managed pasture can reduce emissions of greenhouse gas when combined with other techniques, such as a crop-livestock-forest integrated system, the intensification of cattle yields and the potential for carbon sinks in soil and biomass to offset cattle-related emissions (SILVA et al., 2015; FIGUEIREDO et al., 2017; AZEVEDO; RODRIGUES; SILVA, 2021).

So, the conversion of degraded pastures into productive agricultural areas is an important element in the intersection between agricultural expansion and environmental conservation. But it is also important to know, what additional income accrues when degraded pasture is converted into well-managed pasture?

The improvement of pastures efficiency implies increase of production (FELTRAN-BARBIERI; FÉRES, 2021), slowdown of deforestation (AZEVEDO; RODRIGUES; SILVA, 2021) and reduction of the GHG emission (SILVA et al., 2015). So, this research offers economic parameters for the adoption of public and private actions to mitigate environmental issues and support livestock production. The sizing of additional marginal gain from the pasture restoration can support the design of rural advisory services. Additionally, it can also be a guideline related to rural credit from ABC program, pointing out regions with the amount of credit per hectare lower than the marginal gains of recover, as in Piauí and Maranhão.

This discussion is associated with the microeconomics theory of marginal incentives. This association with an environmental incentive is similar to Richards et al. (2020), but instead of develop a public tool to pay for ecosystem services, the results indicate a direct incentive based on GPV gains.

So, considering the difference in pasture qualities over the elasticity of pasture productivity, this article contributes to the literature by measuring income gains in livestock production from the conversion of degraded pasture into the good planted pasture. To do this, we estimated an Output Distance Function associated with a technology-changing variable using data from the last two Brazilian agricultural and livestock censuses (IBGE, 2006; IBGE, 2017a). The measure established is directly and objectively based on local productivity and livestock Gross Production Value.

The body of this paper is divided into five additional parts. The first is background, examining degraded pasture and deforestation in Cerrado. The second is a theoretical model; the third is an empirical model and data. The fourth presents results and the last part is the conclusion.

3.2 Background

Pasture accounts for 27% of 203.4 million of hectares in the Brazilian Cerrado. In more than 10% of municipalities, at least 50% of the pasture is degraded to some degree(ANDRADE et al., 2017). In addition, the Cerrado has the highest potential for deforestation among Brazilian biomes, due to the absence of well-defined monitoring and surveillance programs (FILHO, 2018). Between 2006 and 2017, 11,555,342.43 ha was deforested in the Cerrado, as shown in figure 6 (PRODES/INPE, 2021).

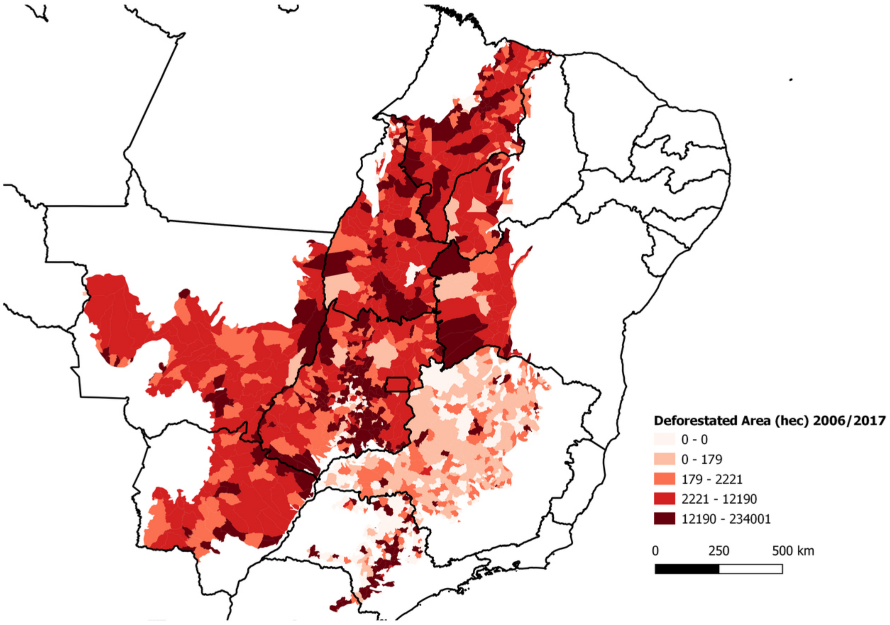


Figure 6 – Accumulated Deforestation in Cerrado - 2006 to 2017

Source: Own elaboration from Terra Brasilis Data

The high level of deforestation and a large amount of degraded pasture contradict Brazil’s commitments under the Paris Agreement (Observatório ABC, 2017a) and the Low Carbon Agricultural Program (Programa ABC - Agricultura de Baixo Carbono). The guidelines of this agreement call for reducing deforestation by 40% and recovering 15 million hectares of degraded pastures, implying potential mitigation between 83 and 104 Millions/t of $CO_2\ equivalent$ until 2030.

In addition to its environmental benefits, recovered pasture can expand the production of meat, grain, and timber while conserving the remainder of the Cerrado biome (SPERA, 2017).

Conversion of degraded pasture into planted pasture makes possible the intensification of livestock production in some regions of the Cerrado, increasing the number of cattle produced per hectare (FILHO, 2018). The advance in efficiency from profitable technological improvements creates further financial incentives to avoid deforestation

(LAPOLA et al., 2014; STRASSBURG et al., 2014; AZEVEDO; RODRIGUES; SILVA, 2021).

The conversion of forest to pasture can lead to expanded cropland (COSTA, 2010). This indirect expansion of crops is known as Displacement Deforestation (BARONA et al., 2010). First, the deforested area is converted to pasture for grazing, then it is planted for sugarcane and soybean crops (BRANDÃO; REZENDE; MARQUES, 2006; DIAS et al., 2016; FILHO, 2018; ARAÚJO et al., 2019).

Reclaiming degraded pasture can also relieve pressure on the price of land (REZENDE; HELFAND; REZENDE, 2003). Filho, Ribera e Horridge (2015) explain that large pastures can be an ”intensive frontier”, where land can be used for more profitable agricultural activities. Likewise, transforming pasture to cropland can stabilize or reduce land prices, especially in frontier regions where the price of virgin land for farming is rising (as in the MATOPIBA frontier) (LIMA FILHO; AGUIAR; JUNIOR, 2013). It also becomes more profitable to recover degraded pasture than to buy prime land for cultivation. So, the market price of land can also be a parameter when compared with the cost recovery of degraded pasture and the potential GPV from the recovered area.

So, the conversion of degraded pasture can have multiple benefits: It can decrease deforestation and reduce CO_2 emission, thereby addressing environmental issues. It can support food production, stimulate livestock intensification, and alleviate pressure on agricultural land price.

3.3 Theoretical Model

The singular nature of agricultural production requires precise terminology to define technological possibilities. Assuming the output properties described in Färe (1988), allow us to use the duality theory to obtain the shadow prices created by technology.

Modern agriculture is an aggregated production system with multiple inputs and outputs, in which function following a multi-output and multi-input process in which a set of inputs (x) is transformed into a set of outputs (y). A distance function is useful in evaluating such a system form (SHEPHARD, 1970). The output distance function provides a means to determine the maximum amount by which outputs could be expanded given available inputs (FULGINITI, 2010) and also determine how to maintain or increase outputs while decreasing inputs.

The output set $P(x)$ (or production possibility set) is defined for all output bundles that can be produced from input bundle x_t with technology Γ_t:

$$P(x_t) = \{y \in \mathbb{R}_+ : y \; is \; producible \; from \; x\} \tag{3.1}$$

So, the output distance function ($D_o(x_t, y_t, \Gamma_t)$), can be defined as:

$$D_o(x_t, y_t, \Gamma_t) = \ min\ \{\theta : \left(x; \frac{y_t}{\theta}\right) \in P(x)\} \tag{3.2}$$

where θ is the smallest factor by which is possible to deflect the output vector to find the maximum amount using the given input vector x in time t. For the most efficient municipalities, that is producing at the border of the output set ($\theta = 1$), while for inefficient municipalities is $\theta < 1$.

Equations 3.3 and 3.4 show the output distance function of non-decreasing, positive linearly homogeneous of degree 1 in output, convex in output, and decreasing in inputs.

$$D_o(x_t, y_t, \Gamma_t) \leq 1 \Longleftrightarrow y \in P(x) \tag{3.3}$$

$$D_o(x_t, y_t, \Gamma_t) = 1 \Longleftrightarrow y \in Iso\ P(x) \tag{3.4}$$

In the equations, $Iso\ P(x)$ is the boundary of the output set. If $D_o(x_t, y_t) < 1$, the output lies inside the border of the frontier, so technical inefficiency.

Using an output distance function instead of a production function has several advantages. One is a multiple input/output technology. A second is the duality of the revenue function. Using Sheppard's lemma, we can obtain the shadow prices directly from the distance function. Because the technology has convex sets $P(x)\ \forall\ x\ \in\ \mathbb{R}_+$ it is possible to prove that the following duality holds (GROSSKOPF; MARGARITIS; VALDMANIS, 1995).

$$R(x_t, y_t, \Gamma_t) = max_y\{ry : D_o(x_t, y_t, \Gamma_t) \leq 1\} \tag{3.5}$$

$$D_o(x_t, y_t, \Gamma_t) = max_y\{ry : R(x_t, y_t, \Gamma_t) \leq 1\} \tag{3.6}$$

where $r \in \mathbb{R}_+$ is a vector of output prices, and $R(x, r)$ is the revenue function.

In order to explore the duality of the output distance function and revenue function. we can differentiate $D_o(x, y)$ in respect of m^{th} output. This provides the marginal cost for output m ($\psi_m(x, y)$) (FULGINITI, 2010), also called shadow revenue (FENG; SERLETIS, 2010). Following the same assumption, differentiating $D_o(x, y)$ in respect of n^{th} input we obtain the marginal revenue for input n:

$$\frac{\partial D_o^t(x_t, y_t, \Gamma_t)}{\partial y_m} = \psi_m \tag{3.7}$$

$$\frac{\partial D_o^t(x_t, y_t, \Gamma_t)}{\partial x_n} = \omega_n \tag{3.8}$$

Changes in the distance function over time can reflect productivity. The increase in municipal productive efficiency is demonstrated in the displacement of its output distance function toward to the production possibility curve (Technical Efficiency change) (NEWMAN; MATTHEWS, 2007).

Over time, new technology shifts the boundary of maximum production possible, defined by the production frontier. To calculate the amount that the production frontier has shifted over time due to technological change, we use this equation:

$$\delta^t(x_t, y_t, A_t) = \frac{-\partial D_o(x_t, y_t, \Gamma_t)}{\Gamma_t} \tag{3.9}$$

The primal measure in equation 3.9 is productivity growth over time, not the level of efficiency.

In addition to the theoretical model ODF, in order to include the input quality, we make use of the technology-changing variable. Technology-changing variables are related to the quality of the endowments and also support the innovations and adoption of new technology. the resources (FULGINITI; PERRIN, 1993; FULGINITI; PERRIN, 1998). This technology-changing variable implies a variable coefficient, allowing it to be determined at any place and time. In this case, a vector of technology-changing variables is used to capture the coefficient of pastures, considering different qualities which impact productivity.

3.4 Empirical Model and Data

3.4.1 Data

The present analysis uses data at the municipal level from the last two Brazilian agricultural censuses (IBGE, 2006; IBGE, 2017a), which provide a pooled database on all municipalities from Cerrado. The classification of municipality occurs according to specifications of the Brazilian Agency of Agriculture Research (EMBRAPA), totaling 1390 municipalities.

The information about production is represented by a local agricultural GPV per activity: livestock (Y_{LS}), agriculture (Y_{Agri}), and other activities (Y_{Others}), which is basically timber. Those GPV are deflated by an implicit price deflator, as in Rada, Helfand e Magalhães (2019). Due to the estimation method, the GPV values from 2006 are normalized to the 2017 basis using the Internal Availability General Index Price (IGP- DI) and shown in table 5 per R$/1000.

The input variables for Labor (L) is measured by the number of farm workers [1],

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[1] Family and non-family workers, older than 14 years old, including permanent, temporary and partner

and that for capital (K) by the number of tractor for capital. The productive agricultural areas are divided into four parts: crops land (A_{Crops}), good planted pasture (A_{GP}), degraded pasture (A_{DP}) and Natural pasture (A_{NP}). Additionally, to control the productivity considering the soil characteristics, the frontier is also parameterized by the mean soil Suitability Index from each municipality from Sparovek et al. (2015). This index of soil quality varies between 0 (worst) and 1 (better).

Three exogenous determinants are included: *Schooling* represents the share of farm managers who have, at least, a bachelor's degree; *Social Capital*, represents the amount of agricultural land area in each municipality in production by a member of cooperatives [2] associated to the cooperative. The Aridity Index (AI) is based on the method proposed by Davis, Giuseppe e Zezza (2014), with the mean annual precipitation and mean annual potential evapotranspiration.

$$IA_{i,t} = \frac{\overline{Precipitation_{i,t}}}{\overline{Potential\ Evapotranspiration_{i,t}}}$$

The database of precipitation and evapotranspiration of 2006 and 2016 are from by Sheffield, Goteti e Wood (2006) and Xavier, King e Scanlon (2016), respectively.

Analysing the relation between GPV and land destined for livestock, GPV per hectare of pasture increased, on average, 88% between the two censuses. In 2006, the GPV average was R$ 428.53 with 47% of the municipalities in Cerrado having lower averages. In 2017, Cerrado's average GPV per hectare of pasture was R$ 805.87, with 48,75% of municipalities at less than the biome average.

It is important to note that the degraded pasture variable is obtained by self-report, so the information is not necessarily based on technical parameters. Not having data derived from standardized technical measurement introduces some uncertainty in data. The census respondents may categorize as degraded those areas whose productivity is lower than the other areas of the property.

The average share of degraded pasture among of pastures increased from 6.66% in 2006 to 8.11% in 2017.

Figure 7 shows the local percentage of degraded pasture in respect of the total agricultural area in the Cerrado. In 2006, areas of degraded pasture were spread throughout the region and displayed no pattern. By the 2017 census, degraded pasture had become more prevalent in deforested areas of the region, as shown in figure 6.

There was an expansion of the maximum share of degraded pasture, being 78.48% of the Nortelândia's (MT) pastures land in 2006, while in 2017 Padre Carvalho

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workers

[2] The share of land was used instead of the number of local farms to minimize any scale issue

Table 5 – Descriptive Statistics for agricultural inputs and output in Brazilian Cerrado - 2006 and 2017

2006	N	Mean	SD	Min	Max
Livestock GPV (R$/millions)	1387	24.95	59.06	0	1667
Agriculture GPV (R$/millions)	1387	61.02	12.81	0	1502
Other GPV (R$/millions)	1387	0.422	1.99	0	48
Capital (number of tractors)	1372	208.37	269.90	0	2424
Labor (number of workers)	1387	3500	3733	59	33284
Crop Land (ha)	1387	17690.92	37216.15	17	500981
Natural Pasture (ha)	1384	17058.68	86362.01	0	2957015
Good Planted Pasture (ha)	1384	37306.19	73340.25	0	1030769
Degraded Pasture (ha)	1384	3869.31	7397.72	0	103006
Natural Pasture (%)	1384	0.367	0.261	0	1
Good Planted Pasture (%)	1384	0.565	0.250	0	1
Degraded Pasture (%)	1384	0.066	.072	0	0.7848
Total Pasture (ha)	1387	58234.12	138692.4	0	3695164
Schooling (%)	1390	0.0734	0.0763	0	0.6190
Aridity Index	1390	30.8802	5.9969	0	51.1272
Social Capital Land (%)	1390	0.3927	0.2396	0	0.9987
Suitability Index Mean	1390	469.09	76.24	206.87	703.55
2017	N	Mean	SD	Min	Max
Livestock GPV (in millions)	1389	44.89	73.10	39	993
Agriculture GPV (in millions)	1389	107.38	24.88	0	2993
Other GPV (in millions)	1359	5.13	24.36	0	538
Capital	1383	301.97	384.19	0	3777
Labor	1383	2372	2372	0	21812
Crop Land	1389	22772.99	50704.63	0	579271
Natural Pasture	1384	13842.45	72273.57	0	2359794
Good Planted Pasture	1384	37463.58	71605.95	0	923658
Degraded Pasture	1384	4414.58	9348.23	0	98092
Natural Pasture (%)	1384	0.306	0.260	0	1
Good Planted Pasture (%)	1384	0.612	0.261	0	1
Degraded Pasture (%)	1384	0.081	0.117	0	0,906
Total Pasture (ha)	1387	55720.62	128185.8	0	3199736
Schooling (%)	1389	0.1313	0.0957	0	0.500
Aridity Index	1390	28.5337	7.3089	0	54.5096
Social Capital Land (%)	1389	0.1389	0.1667	0	0.7987
Suitability Index Mean	1390	469.09	76.24	206.87	703.55

Source: Research Results

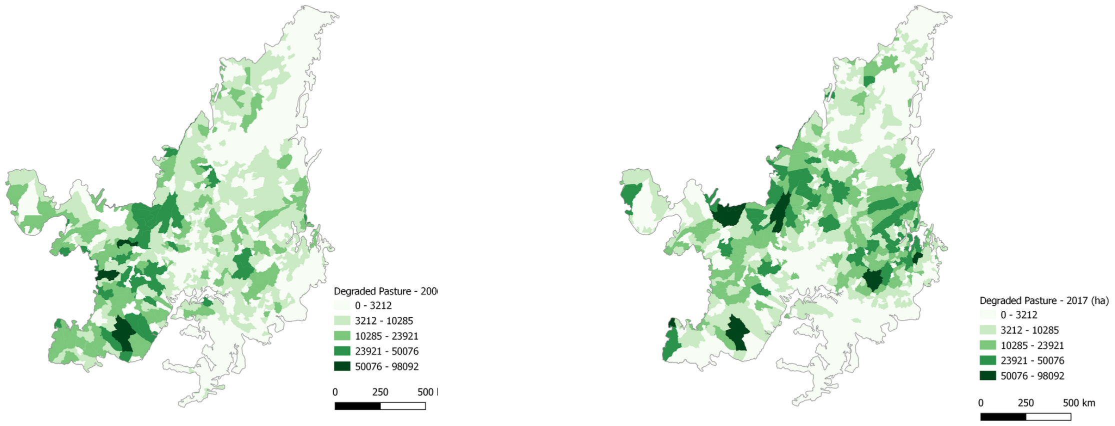
(MG) got 90.6% of its pasture were degraded. It is noteworthy that regions with greater degradation show a possible management problem. Municipalities with the highest shares of degraded pasture in both years of analysis do not have a great number of animals per hectare of pasture.

When analyzed the dynamics of degraded pastures between 2006 and 2017, the regions that showed a decrease in the portion of degraded pasture are those with more consolidated livestock production, such as southeast of Mato Grosso, central region of Goiás, a major part of Mato Grosso do Sul and a large part of the west of Minas Gerais. Within these, some regions stand out, such as Rondonópolis (MT), Coxim (MS), Goiás (GO) and Uberlândia (MG), Bom Despacho (MG). These regions had a decrease in the share of degraded pasture, even with an increase in the herd.

Considering regions that showed an increase in the share of degraded pasture, there is a major part of MATOPIBA and the North of Minas Gerais. The negative highlight is precisely the North of Minas Gerais and also the northern region of the Cerrado from Maranhão, which had an increase in their degraded pastures, even with a diminishing in the cattle herd.

Even with the dynamics from Agricultural Census, these scenarios are very optimistic when compared with analyses based on technical classifications, obtained from satellite and remote sensing technology. Using this technology (ANDRADE et al., 2016) and Andrade et al. (2019) show three scenarios (realistic, moderated and optmistic). In the optimistic scenario, 24% of pasture in the Cerrado exhibits some level of degradation. In the realistic scenario, 55% of pasture shows some level of degradation. In the middle, or moderated, scenario, 43.3% of pasture shows some level of degradation.

Based on the number of cattle per hectare, the database from the Image Processing and geoprocessing Laboratory (LAPIG/UFG, 2020) agrees with the moderated scenario points out that 43% of the pasture is degraded. Working with underestimated (optimistic) results for the amount of degraded pasture can have a ripple effect on other data and affect other results. Merging data obtained from different systems of measurement introduces errors in the results. For example, mixing databases of the amount of degraded pasture produced land area totals exceeding those found in the censuses.



((a)) 2006 ((b)) 2017

Figure 7 – Percentage of Degraded Pasture per municipalities

Source: Own elaboration from Agricultural Census

3.4.2 Specification

To demonstrate the effectiveness of the agricultural technology used in reclaiming degraded pasture, we use this Output Distance Function:

$$D_o(x,y) = f(A_{Crops}, A_{Pasture}, K, L, Apt, Y_{Agri}, Y_{LS}, Y_{Others}) \tag{3.10}$$

In this analysis we used a Cobb-Douglas functional form, which allows the imposition of homogeneity of degree 1 on outputs and the separability among inputs in a short term (COELLI; PERELMAN, 1999; BRAVO-URETA et al., 2007). Thus, the estimated parameters α_* give the elasticities for output distance for each input and β_* for each output.

So, the distance function including the technology change variable (FULGINITI; PERRIN, 1993) can be demonstrated as:

$$D_o = A_{Crops}^{\alpha_1}.A_{Past}^{\zeta}.K^{\alpha_3}.L^{\alpha_4}.Y_{Agri}^{\beta_1}.Y_{LS}^{\beta_2}.Y_{Others}^{\beta_3} \tag{3.11}$$

where

$$\zeta = \alpha_{20} + \alpha_{21}.\%A_{GP} + \alpha_{22}.\%A_{DP}$$

Knowing that $A_{DP} = A_{Past} - A_{GP} - A_{NP}$ [3], an increase in the amount of good pasture (A_{GP}) is from degraded pasture (A_{DP}) [4] would affect the level of livestock production.

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[3] $\%A_{GP}$ and $\%A_{DP}$ are the share of good and degraded pasture per municipality, respectively

[4] the same local productivity level

Using the homogeneity property, as follows, outputs and inputs can be adjusted:

$$D_o = \Lambda . Y_{Agri}^{\beta_1} . Y_{LS}^{\beta_2} . Y_{Others}^{\beta_3} \tag{3.12}$$

where $\Lambda = A_{Crops}^{\alpha_1} . A_{Past}^{\Gamma} . K^{\alpha_3} . L^{\alpha_4}$, so dividing both sides for Y_{Others}:

$$\begin{aligned} \frac{D_o}{Y_{Others}} =& \Lambda . \frac{Y_{Agri}^{\beta_1} . Y_{LS}^{\beta_2} . Y_{Others}^{\beta_3}}{Y_{Others}} \\ =& \Lambda . \frac{Y_{Agri}^{\beta_1} . Y_{LS}^{\beta_2}}{Y_{Others}^{1-\beta_3}} \end{aligned} \tag{3.13}$$

for homogeneity of degree 1, $\beta_1 + \beta_2 + \beta_3 = 1$, so:

$$\begin{aligned} \frac{D_o}{Y_{Others}} =& \Lambda . \frac{Y_{Agri}^{\beta_1} . Y_{LS}^{\beta_2}}{Y_{Others}^{\beta_1+\beta_2}} \\ =& \Lambda . \frac{Y_{Agri}^{\beta_1} . Y_{LS}^{\beta_2}}{Y_{Others}^{\beta_1} . Y_{Others}^{\beta_2}} \\ =& \Lambda . \left(\frac{Y_{Agri}}{Y_{Others}} \right)^{\beta_1} . \left(\frac{Y_{LS}}{Y_{Others}} \right)^{\beta_2} \\ =& \Lambda . \left(\widetilde{Y_{Agri}} \right)^{\beta_1} . \left(\widetilde{Y_{LS}} \right)^{\beta_2} \end{aligned} \tag{3.14}$$

Using homogeneity of Degree 1 in inputs, we can take logarithms from both sides of the equation, as shown in equation 3.15. The varying inefficiency among municipalities is accounted for by setting the distance between 0 and 1 $(0 \geq D_o \geq 1)$:

$$\begin{aligned} -\ln Y_{Others_{ti}} =& \beta_{0_{ti}} + \beta_1 . \ln \widetilde{Y_{Agri}} + \beta_2 . \ln \widetilde{Y_{LS}} + \alpha_1 . \ln A_{Crops} + \\ & \alpha_{20} . \ln A_{Past} + \alpha_{21} . \% A_{GP} . \ln A_{Past} + \alpha_{22} . \% A_{DP} . \ln A_{Past} + \\ & \alpha_5 . \ln K + \alpha_6 . \ln L + \delta t_i + \sum_{h=1}^{9} \psi_i \; FS_i + v - D_{o_{ti}} \end{aligned} \tag{3.15}$$

To support the control of heterogeneity, We also included FS_i to represent dummies for federative states and t is Technical Change.

In equation 3.15, the inefficient error term takes as given a half-normal distribution $[D_o = u \sim i.i.d \; N^{+}(0, \sigma_u)]$.

The exogenous determinants of inefficiency (schooling, social capital, and aridity index, as described previously) supports the control of heteroscedasticity (CAUDILL; FORD, 1993).

The estimation of parameters by maximum likelihood was done using Stata 15 following the command *sfmodel* suggested by Kumbhakar, Wang e Horncastle (2015).

3.4.3 Impacts of Transformations of Degraded Pastures into Productive Land

Adjusting equation 3.12, we have:

$$\begin{aligned} D_o = \alpha_1 \ln A_{Crops} + \alpha_{21}\left(\frac{A_{GP}}{A_{Past}}\right)\ln A_{Past} + \alpha_{22}.\left(\frac{A_{DP}}{A_{Past}}\right)\ln A_{Past} \\ + \alpha_{20}\ln A_{Past} + \alpha_3 \ln K + \alpha_4 \ln L + \beta_1 \ln \widetilde{Y_{Agri}} + \beta_2 \ln \widetilde{Y_{LS}} \end{aligned} \tag{3.16}$$

Applying the implicit function theorem as in Rada, Buccola e Fuglie (2011), Rada e Valdes (2012) and Rada (2013) we can analyze the transformation of the region degraded pasture area into good planted pastures with the same yields average from the region.

Defining the various types of pasture as being related just about quality in all areas of the region, as shown in the following equations, eliminating their effects on efficiency (Distance).

$$\begin{aligned} \frac{\partial Y_{LS}}{\partial A_{GP}} =& Y_{LS}.\left[\frac{(\alpha_{22}-\alpha_{21}).\ln A_{Past}}{\beta_2 A_{Past}}\right] \\ &= Y_{LS}.\gamma_{GPLS} \end{aligned} \tag{3.17}$$

where γ_{GPLS} is a semi-elasticity for good planted pastures to livestock production, that means, a hectare of good pasture affecting livestock production $\gamma_{GPLS}\%$.

3.5 Results and Analysis

The Cobb-Douglas output distance function, defined by equation 3.15 in a polled data structure, was estimated for all municipalities of Cerrado with information in all variables from the 2006 and 2017 agricultural census. Its relevant to point out that some potential bias selection due to endogeneity issues arising from the data structure. The table 6 shows the estimated parameters obtained by COLS, for the first step, and MLE with different assumptions. The difference between MLE models is the presence of exogenous controls of heteroscedasticity in the inefficiency term.

The specification of technical inefficiency and the model which controls the heteroscedasticity of one-sided error term was defined by the LR test based on the log-likelihood values. The model's statistical test is 238.32 and the critical value at 1%

significance level is 12.48 (KODDE; PALM, 1986), so the null hypothesis of no technical inefficiency ($\sigma_u^2 = 0$) was rejected. So, the best model estimated is the ODF with exogenous inefficiency determinants.

Table 6 – Estimated coefficients from Output Distance Function

	COLS	MLE	MLE
Crop Land	-0.1815***	-0.2197***	-0.1739***
	(0.0140)	(0.01441)	(0.0137)
Share of Degraded Pasture	0.1008***	0.1028***	0.0799***
	(0.0137)	(0.0137)	(0.0129)
Share of Good Pasture	-0.0482***	-0.0402***	-0.0430***
	(0.0057)	(0.0057)	(0.0056)
Pasture Land	-0.2759***	-0.2212***	-0.2671***
	(0.0154)	(0.0162)	(0.0151)
Capital	-0.2801***	-0.2881***	-0.2438***
	(0.0179)	(0.0172)	(0.0178)
Labor	-0.2721***	-0.2727***	-0.2921***
	(0.0188)	(0.0187)	(0.0189)
Agriculture GPV	0.2515***	0.3002***	0.2470***
	(0.0091)	(0.0108)	(0.0094)
Livestock GPV	0.6745***	0.6271***	0.6847***
	(0.0095)	(0.0109)	(0.0097)
t	-0.7025***	-0.6832***	-0.6997***
	(0.0331)	(0.0322)	(0.0364)
Suitability Index	-0.0013***	-0.0012***	-0.0011****
	(0.0002)	(0.0002)	(0.0002)
Constant	-0.6397***	-0.6387***	-1.1907***
	(0.2176)	(0.5671)	(0.2139)
States	Yes	Yes	Yes
Inefficiency Control	-	No	Yes
Log-Likelihood	-	-2473.91	-2393.51
Wald Test	-	68112.75	63627.67
Prob > χ^2	0.0000	0.0000	0.0000
Observations	2718	2718	2718
Source: Search Results			

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Source: Research Results

In Table 6, shows that the properties of output distance function are obtained, so was expected a monotonic model, increasing in the outputs and non-increasing among inputs. The technology change variable (ζ) is calculated based on equation 3.12, which means that a 10% change in the pasture area shifts the production function -0.2866. Complementary, the sum along with the other inputs coefficients (α_1, α_3 and

α_4) is equal to 0.9964, showing the aggregated technology has constants return to scale. The possibility to define a duality among output distance function, revenue function and indirect output distance function is defined by the constant return to scale property (FÄRE; GROSSKOPF, 1994).

In Table 6, assumptions expected for an output distance function is verified. The average marginal cost of livestock is greater than the agriculture and other activities marginal cost [5]. When observing the marginal GPV for each input, the same dynamic is observed, by which pasture land shows the highest marginal GPV.

The elasticity of productivity of the technology changing variable related to pasture area is obtained by the mean value of pasture area variables and their coefficients. The effect of pasture degradation indicates a negative impact on the productivity of the land, while the increment of good pasture has a positive impact. Considering the huge stock of good and natural pasture, the direct marginal contribution of good pasture can be short. Although the impact of increment of pastures without management can result in a significant consequence, directly overproduction and also environmentally.

As shown in equation 3.15, the distance from the frontier is analyzed as an inefficiency. The average distance estimated was 0.8354, so, for an average municipality, the output production is 83.54% of the potential output.

The technical change shows an increase in technology between the two agricultural censuses. In an ODF, keeping the same level of efficiency, is necessary for an increase in production, with an annual rate is 4.95% [6]. Rada (2013) estimated an Input Distance Function, for the period of time between 1985 and 2006 and got an average technical change for Cerrado equal to 4.17% for Crops and 4.51% for Livestock.

All the exogenous variables to control the inefficiency of the ODF behave as expected. Social capital, represented by the cooperative association, works to increase local efficiency. This contribution can be related to technical assistance (WOLLNI; ZELLER, 2007; GONG; BATTESE; VILLANO, 2019) and also be related to a more equal distribution of wealth/income (MA et al., 2018). And, where describe that share of farmers with high educational level works with more technical efficiency (BATTESE; COELLI, 1995). The Aridity Index also has a positive impact on the technical efficiency, so as much as the environment has humidity, the less inefficient is the local agricultural production.

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[5] Follow the Homogeneity of degree one, that marginal cost of other activities is 0.0683

[6] $\sqrt[11]{1+t}$

Table 7 – Technical Efficiency Exogenous Control

Social Capital	4.0677*** (0.7583)
Aridity Index	0.0613*** (0.0136)
Schooling	23.4483*** (4.4839)
Constant	-1.5581*** (0.3595)

Source: Research Results

3.5.1 GPV from Recovered Pastures

The figure 8 shows the average semi-elasticity of livestock GPV from good converted pastures. This semi-elasticity is sensitive in relation to the size of the pasture area, as shown in equation 3.17. Comparing the magnitude of it and the pasture area (figure 10 in appendix), in regions where the livestock is a traditional and consolidated activity, as in Mato Grosso do Sul or in the west of Minas Gerais, the γ_{GPLS} shows a short impact of restoration of pastureland.

Regions with a high γ_{GPLS}, São Paulo and north of Maranhão, don't have large pasture areas. São Paulo concentrated, in 2017, almost 60% of sugarcane planted area in the biome (IBGE, 2017b), while Maranhão, is close to the Atlantic Ocean and is a traditional tourist area, as Primeira Cruz and Barreirinhas, cities located in Lençóis Maranhenses National Park. The concentration of animals per hectare (figure 11 in appendix) is also more intensive in those regions where the γ_{GPLS} is bigger, resulting in a more prominent impact on recovery.

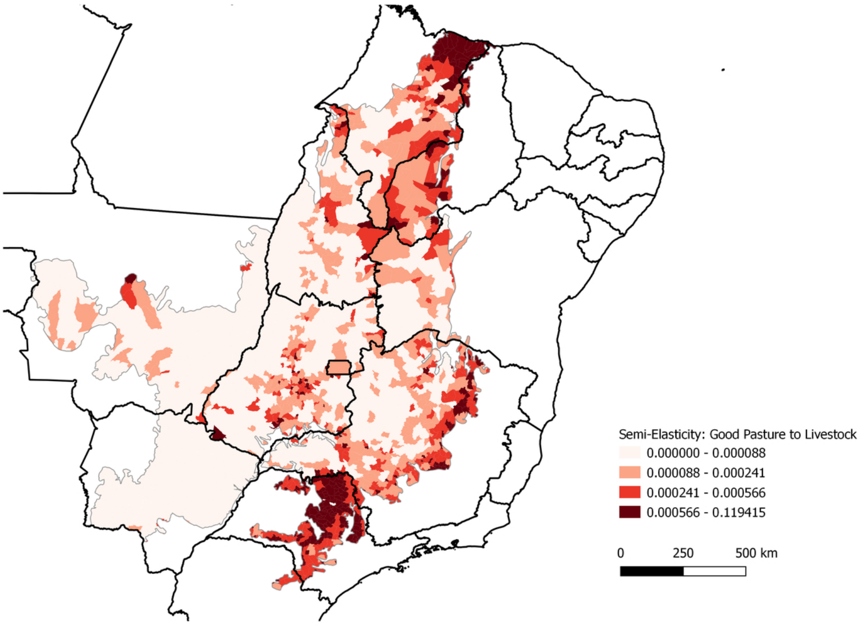

Figure 8 – Semi-Elasticity of Livestock GPV from Good Pastures (γ_{GPLS})

Source: Own elaboration from the research results

The table 8 shows a sample of municipalities and their γ_{GPLS}. The γ_{GPLS} from cities with large pastureland areas is lower than regions with reduced pasture area. In fact, in regions where the activity is consolidated (Mato Grosso, Mato Grosso do Sul, and west of Minas Gerais) the marginal conversion of one hectare has a small impact on production when compared with other regions, as in the north of Maranhão, west of Piauí and São Paulo.

Table 8 – Sample of some local results

Municipality	A_{Past}	γ_{GPLS}	Size of Herd in 2017	Deforestation
Belágua (MA)	12 ha	0.106445	1430	33522 ha
Guariba (SP)	43 ha	0.0438	794	0 ha
Americana (SP)	57 ha	0.0354	1000	0 ha
Água Doce do Maranhão (MA)	156	0.0161	1755	401 ha
Padre Carvalho (MG)	2757	0.001431	1563	5 ha
Santa Isabel (GO)	36021	0.000145	75185	12659 ha
Patrocínio (MG)	59841	9,15E-07	115004	1274 ha

Source: Research Results

When analyzing the municipalities from the northwest of Cerrado, especially Piauí and Maranhão, those municipalities also have the highest coefficients. Even municipalities with big γ_{GPLS} without large pasture area and a significant amount of animals, as in Maranhão and Piauí, presented high deforestation between 2006 and 2017. The share of degraded pasture increased in the main part of that region, and in the north of

Maranhão increased even with a diminishing of animals. An implication of this degradation and a great amount of animals per hectare is the significant amount of farms that started a nutritional supplementation to the herd, increasing the cost of production.

In the figure 9, verified the economic impact to convert degraded pasture into a good planted pasture. It means a marginal increase of local GPV caused by the recovery of one hectare of degraded pasture.

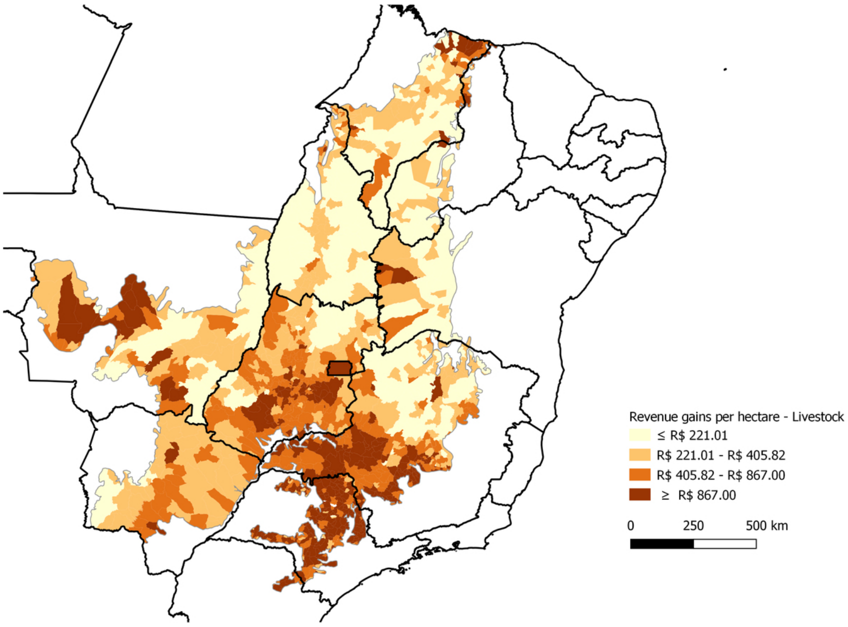

Figure 9 – GPV of Livestock from Good Pastures

Source: Own elaboration from the research results

Figure 9 shows regions where the livestock GPV is bigger, the economic incentive to recover degraded pasture is higher. In those regions, such as MATOPIBA, where the return of recovery is lower, the incentives to do deforestation are bigger. So, it could explain the high levels of deforestation to convert in the agricultural areas in this region in the northeast of Cerrado.

Costa (2010) and Zimmer et al. (2012), from Brazilian public agricultural research corporation (EMBRAPA) developed parameters of pasture recovery cost. The cost per hectare to recovery obtained by Costa (2010), based on Mato Grosso do Sul costs, was R$ 300.62 [7]. Zimmer et al. (2012) in turn, showed different techniques of recovery and, consequently, different costs of pasture conversion. The range obtained by then was between R$ 14.10 and R$ 652.46[8].

Analysing the cost of recovery of one hectare of degraded pasture to increase the average local productivity, both costs are lower than the livestock GPV per hectare

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[7] This value was restated by IGP-DI from 2010 to 2017

[8] These values were restated by IGP-DI from 2012 to 2017

in 2017 of all municipalities.

So, considering the marginal GPV, which means additional local livestock GPV, to convert one hectare of degraded pasture into the good planted pasture, in 2017 34% of municipalities from Cerrado showed average gains per hectare higher than the most expansive cost of recovery (R$ 652.46), while 61.8% showed marginal GPV higher than R$ 300.62.

Estimating the additional GPV in 2017 to recover all degraded pasture area in Cerrado, considering just local net GPV based on the highest cost of recover [9] and local degraded pasture area, the residual livestock GPV to recover all area could be R$ 332 million.

Some regions, such as MATOPIBA, where the level of deforestation in recent years increased, show that 77 municipalities from the total of 322 show a gain higher than R$ 300.62 and 17 in respect of R$ 652.46. A great part of those municipalities are from Maranhão and Tocantins, both states with the highest level of deforestation between 2006 and 2017 in Cerrado (PRODES/INPE, 2021). So, if the land use of the deforested areas is being directed to pasture, those municipalities have incentives to avoid deforestation and recover their degraded pastures.

A very important issue about this pastures conversion in respect of this maintenance of forest and diminishing GHG emission, in which those values analyze just direct gains, without measuring any environmental benefits. These environmental issues can be pointed out by rural credit lines from ABC Program to recovery pasture. In 2016/17, the amount of R$ 933 million was destined to states where Cerrado is present [10] (Observatório ABC, 2017b). The average of credits destined for one hectare of degraded pasture was just R$ 6.24 in Piauí, R$ 16.51 in Bahia and R$ 94.22 in Maranhão. Considering the regions where the advances of deforestation are higher, the amount of resources per hectare is low, especially when compared with potential returns of restoration.

Is important to indicate the amount of degraded pasture used to estimate semi-elasticity is self-reported by the farmer. The crucial element of the implementation of more efficient and productive technologies is the recognition of producers about the quality of pasture (LATAWIEC et al., 2017). Considering the analysis of Andrade et al. (2016), Andrade et al. (2019) our values could be underestimated, so it can inflate the marginal GPV of livestock from each municipality.

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[9] Local GPV per Hectare - Cost of recover (R$ 652.46)

[10] This amount also includes resources destined to regions out of Cerrado

3.5.2 Robustness checks

We carried out some robustness analysis to test the sensitivity of estimation results to changes in some samples of Cerrado. Details of these estimations from different samples are shown in table 9 (Appendix). Sample I is related to the Cerrado, excluding the new agricultural expansion area (MATOPIBA). Its sample has 83.2% of whole degraded pasture in the Cerrado, according to IBGE (2017a). Sample II is municipalities from the three states with the highest percentage of degraded pasture area expansion (Minas Gerais, Bahia, and Piauí).

We included information from the original model. The magnitude of the Degraded Pasture changes a little, as one would expect because Degraded pasture is correlated with other pasture areas, such as natural and good pasture, and also the farmer's metric about the degradation level of the area. However, the signs of the whole coefficients do not change.

3.6 Conclusion

The necessity to the expansion of agricultural output along with environmental preservation is challenging. Recovery of degraded pasture is a potential solution to the lack of agricultural land.

The present paper estimated the marginal GPV to convert degraded pasture into the good planted pasture. The results show that having two technical parameters of costs of recovery of a degraded pasture, 34% of municipalities of Cerrado show positive net earnings.

Beyond the diminishing efficiency and productivity, degraded pasture can implies deforestation and GHG emission. More than just boosting agricultural production, the recovery of degraded pasture also has environmental benefits. Due to the externalities caused, pasture actions make this a strategic factor beyond the producer. Policymakers and private sector agents come into the discussion in favor of environmental issues.

The estimation of marginal gains to recovery pasture can support the development of actions, such as adjustments in rural credit line focused on restoration, as developed by the ABC Plan, especially in regions with high levels of deforestation and a large area of degraded pasture, as in northeast of Cerrado.

Additionally, the good balance between agricultural improvements and environmental protection requires efforts further than just offering rural credit. Instruments to minimize problems of credit access, as rural assistance advisory can be a supportive plan of action (LATAWIEC et al., 2017). It looks relevant when just 41.2% of Cerrado's pasture area has some kind of technical assistance (IBGE, 2017a). The majority of these areas are located in Mato Grosso, Mato Grosso do Sul, south of Goiás, and west of Minas Gerais.

Furthermore, new market strategies, such as green bonds, aimed at developing actions focused on environmental issues can take advantage based on these results. This market instrument can also be an alternative investment in climate change and sustainable development finance frameworks.

For future works, we can work on a dimension of environmental gains earned by non-deforestation; the estimation of marginal GPV of conversion of degraded pasture into agricultural land, considering the livestock impact. To support an expansion of literature discussion, the implementation of quantity index is also a future discussion, focusing on minimization of price issues, as described in Malikov e Lien (2021).

Appendix - Chapter 3

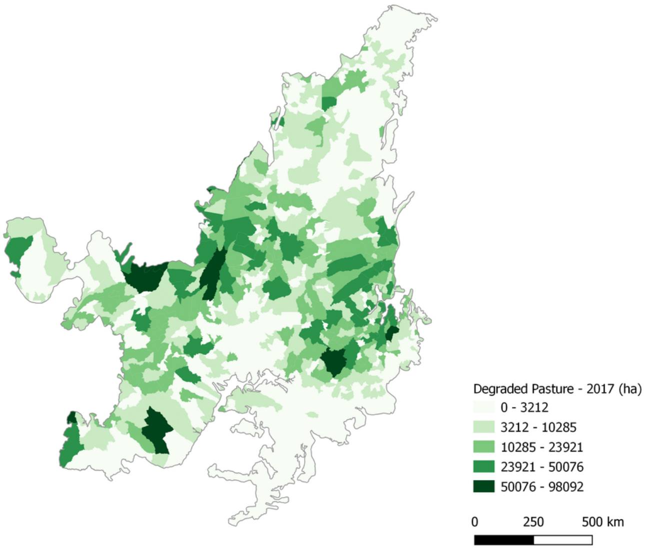

Figure 10 – Pasture Area - 2017

Source: Own elaboration from 2017 Agricultural Census

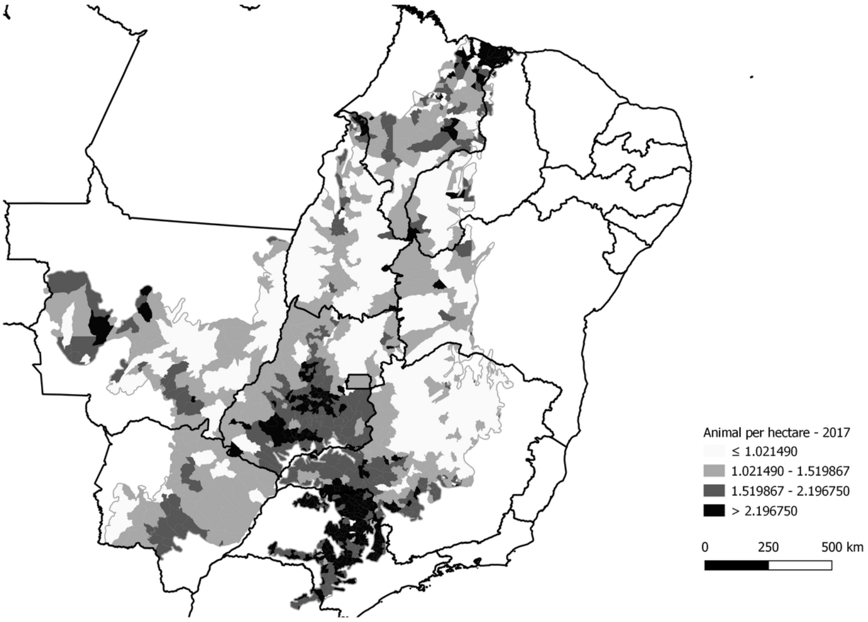

Figure 11 – Animal per Hectare - 2017

Source: Own elaboration from 2017 Agricultural Census

Table 9 – Robustness Check

	sample I	sample II
Crop Land	-0.2178***	-0.1599***
	(0.0168)	(0.0232)
Share of Degraded Pasture	0.1100***	0.0902***
	(0.0148)	(0.0164)
Share of Good Pasture	-0.0316***	-0.0538***
	(0.0064)	(0.0091)
Pasture Land	-0.3046***	-0.2213***
	(0.0178)	(0.0236)
Capital	-0.2417***	-0.2535***
	(0.0218)	(0.0237
Labor	-0.2342***	-0.2908***
	(0.0226)	(0.0286)
Agricultural GPV	0.2543***	0.2411***
	(0.0110)	(0.0149)
Livestock GPV	0.6752***	0.6791***
	(0.0113)	(0.0148)
t	0.6886***	-0.6562***
	(0.0424)	(0.0534)
Suitability Index	0.0007**	-0.0009***
	(0.0002)	(0.0720)
Constant	-0.7821***	-1.1991***
	(0.2244)	(0.2741)
States	Yes	Yes
Inefficiency($Usigmas$)		
Schooling	-35.1116***	-46.6630***
	(8.1117)	(11.4067)
Social Capital	-3.0760	-1.8579***
	(0.7745)	(0.7027)
Aridity Index	-0.0847***	-0.1068***
	(0.0222)	(0.0264)
Constant	2.1184**	1.7876***
	(0.5539)	(0.5443)
Inefficiency($Vsigmas$)		
Schooling	2.8005***	1.1195
	(0.3821)	(0.7964)
Social Capital	0.3066**	-0.2624
	(0.1317)	(0.2199)
Aridity Index	0.0134*	0.0421***
	(0.0065)	(0.0102)
Constant	-1.9814***	-2.5106***
	(0.2168)	(0.2734)
Log-Likelihood	-1851.91	-777.2416
Wald Test	50571.24	22238.76
Prob > χ^2	0.0000	0.000
Observations	2,083	1,007

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Source: Research Results

4 Final Remarks

Today the world faces a dilemma. Are the dual necessities of increasing agricultural production to feed a growing population and of preserving the balance of nature to counter global warming compatible? Brazil, as a major agricultural producer and the possessor of vast natural resources, is at the center of this discussion.

The Cerrado, Brazil's main agricultural area is central to this debate. Between 2010 and 2019, this biome suffered the second largest loss in Latin America of native vegetation, with a deforestation average annual rate of 0.86%, while Amazon this rate was 0.18% (TRASE, 2021). However, this increased deforestation was accompanied by gains in agricultural production. This mismatch has led to discussion of more environmentally rational means of production.

Technology may provide one way out of this dilemma. Biotechnological advances, such as GMO crops, can increase production on already cultivated land, while the recovery of degraded pastureland can reduce the incentive to deforestation.

In this thesis we seek to identify the impact of these two elements on the Cerrado's agricultural sector. In the first paper, we examine the impact of biotechnological seeds and the productivity advances in new agricultural frontier, the MATOPIBA. In the second, we measure the marginal incentives of recovering degraded pastureland.

Our results suggest that biotechnological seeds increase productivity, which in turn supports a slowdown of deforestation and other environmentally negative impacts. In addition to GM technology, the first paper also analyzes productivity in Brazil's newest agricultural frontier, the MATOPIBA region of the Cerrado, where productivity has been higher than in the other regions of the biome.

These advances share and complement the idea of the second paper: The possibility that recovering degraded pastureland can increase its efficiency and reduce its environmental footprint. Our results show the gains of a marginal recovery can be very attractive, especially combined with the rural credit available to recovery. The second paper addresses issues raised in COP26, the Paris agreement and discussions about minimizing the impact of agriculture on environmental stresses.

In sum, the results presented in this thesis offer policy makers, private players and farmers support for implementing means of production with environmental gains.

References

AGROCONSULT. *20 anos de transgênicos: Benefícios ambientais, econômicos e sociais no Brasil*. [S.l.]: CIB - Conselho de Informação Biotecnológica, 2018.

ALMEIDA, V. E. S. d. et al. Use of genetically modified crops and pesticides in brazil: growing hazards. *Ciencia & saude coletiva*, SciELO Public Health, v. 22, p. 3333–3339, 2017.

ALSTON, J. M.; BEDDOW, J. M.; PARDEY, P. G. Agricultural research, productivity, and food prices in the long run. *Science*, American Association for the Advancement of Science, v. 325, n. 5945, p. 1209–1210, 2009.

ANDERSON, K.; JACKSON, L. A.; NIELSEN, C. P. Genetically modified rice adoption: implications for welfare and poverty alleviation. *Journal of Economic Integration*, JSTOR, p. 771–788, 2005.

ANDRADE, R. G. et al. Avaliação das condições de pastagens no cerrado brasileiro por meio de geotecnologias. *Embrapa Gado de Leite-Artigo em periódico indexado (ALICE)*, Revista Brasileira de Agropecuária Sustentável, v. 7, n. 1, p. 34-41, mar. 2017., 2017.

ANDRADE, R. G. et al. Geotecnologias aplicadas em sistemas de produção integrada e apoio a políticas públicas. *Embrapa Gado de Leite-Capítulo em livro técnico (INFOTECA-E)*, In: BUNGENSTAB, DJ; ALMEIDA, RG de; LAURA, VA; BALBINO, LC; FERREIRA, AD (Ed., 2019.

ANDRADE, R. G. et al. Recuperação de pastagens no cerrado. *AgroANALYSIS*, v. 36, n. 2, p. 30–32, 2016.

ARAÚJO, M. L. S. de et al. Spatiotemporal dynamics of soybean crop in the matopiba region, brazil (1990–2015). *Land use policy*, Elsevier, v. 80, p. 57–67, 2019.

ASSAD, E. D. et al. Efeito das mudanças climáticas na agricultura do cerrado. *Embrapa Informática Agropecuária-Capítulo em livro científico (ALICE)*, In: BOLFE, EL; SANO, EE; CAMPOS, SK (Ed.). Dinâmica agrícola no cerrado …, 2020.

AZEVEDO, W. C.; RODRIGUES, M.; SILVA, D. C. C. Does agricultural efficiency contribute to slowdown of deforestation in the brazilian legal amazon? *Journal for Nature Conservation*, Elsevier, p. 126092, 2021.

BACHA, C. J. C.; STEGE, A. L.; HARBS, R. Ciclos de preços de terras agrícolas no brasil. *Revista de Política Agrícola*, v. 25, n. 4, p. 18–37, 2016.

BAKHSH, K. Impacts of bt cotton on profitability, productivity and farm inputs in pakistan: use of panel models. *Environment and Development Economics*, Cambridge University Press, v. 22, n. 4, p. 373–391, 2017.

BARICELO, L. G.; VIAN, C. E. d. F. A relação entre a demanda de máquinas agrícolas e a política agrícola. *Revista de Política Agrícola*, v. 26, n. 1, p. 38–48, 2017.

BARONA, E. et al. The role of pasture and soybean in deforestation of the brazilian amazon. *Environmental Research Letters*, IOP Publishing, v. 5, n. 2, p. 024002, 2010.

BARRETTO, A. G. et al. Agricultural intensification in brazil and its effects on land-use patterns: an analysis of the 1975–2006 period. *Global change biology*, Wiley Online Library, v. 19, n. 6, p. 1804–1815, 2013.

BARROWS, G.; SEXTON, S.; ZILBERMAN, D. Agricultural biotechnology: the promise and prospects of genetically modified crops. *Journal of economic perspectives*, v. 28, n. 1, p. 99–120, 2014.

BATTESE, G.; COELLI, T. A model for technical inefficiency effects in a stochastic frontier production function for panel data. *Empir. Econ.*, n. 20, p. 325–332, 1995.

BOLFE, E.; SANO, E.; CAMPOS, S. *Dinâmica agrícola no Cerrado: Análises e Projeções*. Brasília, Brazil: Embrapa, 2020.

BOLFE, E. et al. Matopiba: análise do uso da terra e a produção agrícola. In: IN: SIMPÓSIO BRASILEIRO DE SENSORIAMENTO REMOTO, 18., 2017, SANTOS. ANAIS .... *Área de Informação da Sede-Artigo em anais de congresso (ALICE)*. [S.l.], 2017.

BRAGAGNOLO, C.; SPOLADOR, H. F.; BARROS, G. Regional brazilian agriculture tfp analysis: a stochastic frontier analysis approach. *Revista Economia*, Selecta Brasília, v. 11, n. 4, p. 217–242, 2010.

BRANDÃO, A. S. P.; REZENDE, G. C. d.; MARQUES, R. W. d. C. Crescimento agrícola no período 1999/2004: a explosão da soja e da pecuária bovina e seu impacto sobre o meio ambiente. *Economia Aplicada*, SciELO Brasil, v. 10, n. 2, p. 249–266, 2006.

BRASIL. *Plano de Desenvolvimento Agropecuário do MATOPIBA*. 2015. 1–5 p.

BRAVO-URETA, B. E. et al. Technical efficiency in farming: a meta-regression analysis. *Journal of productivity Analysis*, Springer, v. 27, n. 1, p. 57–72, 2007.

BRIEFS, I. *Global status of commercialized biotech/GM crops in 2017: Biotech crop adoption surges as economic benefits accumulate in 22 years*. 2017.

BUAINAIN, A. M.; GARCIA, J. R.; FILHO, J. E. R. V. Dinâmica da economia e da agropecuária no matopiba. IPEA, TD 2283, 2017.

BURACHIK, M. Experience from use of gmos in argentinian agriculture, economy and environment. *New Biotechnology*, Elsevier, v. 27, n. 5, p. 588–592, 2010.

BUSTOS, B. P.; CAPRETTINI, B.; PONTICELLI, J. Agricultural Productivity and Structural Transformation : Evidence from Brazil. *Am. Econ. Rev.*, v. 106, n. 6, p. 1320–1365, 2016.

CAMPOS, M. C. *A EMBRAPA Soja em Londirna-PR a pesquisa agrícola de um país moderno*. Tese (Doutorado) — Geography Graduate Program of Federal University of Santa Catarina, Florianópolis, Brazil, 10 2010. An optional note.

CATTELAN, A. J.; DALL'AGNOL, A. The rapid soybean growth in brazil. *Oilseeds and fats, Crops and Lipids Journal*, EDP Science, v. 25, n. 1, p. D102, 2018. ISSN 2272-6977.

CAUDILL, S. B.; FORD, J. M. Biases in frontier estimation due to heteroscedasticity. *Economics Letters*, Elsevier, v. 41, n. 1, p. 17–20, 1993.

CELERES, C. *20 anos da adoção da biotecnologia agrícola no Brasil: Lições aprendidas e novos desafios*. Uberlândia, 2018. 53 p.

CHADDAD, F. *The economics and organization of Brazilian agriculture: recent evolution and productivity gains*. [S.l.]: Academic Press, 2016.

CHADDAD, F. R.; JANK, M. S. The evolution of agricultural policies and agribusiness development in brazil. *Choices*, JSTOR, v. 21, n. 316-2016-6401, p. 85–90, 2006.

CHAMBERS, R. G. *Applied production analysis: A dual approach*. [S.l.]: Cambridge University Press, 1988.

COELLI, T.; PERELMAN, S. A comparison of parametric and non-parametric distance functions: With application to european railways. *European journal of operational research*, Elsevier, v. 117, n. 2, p. 326–339, 1999.

COELLI, T. J. et al. *An introduction to efficiency and productivity analysis*. [S.l.]: Springer Science & Business Media, 2005.

CONTINI, E. et al. O papel das políticas públicas no cerrado. In: BOLFE, E. S.; CAMPOS, S. E. (Ed.). *Dinâmica Agrícola do Cerrado*. [S.l.]: Embrapa, 2020. v. 1, cap. 3, p. 59 – 88.

COSTA, F. P. Natureza econômica e impacto das pastagens no custo de produção da pecuária de corte. *Embrapa Gado de Corte-Documentos (INFOTECA-E)*, Campo Grande, MS: Embrapa Gado de Corte, 2010., 2010.

CROST, B. et al. Bias from farmer self-selection in genetically modified crop productivity estimates: Evidence from indian data. *Journal of Agricultural Economics*, Wiley Online Library, v. 58, n. 1, p. 24–36, 2007.

DAVIS, B.; GIUSEPPE, S. D.; ZEZZA, A. Income diversification patterns in rural sub-saharan africa: reassessing the evidence. *World Bank Policy Research Working Paper*, n. 7108, 2014.

DIAS, L. C. et al. Patterns of land use, extensification, and intensification of brazilian agriculture. *Global change biology*, Wiley Online Library, v. 22, n. 8, p. 2887–2903, 2016.

DICKIE, A. et al. Desafios e Oportunidades para Preservação, Produção Agrícola e Inclusão Social no Bioma cerrado. CEA Consulting, I, p. 1–54, 2016.

DROS, J. M. Managing the soy boom: Two scenarios of soy production. *Amsterdam, AIDEnvironment*, 2004.

ECONOMIST, T. The miracle of cerrado: Brazil has revolutionised its own farms. <*http://economist.com/node/16886442*>, August 26 2010.

FAO, F. A. O. o. t. U. N. The future of food and agriculture - trends and challenges. *Annual Report*, Food and Agriculture Organisation Rome, 2017.

FÄRE, R. *Fundamentals of production theory*. [S.l.]: Springer, 1988.

FÄRE, R.; GROSSKOPF, S. *Cost and revenue constrained production*. [S.l.]: Springer Science & Business Media, 1994.

FELTRAN-BARBIERI, R.; FÉRES, J. G. Degraded pastures in brazil: improving livestock production and forest restoration. *Royal Society Open Science*, The Royal Society, v. 8, n. 7, p. 201854, 2021.

FENG, G.; SERLETIS, A. Efficiency, technical change, and returns to scale in large us banks: Panel data evidence from an output distance function satisfying theoretical regularity. *Journal of Banking & Finance*, Elsevier, v. 34, n. 1, p. 127–138, 2010.

FERNANDEZ-CORNEJO, J. et al. Genetically engineered crops in the united states. *USDA-ERS Economic Research Report*, n. 162, 2014.

FIGUEIREDO, E. B. de et al. Greenhouse gas balance and carbon footprint of beef cattle in three contrasting pasture-management systems in brazil. *Journal of cleaner production*, Elsevier, v. 142, p. 420–431, 2017.

FIGUEIREDO, L. et al. An overview of intellectual property within agricultural biotechnology in brazil. *Biotechnology Research and Innovation*, Elsevier, v. 3, n. 1, p. 69–79, 2019.

FILHO, A. C.; COSTA, K. A expansão da soja no cerrado. *Caminhos para a ocupação territorial, uso do solo e produção sustentável. São Paulo, Agroicone*, p. p1–30, 2016.

FILHO, J. Bento de S. F.; RIBERA, L.; HORRIDGE, M. Deforestation control and agricultural supply in brazil. *American Journal of Agricultural Economics*, Wiley Online Library, v. 97, n. 2, p. 589–601, 2015.

FILHO, J. E. R. V. *Efeito poupa-terra e ganhos de produção no setor agropecuário brasileiro*. [S.l.], 2018. TD 2386.

FOLEY, J. A. et al. Solutions for a cultivated planet. *Nature*, Nature Publishing Group, v. 478, n. 7369, p. 337–342, 2011.

FULGINITI, L. E. Estimating griliches'k-shifts. *American Journal of Agricultural Economics*, Oxford University Press, v. 92, n. 1, p. 86–101, 2010.

FULGINITI, L. E.; PERRIN, R. K. Prices and productivity in agriculture. *The review of economics and statistics*, JSTOR, p. 471–482, 1993.

FULGINITI, L. E.; PERRIN, R. K. Agricultural productivity in developing countries. *Agricultural economics*, Elsevier, v. 19, n. 1-2, p. 45–51, 1998.

GARCIA, E. et al. Costs, benefits and challenges of sustainable livestock intensification in a major deforestation frontier in the brazilian amazon. *Sustainability*, Multidisciplinary Digital Publishing Institute, v. 9, n. 1, p. 158, 2017.

GARDNER, J. G.; NEHRING, R. F.; NELSON, C. H. Genetically modified crops and household labor savings in us crop production. AgBioForum, 2009.

GASQUES, J. G. et al. Produtividade da agricultura brasileira e os efeitos de algumas políticas. *Revista de Política Agrícola*, v. 21, n. 3, p. 83–92, 2012.

GEZAHEGN, T. W. et al. Big is efficient: Evidence from agricultural cooperatives in ethiopia. *Agricultural economics*, Wiley Online Library, v. 50, n. 5, p. 555–566, 2019.

GIUSTINA, C. C. D. *Degradação e Conservação do Cerrado: Uma história do estado de Goiás*. 211 p. Tese (Philosophiae Doctor) — UNB, 2013.

GODFRAY, H. C. J. et al. Food security: the challenge of feeding 9 billion people. *science*, American Association for the Advancement of Science, v. 327, n. 5967, p. 812–818, 2010.

GOEDERT, W.; WAGNER, E.; BARCELLOS, A. Savanas tropicais: dimensão, histórico e perspectivas. In: FALEIRO F.; Farias Neto, A. (Ed.). *Savanas: Desafios e estratégias para o equilíbrio entre sociedade, agronegócio e recursos naturais*. [S.l.]: Embrapa Cerrados, 2008. v. 1, cap. 2, p. 49 – 77.

GONG, T. C.; BATTESE, G. E.; VILLANO, R. A. Family farms plus cooperatives in china: Technical efficiency in crop production. *Journal of Asian Economics*, Elsevier, v. 64, p. 101129, 2019.

GRANDE, T. O.; AGUIAR, L. M.; MACHADO, R. B. Heating a biodiversity hotspot: connectivity is more important than remaining habitat. *Landscape Ecology*, Springer, p. 1–19, 2020.

GROSSKOPF, S.; MARGARITIS, D.; VALDMANIS, V. Estimating output substitutability of hospital services: A distance function approach. *European Journal of Operational Research*, Elsevier, v. 80, n. 3, p. 575–587, 1995.

Guimarães Rosa, J. *The Devil to Pay in the Backlands:"The Devil in the Street, in the Middle of the Whirlwind."*. [S.l.]: New York: Knopf, 1963.

HAYAMI, Y.; RUTTAN, V. W. Agricultural productivity differences among countries. *The American economic review*, JSTOR, v. 60, n. 5, p. 895–911, 1970.

HELFAND, S. M.; LEVINE, E. S. Farm size and the determinants of productive efficiency in the brazilian center-west. *Agricultural economics*, Wiley Online Library, v. 31, n. 2-3, p. 241–249, 2004.

HELFAND, S. M.; MAGALHÃES, M. M.; RADA, N. E. Brazil's agricultural total factor productivity growth by farm size. IDB Working paper series, 2015.

HELFAND, S. M.; TAYLOR, M. P. The inverse relationship between farm size and productivity: Refocusing the debate. *Food Policy*, Elsevier, p. 101977, 2020.

IBGE. *Censo Agropecuário 2006*. [S.l.]: Instituto Brasileiro de Geografia e Estatística, 2006.

IBGE. *Censo Agropecuário 2017*. [S.l.]: Instituto Brasileiro de Geografia e Estatística, 2017.

IBGE. *Pesquisa Agrícola Municipal*. [S.l.]: Brasília, 2017.

IBGE. *Sistama de Contas Nacionais*. [S.l.]: Brasília, 2017.

GIANNAKAS, K. (Ed.). *Innovation and policy against hunger in a water-constrained world*. Institute of Science for Global Policy, Washington, DC: Food Safety, Security, and Defense: Focus on Food and Water, 2014.

KASSIE, M.; SHIFERAW, B.; MURICHO, G. Agricultural technology, crop income, and poverty alleviation in uganda. *World Development*, Elsevier, v. 39, n. 10, p. 1784–1795, 2011.

KLÜMPER, W.; QAIM, M. A meta-analysis of the impacts of genetically modified crops. *PloS one*, Public Library of Science, v. 9, n. 11, p. e111629, 2014.

KODDE, D. A.; PALM, F. C. Wald criteria for jointly testing equality and inequality restrictions. *Econometrica: journal of the Econometric Society*, JSTOR, p. 1243–1248, 1986.

KOUSER, S.; QAIM, M. Bt cotton, pesticide use and environmental efficiency in pakistan. *Journal of Agricultural Economics*, Wiley Online Library, v. 66, n. 1, p. 66–86, 2015.

KUMBHAKAR, S. C.; WANG, H.; HORNCASTLE, A. P. *A practitioner's guide to stochastic frontier analysis using Stata*. [S.l.]: Cambridge University Press, 2015.

LAPIG/UFG. *Laboratório de Processamento de Imagens e Geoprocessamento - Universidade Federal de Goiás*. 2020. <http://www.lapig.iesa.ufg.br>. [Online; accessed January-2020].

LAPOLA, D. M. et al. Pervasive transition of the brazilian land-use system. *Nature climate change*, Nature Publishing Group, v. 4, n. 1, p. 27–35, 2014.

LATAWIEC, A. E. et al. Improving land management in brazil: A perspective from producers. *Agriculture, Ecosystems & Environment*, Elsevier, v. 240, p. 276–286, 2017.

LENCE, S. H.; HAYES, D. J. Genetically modified crops: their market and welfare impacts. *American Journal of Agricultural Economics*, Wiley Online Library, v. 87, n. 4, p. 931–950, 2005.

LIMA FILHO, R. R. d.; AGUIAR, G. A. M.; JUNIOR, A. d. M. T. Preços em alta, liquidez em baixa. *Agroanalysis*, v. 33, n. 02, p. 19–20, 2013.

LINS, M. A. D. T.; PINAZZA, L. A. Para produzir, e não para especular. *AgroANALYSIS*, v. 24, n. 7, p. 44–45, 2004.

MA, W. et al. Agricultural cooperative membership and technical efficiency of apple farmers in china: An analysis accounting for selectivity bias. *Food Policy*, Elsevier, v. 81, p. 122–132, 2018.

MALIKOV, E.; LIEN, G. Proxy variable estimation of multiproduct production functions. *American Journal of Agricultural Economics*, Wiley Online Library, 2021.

MARGULIS, S. Causas do desmatamento da amazônia brasileira. Banco Mundial Brasília, 2003.

MARTHA Jr., G.; VILELA, L. Pastagens no cerrado: baixa produtividade pelo uso limitado de fertilizantes. *Embrapa Cerrados-Documentos (INFOTECA-E)*, Planaltina, DF: Embrapa Cerrados, 2002., 2002.

MATTOS, F. Will “matopiba” change the competitive landscape in the international grain market? *Cornhusker Economics*, 2019.

MENDOLA, M. Agricultural technology adoption and poverty reduction: A propensity-score matching analysis for rural bangladesh. *Food policy*, Elsevier, v. 32, n. 3, p. 372–393, 2007.

MORAIS, G. A. d. S. *Three essays on irrigated agriculture in Brazil*. Tese (Doutorado) — Applied Economics Graduate Program of Federal University of Viçosa, Viçosa, Brazil, 2019.

MUELLER, C.; MARTHA Jr.., G. A agropecuária e o desenvolvimento socioeconômico recente do cerrado. In: FALEIRO F.; Farias Neto, A. (Ed.). *Savanas: Desafios e estratégias para o equilíbrio entre sociedade, agronegócio e recursos naturais*. [S.l.]: Embrapa Cerrados, 2008. v. 1, cap. 4, p. 104 – 169.

MUELLER, C. C. Agricultural, agrarian, and environmental policy formation under lula: The role of policy networks. In: LOVE JOSEPH.; BAER, W. (Ed.). *Brazil under Lula: Economy, Politics, and Society under the Worker-President*. [S.l.]: Palgrave Macmillan, 2008. v. 1, cap. 7, p. 135 – 150.

NEPSTAD, D. et al. Slowing amazon deforestation through public policy and interventions in beef and soy supply chains. *science*, American Association for the Advancement of Science, v. 344, n. 6188, p. 1118–1123, 2014.

NEWMAN, C.; MATTHEWS, A. Evaluating the productivity performance of agricultural enterprises in ireland using a multiple output distance function approach. *Journal of Agricultural Economics*, Wiley Online Library, v. 58, n. 1, p. 128–151, 2007.

NOGUEIRA, M.; HUNGRIA, M. Oportunidades e ameaças à contribuição da fixação biológica de nitrogênio em leguminosas no brasil. In: IN: IBEROAMERICAN CONFERENCE ON BENEFICIAL PLANT-MICROORGANISM-ENVIRONMENT …. *Embrapa Soja-Artigo em anais de congresso (ALICE)*. [S.l.], 2013.

Observatório ABC. *Impactos econômicos e ambientais do Plano ABC*. 2017. <http://www.observatorioabc.com.br/>. [Online; accessed December-2020].

Observatório ABC. *Sistema ABC*. 2017. <http://www.observatorioabc.com.br/sistema-abc/>. [Online; accessed November-2021].

OECD/FAO. Oecd-fao agricultural outlook 2016-2025. oecd publishing, paris. 2016. Disponível em: <http://dx.doi.org/10.1787/agr_outlook-2016-en>.

OLESEN, J. E.; BINDI, M. Consequences of climate change for european agricultural productivity, land use and policy. *European journal of agronomy*, Elsevier, v. 16, n. 4, p. 239–262, 2002.

PRODES/INPE. *TerrBrasilis - PRODES (Desmatamento) - Instituto Nacional de Pesquisa Espacial*. 2021. <http://terrabrasilis.dpi.inpe.br/>. [Online; accessed March-2021].

QAIM, M.; ZILBERMAN, D. Yield effects of genetically modified crops in developing countries. *Science*, American Association for the Advancement of Science, v. 299, n. 5608, p. 900–902, 2003.

RADA, N. Assessing brazil's cerrado agricultural miracle. *Food Policy*, Elsevier, v. 38, p. 146–155, 2013.

RADA, N.; HELFAND, S.; MAGALHÃES, M. Agricultural productivity growth in brazil: Large and small farms excel. *Food Policy*, Elsevier, v. 84, p. 176–185, 2019.

RADA, N.; VALDES, C. Policy, technology, and efficiency of brazilian agriculture. *USDA-ERS Economic Research Report*, n. 137, 2012.

RADA, N. E.; BUCCOLA, S. T. Agricultural policy and productivity: evidence from brazilian censuses. *Agricultural Economics*, Wiley Online Library, v. 43, n. 4, p. 355–367, 2012.

RADA, N. E.; BUCCOLA, S. T.; FUGLIE, K. O. Government policy and agricultural productivity in indonesia. *American journal of agricultural economics*, Wiley Online Library, v. 93, n. 3, p. 867–884, 2011.

REZENDE, G. d.; HELFAND, S.; REZENDE, G. Ocupação agrícola, estrutura agrária e mercado de trabalho rural no cerrado: o papel do preço da terra, dos recursos naturais e das políticas públicas. *Região e espaço no desenvolvimento agrícola brasileiro. Rio de Janeiro, IPEA*, p. 173–212, 2003.

RICHARDS, R. C. et al. Farmer preferences for reforestation contracts in brazil's atlantic forest. *Forest Policy and Economics*, Elsevier, v. 118, p. 102235, 2020.

SCARANO, F. R.; CEOTTO, P. Brazilian atlantic forest: impact, vulnerability, and adaptation to climate change. *Biodiversity and Conservation*, Springer, v. 24, n. 9, p. 2319–2331, 2015.

SHEFFIELD, J.; GOTETI, G.; WOOD, E. F. Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. *Journal of climate*, American Meteorological Society, v. 19, n. 13, p. 3088–3111, 2006.

SHEPHARD, R. W. *Theory of cost and production functions*. [S.l.]: Princeton University Press, 1970.

SILVA, C. M. D. Between fenix and ceres: The great acceleration and the agricultural frontier in the brazilian cerrado. *Varia Historia*, v. 34, n. 65, 2018.

SILVA, F. d. F.; PERRIN, R. K.; FULGINITI, L. E. The opportunity cost of preserving the brazilian amazon forest. *Agricultural Economics*, Wiley Online Library, v. 50, n. 2, p. 219–227, 2019.

SILVA, F. de F. et al. The increasing opportunity cost of sequestering co 2 in the brazilian amazon forest. *Empirical Economics*, Springer, p. 1–22, 2021.

SILVA, R. de O. et al. Developing a nationally appropriate mitigation measure from the greenhouse gas ghg abatement potential from livestock production in the brazilian cerrado. *Agricultural Systems*, Elsevier, v. 140, p. 48–55, 2015.

SILVA, R. de O. et al. Sustainable intensification of brazilian livestock production through optimized pasture restoration. *Agricultural systems*, Elsevier, v. 153, p. 201–211, 2017.

SPAROVEK, G. et al. Effects of governance on availability of land for agriculture and conservation in brazil. *Environmental science & technology*, ACS Publications, v. 49, n. 17, p. 10285–10293, 2015.

SPERA, S. Agricultural intensification can preserve the brazilian cerrado: Applying lessons from mato grosso and goiás to brazil's last agricultural frontier. *Tropical Conservation Science*, Sage Publications Sage CA: Los Angeles, CA, v. 10, p. 1940082917720662, 2017.

STRASSBURG, B. B. et al. When enough should be enough: Improving the use of current agricultural lands could meet production demands and spare natural habitats in brazil. *Global Environmental Change*, Elsevier, v. 28, p. 84–97, 2014.

TRASE. Cop26 must commit to eliminating deforestation. <*https://insights.trase.earth/insights/cop26-must-commit-to-zero-deforestation/*>, October 27 2021.

TRIGUEIRO, W. R.; NABOUT, J. C.; TESSAROLO, G. Uncovering the spatial variability of recent deforestation drivers in the brazilian cerrado. *Journal of Environmental Management*, Elsevier, v. 275, p. 111243, 2020.

VELAZCO, S. J. E. et al. A dark scenario for cerrado plant species: Effects of future climate, land use and protected areas ineffectiveness. *Diversity and Distributions*, Wiley Online Library, v. 25, n. 4, p. 660–673, 2019.

VICTORIA, D. d. C. et al. Potencialidades para expansão e diversificação agrícola sustentável do cerrado. *Embrapa Informática Agropecuária-Capítulo em livro científico (ALICE)*, In: BOLFE, EL; SANO, EE; CAMPOS, SK (Ed.). Dinâmica agrícola no cerrado …, 2020.

WOLLNI, M.; ZELLER, M. Do farmers benefit from participating in specialty markets and cooperatives? the case of coffee marketing in costa rica1. *Agricultural economics*, Wiley Online Library, v. 37, n. 2-3, p. 243–248, 2007.

XAVIER, A. C.; KING, C. W.; SCANLON, B. R. Daily gridded meteorological variables in brazil (1980–2013). *International Journal of Climatology*, Wiley Online Library, v. 36, n. 6, p. 2644–2659, 2016.

ZILBERMAN, D.; HOLLAND, T. G.; TRILNICK, I. Agricultural gmos—what we know and where scientists disagree. *Sustainability*, Multidisciplinary Digital Publishing Institute, v. 10, n. 5, p. 1514, 2018.

ZILBERMAN, D.; LU, L.; REARDON, T. Innovation-induced food supply chain design. *Food Policy*, Elsevier, v. 83, p. 289–297, 2019.

ZIMMER, A. H. et al. Degradação, recuperação e renovação de pastagens. *Embrapa Gado de Corte-Documentos (INFOTECA-E)*, Campo Grande, MS: Embrapa Gado de Corte, 2012., 2012.