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PEDRO HENRIQUE BATISTA DE BARROS

ESSAYS ON ENVIROMENTAL AND DEVELOPMENT ECONOMICS

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Dissertação apresentada como requisito parcial à obtenção do grau de Mestre em Economia, no Programa de Pós-Graduação em Economia, Setor de Ciências Sociais Aplicadas, da Universidade Estadual de Ponta Grossa

Orientador: Prof. Dr. Alysson Luiz Stege

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Ponta Grossa, 22 de fevereiro de 2019.

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ABSTRACT

BARROS, Pedro Henrique Batista. **Essays on Environmental and Development Economics.** 2019. 143 p. Dissertação (Mestrado em Economia) – Universidade Estadual de Ponta Grossa. Ponta Grossa, 2019.

This dissertation is composed of two essays on environmental and development economics. The first aims to understand how economic development affected deforestation in the Brazilian Amazon from 2000 to 2015, using an Environmental Kuznets Curve (EKC). We analyzed and controlled the presence of spatial and temporal dependence with ESDA and Dynamic Spatial Panel methodologies. For the EKC model, despite obtaining an inverted "U" format, the majority of municipalities in Amazon are far below the turning point. Therefore, economic development may act as a deforestation inductor in the following decades. We confirmed the importance of the spatial-temporal components, which explains the spatial spillovers and agglomeration along with temporal inertia for deforestation. In addition, cattle herd growth along with rural credit, sugarcane productivity, extraction of wood and scale effects from agricultural sector are statistical significant, acting as environmental degraders. On the other hand, we have the productivity gains on soy and maize that inhibit deforestation. We also highlight the importance of considering land use dynamics and cross-agricultural activities leakages in policies targeting deforestation, since crops indirectly affect environmental degradation in Amazon by shifting cattle production to agricultural frontier regions, where it increase deforestation. The second essay investigates the relationship between socioeconomic development and deforestation in the Cerrado biome, with special focus on the current Brazilian agricultural frontier, known as Matopiba, using the Environmental Kuznets Curve approach. In addition, we seek to contribute methodologically to the EKC estimation, incorporating several advances not yet adopted at the same time in the specialized literature. i) The creation of a Socioeconomic Development Index to replace per capita income as a proxy for economic development; ii) the omitted-variable bias problem consideration, especially from spatial spillovers; iii) and the adoption of spatial regimes to control heterogeneity. In the spatial EKC model, we get an inverted U-shaped curve relationship between development and deforestation for both regimes. After considering indirect spatial effects, we identified that more than 50% of Matopiba and 30% of Cerrado municipalities are lower than the maximum turning point, which highlights environmental concerns, since economic growth could boost degradation. The roads expansion and cattle herd are an important deforestation inductor for both regimes while crop area has considerable indirect effects by displacing cattle to agricultural frontier regions, in addition to directly affecting Matopiba. We also identified positive spatial spillovers from forest conversion. Demographic density, agriculture GDP, crop area, soil suitability, presence of federal reserve, soybean productivity and spillovers from cattle herd, crop area and sugarcane productivity, all presented diverse statistical significance according to the regime. Heterogeneity, spatial interactions and displacements effects present in Cerrado are important to understand the biome deforestation and can help policymaking design by considering possible different outcomes.

Keywords: Environmental Kuznets Curve (EKC). Brazilian Amazon. Agricultural Frontier Expansion. Cerrado. Matopiba.

RESUMO

BARROS, Pedro Henrique Batista. **Essays on Environmental and Development Economics.** 2019. 143 p. Dissertação (Mestrado em Economia) – Universidade Estadual de Ponta Grossa. Ponta Grossa, 2019.

Esta dissertação é composta de dois ensaios sobre economia do meio ambiente e do desenvolvimento. O primeiro buscou entender como o desenvolvimento econômico afetou o desmatamento na Amazônia Brasileira no período de 2000 a 2015, utilizando-se da Curva Ambiental de Kuznets (CAK). Buscou-se analisar a presença de dependência espacial e temporal com as metodologias AEDE e Painel Dinâmico Espacial. Para a CAK, apesar da obtenção de uma curva em "U" invertido, a maioria dos municípios da Amazônia se encontram consideravelmente abaixo do ponto de virada. Dessa forma, o desenvolvimento econômico possivelmente será um indutor de desmatamento nas próximas décadas na região. Confirmou-se a importância dos componentes espaciais e temporais, os quais induzem *spillovers* e aglomerações espaciais conjuntamente a uma inércia temporal. Além disso, o aumento do rebanho bovino, crédito rural, produtividade da cana-de-açúcar, extração de madeira e efeito escala do setor agrícola foram estatisticamente significativo, atuando como degradadores do meio ambiente. Por outro lado, ganhos de produtividade da soja e milho atuam como conservadores da floresta, inibindo o desmatamento. Destaca-se também a importância de se considerar a dinâmica de uso da terra e as ligações existentes entre as atividades agrícolas em políticas visando a redução do desmatamento, pois o cultivo de grãos podem afetar indiretamente a degradação ambiental na Amazônia ao deslocar a produção bovina para regiões de fronteira agrícola, aumentando o desmatamento. O segundo ensaio investiga a relação entre desenvolvimento socioeconômico e desmatamento no bioma Cerrado, com foco especial para a atual fronteira agrícola brasileira, conhecida como Matopiba, utilizando a abordagem da Curva Ambiental de Kuznets (CAK). Além disso, buscou-se contribuir metodologicamente para a estimação da CKA, incorporando diversos avanços ainda não adotados conjuntamente pela literatura especializada. i) A criação de um Índice de Desenvolvimento Socioeconômico visando substituir a renda *per capita* como *proxy* para desenvolvimento econômico; ii) a consideração do problema de viés de variável omitida, especialmente relacionadas a *spillovers* espaciais; iii) a adoção de regimes espaciais para controlar heterogeneidade. No modelo espacial CAK, obteve-se um curva com formato de "U" invertido entre desenvolvimento socioeconômico e desmatamento para ambos os regimes. Após a consideração de efeitos espaciais indiretos, identificou-se nos regimes que mais de 50% do Matopiba e 30% do Cerrado dos municípios estão abaixo do ponto de máximo, fato que levanta preocupações ambientais, pois o crescimento econômico pode amplificar a degradação ambiental. A extensão das rodovias e do rebanho bovino são importantes indutores do desmatamento em ambos os regimes enquanto a área plantada possui efeitos indiretos consideráveis ao deslocar a pecuária para regiões de fronteira agrícola, além de afetar diretamente o Matopiba. Também se identificou *spillovers* espaciais positivos do processo de conversão florestal. Densidade demográfica, PIB agropecuário, área plantada, adequabilidade do solo, presença de reserva federal, produtividade da soja; e spillovers do rebanho bovino, área plantada e produtividade da cana-de-açúcar apresentaram significância estatística de acordo com o regime adotado. A presença de heterogeneidade, interações espaciais e efeitos de deslocamento são, portanto, importantes para entender o desmatamento do bioma e podem ajudar no desenho de políticas inibidoras.

Palavras-chave: Curva Ambiental de Kuznets (CAK). Amazônia Brasileira. Expansão da Fronteira Agrícola. Cerrado. Matopiba.

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1. Introduction

The Amazon and Cerrado biomes holds a considerable part of the planet's natural resources, playing a key role in regulating the carbon cycle and global climate and the balance of the global ecosystem. The Amazon is the largest tropical forest in the world while the Cerrado is the richest savannah. Both biomes have considerable levels of biodiversity, water resources and forest biomass. Nevertheless, the region's deforestation has caused concern worldwide due to irreparable loss of its natural wealth and biodiversity, along with greenhouse gas emissions that leads to climate change (MYERS et al., 2000; ASSAD, 2016).

Several factors can explain deforestation, especially agricultural activities and the advancement of the agricultural frontier in the biomes, which increase the pressure for opening new agricultural areas, inducing considerable land use changes and environmental degradation. In fact, the Amazon is the most active agricultural frontier in the world in terms of forest loss and CO_2 emissions (GIBBS et al., 2015; ASSUNÇÃO et al., 2015; BRAGANÇA, 2018; ARAÚJO et al. 2019). In historical terms, approximately 1/5 and 1/2 of Amazon and Cerrado, respectively, has already been deforested (IBAMA, 2010; INPE, 2018).

The literature have pointed to the impacts of agricultural practices on deforestation in the Amazon and Cerrado biomes. In particular, we have activities related to cattle raising and crops that have recently gained market value, such as soybeans, maize and sugarcane. The increase in the national and international demand for beef, animal feed and biodiesel have been the main responsible for the high profitability that induces its production growth (CARVALHO, 2007; BARONA et al., 2010; MARTINELLI, 2010; ARVOR et al., 2011; ARVOR et al., 2012; GODAR et al.; 2012; (ANDRADE DE SÁ et al., 2013; GOLLNOW and LAKES, 2014). ALENCAR et al., 2015; FARIA and ALMEIDA, 2016).

An important effect of the recent Amazon and Cerrado occupation is the replacement of cattle ranching, characterized with low capital intensity, by the cultivation of soybean that usually adopts more technologically advanced inputs, with greater potential to generate profits. In addition, the Soy Moratorium (SoyM), which restricted the access of soy cultivated in recently deforested areas in Amazon to the markets led to the intensification on the replacement on both biomes. This process induces, due to the demand inelasticity for beef, the displacement of cattle rearing to regions where the price of land is relatively lower, usually in localities belonging to the agricultural frontier. This is an important indirect impact due to land use changes, which may lead to deforestation in the Amazon and Cerrado biomes (MACEDO et al., 2012; ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013; GOLLNOW e LAKES, 2014; ASSUNÇÃO and BRAGANÇA, 2015; GIBBS et al., 2015; NOOJIPADY et al., 2017).

Considering agricultural sector importance for the biomes economy, it would be natural to infer that a slowdown in the pace of expansion of the agricultural frontier in the regions can negatively affect their economic development. However, according to Assunção et al. (2015), Assunção and Bragança (2015), and Bragança (2018) there is no trade-off between economic development and environmental conservation on the biomes. On the contrary, the agricultural sector continued to perform well despite policies to inhibit deforestation in recent years. This fact is in accordance with the Grossman and Krueger (1995) theoretical preposition, known as the Environmental Kuznets Curve (EKC), which proposes an inverted U-relationship between economic development and environmental degradation.

In this context, the main purpose of this dissertation, composed by two papers, one for each biome, are to investigate if the relationship between economic development and environmental degradation fits the EKC theoretical approach. It is worth mentioning, that Legal Amazon, an administrative division of the Brazilian territory created in 1953, for regional policies purposes, covers 20% of the Cerrado, in states as Maranhão, Mato Grosso, Pará, Rondônia and Tocantins. Therefore, the geographic cut used in this dissertation have intersections that can reflect on the results.

In addition, according to Maddison (2006), Robalino, and Pfaff (2012), spatial interactions are a common effect when considering forest conversion and land use changes. In fact, several papers point out that spatial spillovers are relevant to both biomes, with a strong positive spatial interaction that impacts deforestation (IGLIORI, 2006; OLIVEIRA and ALMEIDA, 2011; COLUSSO et al., 2012; ANDRADE DE SÁ et al., 2015; AMIN et al., 2019). Therefore, both papers may also be connect through significant spatial spillovers from deforestation and agricultural activities even in regions not directly connected.

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2. Economic Development and Deforestation in the Brazilian Amazon: a Dynamic Spatial Panel Approach

2.1 Introduction

The Legal Amazon[1] is composed of nine of the twenty-seven Brazilian states, covering all those belonging to the northern region of the country, as well as Mato Grosso in the Central-West and Maranhão in the Northeast. Its territorial extension is of approximately 500 million hectares, with a population superior to 25 million people. According to Assad (2016), the region holds a considerable part of the planet's natural resources, playing a key role in regulating the carbon cycle and global climate. In addition, the Brazilian Amazon is the largest tropical forest in the world, characterizing itself as one of the highest levels of biodiversity, water resources and forest biomass worldwide.

Nevertheless, the occupation and deforestation of this region has caused concern not only because of the irreparable loss of its natural wealth, but also due the perception that economic and social gains are inferior in relation to environmental degradation (MARGUILIS, 2004; MALHI et al., 2008; RODRIGUES et al., 2009; ASSAD, 2016). According to Nascimento (2017), deforestation between 2007 and 2016 (an average of 7,502 km^2 / year) had the potential to add only 0.013% annually to the Brazilian GDP, a negligible value when compared to potential environmental damages. In addition, deforestation, besides causing direct effects on the environment, is also the main responsible for the emissions of greenhouse gases in Brazil. Therefore, combating deforestation has the potential to minimize the threats posed by biodiversity loss and climate change.

Deforestation in the Brazilian Amazon reached its peak in 2004, when it suffered a reduction in its forest area of about 28,000 square kilometers (km^2). Since then, the degradation has shown a considerable decrease in its rate, which reduced to approximately 7,000 km^2 in 2017, a significant drop of 75% (INPE, 2018). According to Assunção et al. (2015), the main factors that led to this reduction are: i) the fall in the price of agricultural commodities after the

[1] The Legal Amazon is an administrative division of the Brazilian territory created in 1953 for regional policies purposes. It covers the entire Amazonian biome of the country, as well as 20% of the Cerrado and part of the Pantanal in Mato Grosso (ASSAD, 2016).

mid-2000s. ii) implementation of the *Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm)* in 2004; and iii) the conditionality of environmental preservation in the concession of agricultural credit to establishments located in the Amazonian biome.

However, the analysis undertaken by Assunção et al. (2015) comprised the period from 2002 to 2009, thus not capturing the possible effects of i), ii) and iii) in recent years. The value of 7,000 km² of deforested area in 2017 are higher when compared to 2012, of 4,500 km², indicating an increase in the rate of deforestation in the Legal Amazon. Therefore, studies and analyzes are necessary to verify the possible reasons for this increase after 2012. In historical terms, approximately 1/5 of the Amazon forest has already been deforested, with Mato Grosso and Pará concentrating around 70% of this area, reaching 80 % when considering also the state of Rondônia (INPE, 2018).

Several factors can explain the deforestation, especially in relation to agricultural activities and the advancement of the agricultural frontier in the Legal Amazon, which has resulted in the incorporation of new production areas and considerable changes in land use. In addition, the Amazon region, with 3.2 million km² of remaining native vegetation, is the most active agricultural frontier in the world, in terms of forest loss and CO_2 emissions (ASSUNÇÃO et al., 2015). A number of studies have pointed to the impacts of agricultural practices on deforestation in the Amazon. In particular, activities related to cattle rearing are the ones that generate the greatest impacts when compared to other commercial or subsistence crops (CARVALHO, 2007; BARONA et al., 2010; MARTINELLI, 2010; GODAR et al.; 2012; ALENCAR et al., 2015; FARIA and ALMEIDA, 2016).

According to Nascimento (2017), the increase in pasture for livestock is the activity that contributed the most to deforestation in the Amazon, comprising 65% of the deforested area. Cattle raising in the region, for example, held 26 million heads in 1990, a number that increased to over 80 million in 2015, with the states of Mato Grosso and Pará being the main recipients of this growth, precisely those with the largest deforested area in the Legal Amazon. Cohn et al. (2014) and Cortner et al. (2019) points out that an intensification stimulus of existing production is a possible solution to the problem, which would enable the country to reduce significantly the deforestation and greenhouse gas emissions, maintaining agricultural growth.

The production of soybeans and maize, often adopted jointly due to crop rotation[2], are the agricultural crops that contribute the most in the occupation of the Amazon rainforest

[2] In most cases, soybeans are adopted as the main production and maize as secondary, a fact that can be reversed when there is a change in the relative prices of these crops (ARVOR et al., 2011).

(BARONA et al., 2010; MARTINELLI et al., 2010; ARVOR et al., 2011; ARVOR et al., 2012; FARIA and ALMEIDA, 2016). However, according to Macedo et al. (2012), many municipalities that produce soybean, especially in the Mato Grosso state, have been able to increase their harvests without significant impacts on deforestation. The author points out that this result reflects a combination of factors, especially the adoption of modern production technologies and due to government policies.

The Soy Moratorium (SoyM), an industry effort to reduce deforestation in Amazon stemming from soy production after 2006, consisted of restrictions on access to the market of soy cultivated in recently deforested areas. However, the SoyM led to an increased in the area cultivated in other regions, such as the Cerrado due the smaller restrictions applied to this region, in a ‘cross-biome leakage’ (MACEDO et al., 2012; GIBBS et al., 2015; NOOJIPADY et al., 2017).

Several studies point to the fact that the indirect impacts of soybean are possibly more important to explain deforestation in the Legal Amazon than the direct ones (BARONA et al., 2010; GOLLNOW and LAKES, 2014). This is mainly due to changes in land use in both the Amazon region and elsewhere in the country, as increased production has occurred on land already occupied, especially those used by extensive livestock (BARONA et al., 2010; ARIMA et al., 2011; MACEDO et al., 2012; RICHARDS et al., 2012).

This process induces, due to the demand inelasticity for beef, the displacement of cattle rearing to regions where the price of land is relatively lower, usually in localities belonging to the agricultural frontier (ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013; GOLLNOW e LAKES, 2014).

The indirect impact of land use is not limited to the production of soybeans but also extends to other crops that have recently gained market value, such as sugarcane and maize. The increase in the national and international demand for animal feed and biodiesel have been the main responsible for the high profitability that induces the growth of the production of these crops and indirectly displaces the cattle to the regions of agricultural frontier in the Amazon (ANDRADE DE SÁ et al., 2013; GOLLNOW and LAKES, 2014).

In addition, we can mention the work of Barona et al. (2010), Andrade de Sá et al. (2012) and Jusys (2017), who found evidence that an increase in sugarcane production for biodiesel production in the São Paulo state, and to a lesser extent in other regions, shifted livestock towards the agricultural frontier in Amazonia, together with other non-fuel crops. According to Jusys (2017), between 2002 and 2012, we had approximately 16,000 km² of forests cleared by economic agents displaced by the advance of sugarcane in Brazil, which corresponds to 12.2%

of the total value deforested in the period. Although sugarcane is not a predominant crop in the region, as soy and maize, the recent expansion of Brazilian ethanol production is also leading to direct deforestation (ASSUNÇÃO and ROCHA, 2019).

The facilitation and expansion of rural credit to the agricultural sector occurred after the 1970s was also an important occupation inductor in the Legal Amazon by agriculture and cattle raising. The Brazilian government, with the purpose of encouraging the interiorization and occupation of the national territory, subsidized the majority of rural credit granted. However, as a side effect, this policy is one of the main factors responsible for deforestation in this biome (ARAÚJO et al., 2012, ASSUNÇÃO et al., 2013; HARGRAVE and KIS-KATOS, 2013; GOLLNOW and LAKES, 2014).

In this context, the Brazilian government, through Resolution 3,545 introduced in 2008 by the *Conselho Monetário Nacional (CMN)*, conditioned the granting of rural credit to agricultural establishments located in the Amazon biome. Credit approval has become possible only based on proof of compliance with legal and environmental regulations, such as, for example, proof of inexistence of embargoes due to economic use of illegally deforested areas (CMN, 2008).

According to Assunção et al. (2013), the conditionality established by Resolution 3,545 has proved to be an effective policy instrument to combat deforestation in the Amazon by restricting rural credit to environmental offenders. The author states that conditionality causes a reduction of approximate R$ 2.9 billion in the credit granted, which affected mainly cattle farmers, which was responsible for 90% of this decrease. In addition, this reduction avoided 2,700 km² of deforestation per year; especially in municipalities that is specialize in livestock production, with less impact on those who have agriculture as their main activity.

In view of the importance of the agricultural sector for the economy in the Legal Amazon, it would be natural to infer that a slowdown in the pace of expansion of the agricultural frontier in the region can negatively affect its economic development. However, according to Assunção et al. (2015) and Assunção and Rocha (2019), there is no trade-off between economic development and environmental conservation on the region. On the contrary, the agricultural sector continued to perform well despite policies to inhibit deforestation. This fact is in accordance with the Grossman and Krueger (1991, 1995) theoretical preposition, known as the Environmental Kuznets Curve (EKC), which proposes an inverted U-relationship between economic development and environmental degradation. In other words, several municipalities in the Amazon region, according to evidences from Assunção et al. (2015) and Assunção and

Rocha (2019), may be located in the downstream part of the EKC, with environmental protection not hindering economic advancement.

Caviglia-Harris et al. (2016) and Silva et al. (2017), specifically analyzing the relationship between deforestation and development, also found evidence that the reduction in environmental degradation did not have a significant impact on the pace of economic and social development in the region. According to the authors, after the policies implemented by the Brazilian government in 2004, which sought a more sustainable development model for the Amazon, a “decoupling” process emerged between growth in well-being and environmental degradation. In addition, Caviglia-Harris et al. (2016) found evidence of a convergence process for economic development in the Brazilian Amazon relative to the rest of the country.

Celentano et al. (2012), despite having identified similar results to those presented by Caviglia-Harris et al. (2016) and Silva et al. (2017), also supports the possibility that the decoupling is only temporary, with the long-term economic development having as a necessary condition the deforestation of the region. According to Chagas and Andrade (2017), human presence in forest areas itself represents a deforestation vector, since the Amazon population demand local resources for their subsistence, income growth and material well-being. Igliori (2006b) highlight that in underdeveloped countries, the economic growth in rural areas is initially associated with land use changes and deforestation. The markets absence for the forest ecosystem services such as biodiversity, climate and ecosystem stability, carbon storage and environmental amenities leads to higher conversion rates than socially desirable.

On the other hand, the empirical evidences found in the literature, specifically using the Environmental Kuznets Curve, do not always support the EKC hypothesis between economic growth and deforestation, which may vary from region to region (SHAFIK and BANDYOPADHYAY, 1992; SHAFIK, 1994; CROPPER and GRIFFITHS, 1994; BHATTARAI and HAMMING, 2001; KOYUNCU and YILMAZ, 2009; CHIU, 2012; CHOUMERT et al., 2013). In this context, Chiu (2012) affirms that the empirical results on the EKC existence is controversial and argues that an analysis must be carried out for each locality of interest, not being possible to infer causalities of studies of other regions.

For deforestation in the Legal Amazon in particular, we have several empirical studies that sought to identify the existence of an EKC. Authors such as Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) found evidence of an inverted "U" relationship, with development inducing the reduction of deforestation in the long run. On the other hand, Araújo et al. (2009) and Jusys (2016) captured a EKC in "U", with development initially decreasing degradation, but again increasing it after a certain income level.

Finally, Oliveira et al. (2011) and Oliveira and Almeida (2011) identified the possibility of deforestation presenting a relationship in the "N" format (as well as its inverted form), that is, with environmental degradation returning to increase after high levels of development. This possibility are proposed by De Bruyn et al. (1998), who defended this hypothesis, specifically stressing the importance of also including per capita income in a cubic format in econometric modeling, in addition to its linear and quadratic format to capture this effect.

Therefore, based on the results for the Legal Amazon, we have contradictory evidences, a fact that prompts the need for further studies. On other words, there is still no consensus on the relationship between economic development and deforestation, from the EKC perspective, for deforestation in the Legal Amazon. Therefore, it is necessary to identify possible misconceptions and adopt complementary methodologies not yet tested to push the literature. In fact, the main goal of this paper is to contribute to this debate, with a new approach to understand the economic development impact on deforestation in the Legal Amazon.

The Environmental Kuznets Curve, according to Stern (2017), is the main method used to verify the relationship between economic development and environmental degradation. Despite this, the author emphasizes the importance of considering econometric problems, often neglected by literature. Among them, the main ones are the relevant variables omission and sample heterogeneity (LIST e GALLET, 1999; DE BRUYN, 2000; LIEB, 2003; STERN, 2004; STERN, 2017). Therefore, the additional variables inclusion and the appropriate methods use is important to avoid spurious results.

An important aspect confirmed by the literature, and often not considered, is the spatial interactions existence in forest conversion and land use changes (MADDISON, 2006; ROBALINO and PFAFF, 2012). In addition, several studies point out these factors as relevant to the Legal Amazon, with a strong positive spatial interaction impacting deforestation in the region (IGLIORI, 2006; AGUIAR et al., 2007; PFAFF et al., 2007; OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; ANDRADE DE SÁ et al., 2015; JUSYS, 2016; AMIN et al., 2019). One of the possible explanations is that centripetal forces, generated by productivity differences, transport costs, climate, topography and soil conditions that can cause significant regional differences; attract productive activities, especially agricultural and livestock (WEINHOLD and REIS, 2008).

In addition, according to Andrade de Sá et al. (2015) and Amin et al. (2019), several deforestation determinants present dynamic aspects, with factors changed in previous periods affecting the current economic agent's decisions. As an example, areas initially occupied can facilitate access to new agents and to deforestation, as well as public policies with subsidized credit and settlement programs, which have an effect that may not occur at the time of adoption but only in future periods.

Using a dynamic-spatial model, Andrade de Sá et al. (2015) and Amin et al. (2019) confirmed the importance of both effects for deforestation in the Legal Amazon. However, considering the EKC proposed by Grossman and Krugman (1991, 1995), there are no studies that have sought to consider the deforestation dynamic aspect, thus characterizing it as a gap in the literature. In addition, although some studies have considered spatial interactions for the Amazon, in the context of EKC (OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; JUSYS, 2016; AMIN et al., 2019), none included the spatial component together with the possible dynamic effects. That said, the present article seeks to estimate a dynamic-spatial model, using the EKC hypothesis for the 2000 to 2015 period, contributing with new evidence for literature.

Finally, we have the paper structured into four sections, including this introduction. In the second section, we bring a debate about the Environmental Kuznets Curve. The third section details the database and methodology adopted, especially the empirical strategy for the Dynamic Spatial Panel with fixed effects, which will allow empirically investigating the deforestation spatial and dynamic interactions in the Legal Amazon. The results and their analysis are in the fourth section, followed by the final considerations.

2.2 Theoretical Framework

The Environmental Kuznets Curve concept are inspired by Kuznets (1955), which established an inverted "U" functional relationship between economic growth and income distribution, known as the Kuznets Curve. Briefly, it establishes that at low level of development, as a nation grows, there is an increase tendency in social inequality. This occurs until it reaches a maximum value (a peak), from which inequality tends to decrease. The relationship is due to the differences in productivity and in income concentration between rural and urban areas, with cities showing higher productivity and income concentration in relation to the countryside. Therefore, as a country develops, the cities attracts individuals from the rural area, leading a rural exodus, which increases urban area population, widening the per capita income gap between those who remain in the countryside and those in the cities.

Grossman and Krueger (1991), in a pioneering work, adapted the Kuznets model (1955) to verify if there are an inverted U-relationship between economic growth and environmental impact due to the North American Free Trade Agreement creation. The authors confirmed an inverted "U" relationship between economic growth, especially per capita income, and environmental degradation. In addition, Grossman and Krueger (1991) attempted to decompose the effects that are behind the relationship between economic growth and environmental quality, which resulted in three main effects identification: scale, composition, and technical. The scale effect occurs due to an increase in production, which causes a pressure on the environment, since greater natural resources use is needed along with pollutants derived from production. The composition effect is the change that occurs in the goods and services composition produced, such as, for example, the displacement of industrial goods (which are more polluting) for services (low pollutants). Finally, the technical effect is related to technological advances that increase productivity and/or can make production more “clean”", generating less waste.

The composition and technical effects can be large enough to minimize the scale effect after a certain development level. In this context, the trajectory between income growth and degradation may reverse, with economic development not necessarily leading to a rise in environmental degradation. The descending part of the environmental Kuznets Curve, therefore, can be explained by this overlay of effects. (GROSSMAN and KRUEGER, 1991).

Several authors have attempted to broaden the understanding of the relationship between economic development and environmental degradation takes on an inverted U-shape. Among them, we can mention Shafik and Bandyopadhyay (1992), Selden and Song (1994), Arrow et al. (1995), Stern et al. (1996), Suri and Chapman (1998), De Bruyn et al. (1998), Culas (2007), which will be discussed in the next paragraphs.

Shafik and Bandyopadhyay (1992) conducted an empirical study to verify if there is in fact an inverted U-shaped relationship between per capita income and environmental degradation. In order to do so, they used various indicators of environmental degradation such as concentration of pollutants in the atmosphere, urban sanitation deficit, access to water, among others. The results found by the authors indicate that, as income grows, the levels of environmental degradation increase considerably. However, from a given level of income, there is a reversal of this dynamics, leading to a reduction in environmental degradation. The only exceptions were the amount of urban waste and CO2 emissions in the atmosphere, both of which presented a monotonic growth in relation to income. However, most of the indicators showed results similar to those found by Grossman and Krueger (1991).

Selden and Song (1994), in turn, argue that the environmental pressure is due to increases in income and consumption, which lead to greater natural resources use. However, the authors claim that there are some damping factors that could mitigate the negative effects on the environment, and even reverse it in the long run. The reasons and processes that lead EKC to have an inverted "U" format, according to Selden and Song (1994), are mainly due positive income elasticity for environmental quality, changes in the production and consumption composition and technological innovations that increase productivity, induced by market competition and / or due to adjustments to imposed legislation.

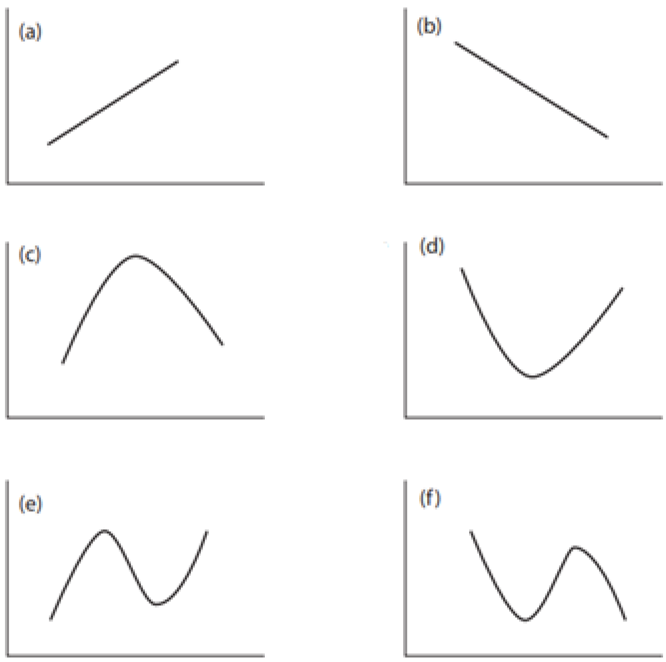
Arrow et al. (1995) argue that the EKC format is due to the natural process of how economic development occurs. That is, it induces a shift of productive activities from the primary (agricultural) sector to the secondary (industrial) sector and finally to the tertiary sector (services). Activities linked to the industrial sector tend to be, on average, more polluting and to use more natural resources than agricultural activities. After this initial transition, where the industrial branch becomes predominant, development leads the nations to shift their activities to the service sector. The service sector by its nature does not generate much waste and does not demand high amounts of natural resources and physical capital like the industry sector, since human capital is its main input. The transition to an economy, which employs the majority of people in the service sector, would therefore be a major cause of EKC's inverted "U" relationship. Thus, for Arrow et al. (1995), the main tool to improve environmental indicators would be through economic development.

Many researchers, however, argue that the descendant part of the EKC occurs because the polluting industries tend to move from developed countries to the underdeveloped ones, due to the restrictions imposed by the legislation, which encourages this displacement. (SURI; CHAPMAN, 1998; ARROW et al., 1995; STERN et al., 1996). This theory is known in the literature as the Pollution Haven hypothesis. Cole (2004) sought to ascertain whether in fact a considerable part of the descendant of the EKC could be explained by this hypothesis. The author used data on imports and exports of polluting products to try to capture whether developed countries would be importing products that generate high level of pollution while reducing their exports of this type of product. If so, there is no change in the consumption composition, thus the curve downward part occurs due industries moving to other countries. However, the author did not find evidence to support such a hypothesis.

Chimeli and Braden (2005), on the other hand, emphasizes the import role from total factor productivity (TPFs) in explaining environmental quality, since it account for much of the variation in income across countries. Institutional changes, according to Culas (2007), is also an important element to explain the relationship in "U" inverted between environmental degradation and per capita income. As income increases, factors such as increased utility from undeveloped areas, population awareness of the environmental sustainability importance, strengthening government capacity for environmental protection, and others, help to explain the decline in environmental impact on reaching higher levels of per capita income.

Despite the evidence for the EKC existence, some authors, such as De Bruyn et al. (1998) argue that this relationship is only sustained in the short term. In the long run, there is another turning point in which per capita income growth leads once again to environmental degradation. Therefore, an “N” -shaped curve and not the inverted “U” shape would better represent the relationship between development and environment. In addition, according to the author, there is the possibility of EKC assuming other formats beyond the usual, making necessary this verification for each specific case. The possible EKC formats are shown in Figure 2.1. According to Carvalho and Almeida (2010), it is possible that the EKC assumes a linear, quadratic or cubic format, as well as unusual relations, such as "U", linear and "N" inverted.

Figure 2.1 - Possible relations between economic development and deforestation.



Source: Adapted from Carvalho and Almeida (2010)

In the specific case of using deforestation as a variable of environmental degradation, the focus of this paper, there is no consensus about the existence of a traditional EKC inverted "U" format. Shafik and Bandyopadhyay (1992), in a pioneering investigation, and Shafik (1994), for example, have not found statistically significant relationships between deforestation and economic growth. On the other hand, analyzing this relationship for three continents, Africa, Latin America and Asia, Cropper and Griffiths (1994) found statistically significant results for the first two.

Bhattarai and Hammig (2001) conducting a similar study for the three continents found statistically significant results for all between growth and forest cover, with an inverted "U" relationship. According to the authors, at low levels of development, the structure of demand as, for example, the consumption of firewood, cause deforestation. On the other hand, as economic growth occurs, such demand structure tends to change, moving to goods that affect less the environment. In addition, income growth induces an increase in replanting efforts, which ends up reversing the deforestation process in the long run. On the other hand, Koyuncu and Yilmaz (2009) found that the increase in demand for arable land also has a significant impact on deforestation along economic growth.

For Brazil, some studies sought to identify the existence of the Environmental Kuznets Curve (EKC) using deforestation. Among the papers for Legal Amazon, we have a controversial empirical evidence, which varies according to the analyzed year or method adopted. For example, Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) found evidence of an inverted "U" relationship while Araújo et al. (2009) and Jusys (2016) captured an EKC in "U"; Oliveira et al. (2011) and Oliveira and Almeida (2011) identified a relationship in the "N" format. Therefore, the results are not conclusive and more studies are necessary to reach a definitive conclusion.

2.3 Methodology

2.3.1 Database

The data for deforestation rate (km²) in the Legal Amazon comes from *Instituto Nacional de Pesquisas Espaciais (INPE)*, consulted through the *Programa de Cálculo do Desflorestamento na Amazônia (PRODES)*. We compiled data on deforestation for a sample of 760 municipalities of the region during the period 2000 to 2015. The variable used is the annual increment in deforestation of the municipality, considered as the forest area converted to deforested land between the year $\boldsymbol{t}$ and $\boldsymbol{t+1}$. Therefore, we use the variable deforestation (DEFOREST) as proxy for environmental degradation, that is, the one that will be presented as the dependent variable in the EKC model.

As economic development proxy, we will use the municipalities per capita GDP, in line with the literature. In addition, per capita GDP are also included in its square and cube version in econometric modeling, in order to seek for the existence of other formats for EKC, that is, a quadratic or cubic function.

The variables described above, as well as the variables used in the present paper are in Chart 2.1. The aim of the inclusion are to improve the econometric model specification, as well as to better represent structurally the region and to identify possible relationships that they may have with deforestation in the Legal Amazon. In addition, we deflate the per capita GDP and rural credit variables to year 2010 BRL, which are expressed as an index with base year 2010 using the *IPCA (Índice de Preços ao Consumidor Amplo)* made available by *IPEA (Instituto Pesquisa Econômica Aplicada)*. The adopted procedure seeks to capture the real values in income growth and concessions in rural credit, since nominal values not affect the resources restrictions that the economic agents face in the decision making process (ASSUNÇÃO and ROCHA, 2019).

Chart 2.1 – Variables used for the period 2000 to 2015.

Abbreviation	**Description**	**Unit**	**Source**
DEFOREST	Deforested area	km²	PRODES/ INPE
GDP	Per capita GDP	R$ (BRL)	SIDRA/IBGE
GDP^2	Per capita GDP - Square	-	-
GDP^3	Per capita GDP - Cube	-	-
RURAL CREDIT	Total rural credit	R$ (BRL)	BACEN
DEM.DENSITY	Demographic density (inhabitants/km2)	km²	SIDRA/IBGE
AGRIC.GDP	Agricultural participation in GDP	%	SIDRA/IBGE
CATTLE	Cattle herd increase	count	SIDRA/IBGE
A.SUGARCANE	Increase in sugar cane plantation.	ha	SIDRA/IBGE
A.SOYBEAN	Increase in soybean plantation.	ha	SIDRA/IBGE
A.MAIZE	Increase in maize plantation.	ha	SIDRA/IBGE
EXTRAC.WOOD	Extraction of wood (charcoal, firewood and wood)	m³	SIDRA/IBGE
SILVICULTURE	Silviculture (Wood)	m³	SIDRA/IBGE
SUGARCANE.PROD	Sugarcane Productivity	kg/ha	SIDRA/IBGE
MAIZE.PROD	Maize Productivity	kg/ha	SIDRA/IBGE
SOYBEAN.PROD	Soy Productivity	kg/ha	SIDRA/IBGE
FOREST.COVER	Remaining forest cover in $(t-1)$	km²	PRODES/INPE

Source: research data.

It is important to note that SIDRA/IBGE - Automatic Recovery System - provides data only on legal wood extraction. Therefore, the wood extracted volume between 2000 and 2015 is probably far below its true level. Illegal logging, mainly from high valued tropical species, has also been an important activity in Amazon, with many environmental and social problems. However, there are a widespread mislabeling for protected species in export documentation and considerable lack of reliable data in illegal logging, which makes difficult to address how this activity affects deforestation (CHIMELI and BOYD, 2010; CHIMELI and SOARES, 2017).

2.3.2 Descriptive Statistics

In order to investigate the municipality's characteristics in Legal Amazon and its changes in the period, Table 2.1 reports the descriptive statistics for the variables used in the EKC model. The column (1) presents the statistics for the initial period, the column (2) bring it for the final and the column (3) reports the difference in the 2000-2015 period. Among the variables, we can highlight some that presented considerable changes. The deforestation, for example, drop from 71.73 km² to 8.08 km², a reduction of approximately 88.73%. On the other hand, per capita GDP increased from R$6,458.96 to 11,028.51 in real value[3]. This supports the "decoupling" process found by Caviglia-Harris et al. (2016) and Silva et al. (2017), since policies that sought the reduction in environmental degradation did not have a significant impact on the pace of economic development in the region.

Table 2.1 – Descriptive statistics.

	Initial (1)	Final (2)	Difference (3)
DEFOREST	71.73	8.08	-63.64
	(185.50)	(26.65)	(179.04)
GDP	6,458.96	11,028.51	4,570.416
	(5,785.78)	(10,190.61)	(7,318.84)
RURAL CREDIT	17,412,287.86	8,393,500.06	-9,018,787.80
	(45497021.66)	(26,537,497.88)	(49,043,623.92)
DEM.DENSITY	20.39	25.34	4.96
	(106.49)	(131.77)	(27.87)
AGRIC.GDP	26.76	25.16	-1.60
	(15.03)	(15.25)	(12.02)

[3] Considering 2010 as year base.

CATTLE	5,462.83	2,621.43	-2,841.40
	(26,531.83)	(13,207.83)	(27,964.53)
AREA.SUGARCANE	47.42	5.53	-41.89
	(555.92)	(600.20)	(798.84)
AREA.SOYBEAN	371.40	885.30	513.90
	(6,429.94)	(4,582.05)	(7,939.80)
AREA.MAIZE	-205.94	295.82	501.75
	(3,109.49)	(3,580.08)	(4,905.87)
EXTRAC.WOOD	12,677.83	8,232.87	-4444.96
	(31,742.70)	(23,564.69)	(29,358.98)
SILVICULTURE	7,791.39	35,835.74	2,8044.35
	(150,327.85)	(262,323.58)	(268,716.25)
SUGARCANE.PROD	16,323.99	16,378.49	54.49
	(19,961.67)	(23,670.77)	(23,549.50)
MAIZE.PROD	1,649.32	2,792.33	1,143.01
	(1,053.69)	(1,948.97)	(1,433.02)
SOYBEAN.PROD	478.40	1,137.56	659.16
	(1,027.09)	(1,463.95)	(1,219.45)
FOREST.COVER	4,439.49	3,907.86	-531.63
	(12,921.10)	(11,880.98)	(1,682.58)

Source: research results.
Note: Standard deviations are reported in parenthesis.

The rural credit, for example, drop from an average value per counties of R$17,412,287.86 in 2000 to R$8,393,500.06. In absolute terms, the rural credit decrease more than 50%, from R$13 billion to R$6 billion, mainly due to restrictions on environmental offenders, which affect mostly cattle ranchers (ASSUNÇÃO et al., 2013). In fact, we have a slowdown in the cattle herd's growth from an average of 5462 heads per year to 2621 in the municipalities, but this still resulted in an increase of approximately 51.2 million heads to 83.5 million in the period (IBGE, 2018).

The soy cultivation, on the other hand, accelerated its expansion; on municipality average terms, form 371 ha to 885 ha per year, resulting in a cultivated area from 3.5 million ha to 11 million ha - growth of 332% (IBGE, 2018). This numbers corroborate Assunção et al. (2015) and Assunção and Rocha (2019) affirmations that there is no trade-off between economic development and environmental conservation on the Legal Amazon, since agricultural sector continued to perform well despite policies to inhibit deforestation. This scenario may resulted from the fact that crop yield grew considerably in the period. For example, soy and maize yield increased 137,78% and 69,3%, respectively, between 2000-2015. However, according to Celentano et al. (2012), the decoupling may be temporary, with long-term increase in material well-being having as a necessary condition the deforestation of the region. In addition, although the reduction in environmental degradation, the remaining forest cover in Amazon drop 531.63 km² (11.97%) per counties, revealing significant land use changes in the region.

Finally, we can mention a recurrent problem in the EKC model: multicollinearity, which can invalidate statistical inferences. According to Lieb (2003), Carson (2010) and Stern (2004; 2017), most of the additional variable included in the model are highly correlated with per capita income. To check this possibility, the Appendix 2.A shows the correlation between the variables used in the EKC for Legal Amazon. From them, we can notice no extremely high correlations that could compromise the estimation of the EKC model.

2.3.3 Empirical Design

Several deforestation determinants presents dynamic aspects, with factors changed in previous period affecting the economic agent's current decisions. (ANDRADE DE SÁ et al., 2015; AMIN et al., 2019). Although its importance, there are no studies that considered the dynamic aspect of deforestation in the EKC model. In addition, spatial interactions in forest conversion and land use changes have a strong impact on the Amazon's deforestation. (IGLIORI, 2006; AGUIAR et al., 2007; PFAFF et al., 2007; OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; ANDRADE DE SÁ et al., 2015; JUSYS, 2016; AMIN et al., 2019). Some empirical works have considered spatial interactions for the Legal Amazon in the EKC model (OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; JUSYS, 2016; AMIN et al., 2019), but none included the spatial spillovers together with dynamic effects.

We used the Dynamic Spatial Autoregressive Model (DSAR) and the Dynamic Spatial Durbin Model (DSDM) to estimate the Kuznets Environmental Curve (EKC) seeking to fill the gap in the literature. In other words, we considered the dynamic-spatial aspects from deforestation using the EKC model, represented in a general format as

$$D_{i,t} = \alpha D_{i,t-1} + \rho W_1 D_{J,t} + \beta_1 GDP_{i,t} + \beta_2 GDP^2{}_{i,t} + \beta_3 GDP^3{}_{i,t} + \beta_4 X_{i,t} + \beta_5 W_1 X_{j,t} + v_{i,t}$$

$$v_{i,t} = u_i + \gamma_t + \epsilon_{i,t} \qquad (1)$$

where $D_{i,t}$ is the Deforestation level for the *i-th* municipality; W_1 is the spatial weight matrix used to represent the neighborhood relationship between municipalities; $X_{i,t}$ is the explanatory variables matrix; $D_{i,t-1}$ and $W_1 D_{J,t}$ are the temporal and spatial lag of deforestation, respectively. $v_{i,t}$ is the model error term, which is divided into three parts: u_i represents the fixed individual effects, γ_t captures specific temporal effects and $\epsilon_{i,t}$ is the error term with mean zero and constant variance. Lastly, $GDP_{i,t}$ is the gross domestic product per capita value, a variable used as proxy for economic development, following Grossman and Krugman (1991; 1995). The GDP inclusion in its square and cube format attempts to verify the existence of a quadratic or cubic relationship between deforestation and development in the Legal Amazon.

The EKC format is related to the signs and significance presented by the coefficients β_1, β_2 and β_3 in the model (1). It is a sufficient condition for the curve to present a linear format, a significant $\beta_1 > 0$, while β_2 and β_3 are not significant. For an inverted "U" shape, it is sufficient that $\beta_1 > 0$, $\beta_2 < 0$ and that both are significant while β_3 is not. In case of $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$, all statistically significant, is configured as a necessary and sufficient condition for an "N" curve shape. Table 2.2 summarizes all possible occurrences in the EKC and their respective interpretations.

Table 2.2 – EKC hypotheses and their interpretations.

Coefficients	Interpretation
$\beta_1 > 0$ and $\beta_2 = \beta_3 = 0$	Linear and monotonic growth
$\beta_1 < 0$ and $\beta_2 = \beta_3 = 0$	Linear and monotonic decrease
$\beta_1 > 0, \beta_2 < 0$ and $\beta_3 = 0$	Quadratic relationship in an inverted "U" shape
$\beta_1 > 0, \beta_2 < 0$ and $\beta_3 > 0$	Cubic relation in an "N" format
$\beta_1 < 0, \beta_2 > 0$ and $\beta_3 = 0$	Quadratic relation in a "U" format
$\beta_1 < 0, \beta_2 > 0$ and $\beta_3 < 0$	Inverted "N" -shaped cubic relationship

Source: Adapted from Almeida (2017).

In addition, according to Stern (2017), after estimating the EKC, if the model presents a β_1 and β_2 statistically significant, it is possible to find the point of the curve that is called the "turning point", which is where the curve reaches its maximum value (in the case of inverted "U" format) or minimum value (if formatted as "U"). We can find the turning point using the following equation

$$\tau = -\frac{\beta_1}{2\beta_2} \tag{2}$$

Regarding the possible econometric problems, we highlight the presence of sample heterogeneity and / or spatial dependence, which can potentially cause bias and inconsistency in the estimated parameters. The heterogeneity problem is recurrent in EKC, especially with geographical units, such as municipalities, since each place potentially has unique characteristics (LIST and GALLET, 1999; DE BRUYN, 2000; LIEB, 2003; STERN, 2004). Therefore, we used in this paper the advantage of the panel structure to control the municipalities fixed effects, as well as fixed effects for each specific year. These procedures can filter intrinsic municipalities characteristics, unusual shocks, heterogeneous initial conditions and different municipal dynamics, making estimates more consistent.

On the other hand, when working with regional data, according to Almeida (2012), normally we have spatial autocorrelation. Thus, it is necessary to adopt techniques to identify and control this spatial effect in order to avoid econometric problems that can invalidate statistical inferences. For the identification and treatment of spatial dependence, we used Exploratory Spatial Data Analysis (ESDA) and Spatial Econometrics techniques. In the next subsection, we detail the methodological procedures mentioned.

2.3.4 Exploratory Spatial Data Analysis (ESDA)

The ESDA are techniques used to capture spatial dependence and heterogeneity effects in the data. For this reason, it is of great importance in the model specification process, since it indicates if there is some type of spatial process, what could lead to econometric problems such as bias and inconsistency in the parameters. ESDA is also able to capture, for example, spatial association patterns (spatial clusters), indicate how the data are distributed, occurrence of different spatial regimes or other forms of spatial instability (non-stationarity), and identify outliers (ANSELIN, 1995)

Spatial dependence means that the variable value in a region depends on its value in other regions. This dependence occurs in all directions, but tends to decrease its impact as increases geographic distance. Spatial heterogeneity, in turn, is related to the regions characteristics and leads to structural instability, so each locality may have a distinct response when exposed to the same influence.

The first step to using ESDA and spatial econometrics techniques is the definition of a spatial weights matrix, which expresses how the phenomenon under analysis is spatially arranged. There are a large number of matrices in the literature, such as the queen, tower and k neighbors matrices that are usually of binary contiguity or receive differentiated weights for each region. The matrix definition is very important for the ESDA and in the estimation of the econometric model, since the results are sensitive to the different matrices. Therefore, it is necessary to search for the one that best represents the phenomenon under study and captures more faithfully the spatial process (ANSELIN, 1995).

The second step is to test whether there is spatial autocorrelation for the variable between regions, in other words, whether the data are spatially dependent or randomly distributed. One way to verify this is through Moran's I, which are a statistics that seeks to capture the spatial correlation degree between a variable across regions. The expected value of this statistic is $E(I) = -1/(n-1)$ and when statistically higher or lower than expected indicate positive or negative spatial autocorrelation respectively. Mathematically, it can represent as

$$I = \frac{n}{S_o} \frac{\sum_i \sum_j w_{ij} z_i z_j}{\sum_{i=1}^{n} z_i^2} \tag{3}$$

where n is the number of regions, S_0 is a value equal to the sum of all elements of matrix W, z is the normalized value for deforestation in the present paper.

However, the Moran's I statistic, according to Anselin (1995), can only capture the global autocorrelation, not identifying the spatial association at a local level. For this, we have complementary measures that aims to capture local spatial autocorrelation, that is, that seek to observe the existence of local spatial clusters. The main one is the LISA (Local Indicator of Spatial Association) statistic.

For an indicator to be considered LISA, it must have two characteristics: (i) for each observation it should be possible to indicate the existence of spatial clusters that are significant; ii) the sum of local indicators, in all places, should be proportional to the global spatial autocorrelation indicator. The Moran's I statistic (LISA), can be represented as

$$I_i = z_i \sum_{j-1}^{J} w_{ij} z_j \tag{4}$$

where z_i represents the investigated variable on region i; w_{ij} is the spatial weighting matrix element (W) and z_j is the value of the variable of interest on region j. The local Moran I (LISA) can represent four spatial clusters: High-High (AA), Low-Low (BB), High-Low (AB) and Low-High (BA). The most analyzed is the High-High cluster, which indicates that a region with a high value for the analyzed variable is surrounded by regions with similar values.

2.3.5 Dynamic Spatial Panel

The Dynamic Spatial Panel Model, besides incorporating the spatial lag of the dependent variable, also incorporates a temporal dependent variable. In addition, it is possible to incorporate a space-time lag of the dependent variable. Therefore, it is a methodology capable of empirically grasping the theoretical model proposed in this article. The estimation of such a model will follow the approach proposed by Yu et al. (2008). The general specification are

$$Y_{nt} = \lambda_0 W_n Y_{nt} + \gamma_0 Y_{nt-1} + \rho_0 W_n Y_{nt-1} + X_{nt}\beta_0 + \boldsymbol{c}_{n0} + V_{nt}, \quad t = 1,2,\dots,T \tag{5}$$

where $Y_{nt} = (Y_{1t}, Y_{2t}, \dots, Y_{nt})'$ and $V_{nt} = (V_{1t}, V_{2t}, \dots, V_{nt})'$ are column vectors with dimension $n \times 1$, V_{nt} is $i.i.d$ with i and t with mean zero and variance ${\sigma^2}_0$; W_n is a spatial weight matrix $n \times n$ that captures the spatial dependence between the cross-section variables y_{it}; X_{nt} is a matrix $n \times k_x$ of non-stochastic regressors; and $\boldsymbol{c}_{n0}$ is a column vector $n \times 1$ of fixed effects. Therefore, the number of parameters in the model will be equal to the number of individuals n plus the other common parameters to be estimated, $(\gamma, \rho, \beta', \lambda, \sigma^2)$, ie, $k_x + 4$.

Denoting $S_n \equiv S_n(\lambda_0) = I_n - \lambda_0 W_n$ and $A_n = S_n^{-1}(\gamma_0 I_n + \rho_0 W_n)$, where S_n is invertible, (5) can be rewritten as $Y_{nt} = A_n Y_{nt-1} + S_n^{-1} X_{nt}\beta_0 + S_n^{-1}\boldsymbol{c}_{n0} + S_n^{-1} V_{nt}$. Assuming that infinite sums, by continuous substitution, are well defined, we have

$$Y_{nt} = \sum_{h=0}^{\infty} A_n^h S_n^{-1}\left(\boldsymbol{c}_{n0} + X_{n,t-h} + V_{n,t-h}\right) = \mu_n + \mathfrak{X}_{nt}\beta_0 + U_{nt} \tag{6}$$

In which $\mu_n = \sum_{h=0}^{\infty} A_n^h S_n^{-1} \boldsymbol{c}_{n0}$, $\mathfrak{X}_{nt} = \sum_{h=0}^{\infty} A_n^h S_n^{-1} X_{n,t-h}$ and $U_{nt} = \sum_{h=0}^{\infty} A_n^h S_n^{-1} V_{n,t-h}$. The next step is to define the maximum likelihood function that should be maximized. For this, it we denoted $\theta = (\delta', \lambda, \sigma^2)'$ and $\zeta = (\delta', \lambda, \boldsymbol{c}'_n)'$, where $\delta = (\gamma, \rho, \beta')'$, being the true value $\theta_0 = (\delta'_0, \lambda_0, \sigma^2{}_0)$ and $\zeta_0 = (\delta'_0, \lambda_0, \boldsymbol{c}'_{n0})$, which results in the following maximum likelihood function

$$\ln L_{n,T}(\theta, \boldsymbol{c}_n) = -\frac{nT}{2}\ln 2\pi - \frac{nT}{2}\ln \sigma^2 + T\ln|S_n(\lambda)| - \frac{1}{2\sigma^2}\sum_{t=1}^{T} V'_{nt}(\zeta)\, V_{nt}(\zeta) \qquad (7)$$

where $V_{nt}(\zeta) = S_n Y_{nt} - \gamma_0 Y_{nt-1} - \rho_0 W_n Y_{nt-1} - X_{nt}\beta_0 - \boldsymbol{c}_n$, ie, $V_{nt} = V_{nt}(\zeta)$. If V_{nt} is normally distributed, we will have the maximum likelihood estimators (MLEs) $\hat{\theta}_{nT}$ and $\hat{\boldsymbol{c}}_{nT}$, derived from the maximization of (7). In the other hand, if V_{nt} is not normally distributed, we have the quasi-maximum likelihood estimators (QMLEs).

However, a problem with equation (7) is that the number of parameters tends to infinity as n tends to infinity. Therefore, Yu et al. (2008) proposes a concentrated function of maximum likelihood; concentrating $\boldsymbol{c}_n$ out, focusing the asymptotic analysis only in the estimator θ_0 by the concentrated function, since it does not change the parameter size when n and/or T change. With the purpose of simplification, the author denoted $\tilde{Y}_{nt} = Y_{nt} - \bar{Y}_{nT}$ and $\tilde{Y}_{nt-1} = Y_{nt-1} - \bar{Y}_{nT-1}$, for $t = 1,2,\dots,T \in \mathbb{N}$ where $\bar{Y}_{nT} = \frac{1}{T}\sum_{t=1}^{T} Y_{nt}$ and $\bar{Y}_{n,T-1} = \frac{1}{T}\sum_{t=1}^{T} Y_{n,t-1}$. Similarly, $\tilde{X}_{nt} = X_{nt} - \bar{X}_{nT}$ and $\tilde{V}_{nt} = V_{nt} - \bar{V}_{nT}$; denoting $Z_{nt} = (Y_{nt-1}, W_n Y_{nt-1}, X_{nt})$, therefore the equation (27), using the first order condition $\frac{\partial \ln L_{n,T}(\theta, \boldsymbol{c}_n)}{\partial \boldsymbol{c}_n} = \frac{1}{\sigma^2}\sum_{t=1}^{T} V_{nt}(\zeta)$, the concentrated estimator of $\boldsymbol{c}_{n0}$ given θ is $\hat{\boldsymbol{c}}_{n0}(\theta) = \frac{1}{T}\sum_{t=1}^{T}(S_n(\lambda)\, Y_{nt} - Z_{nt}\delta)$ and the concentrated maximum likelihood function is

$$\ln L_{n,T}(\theta) = -\frac{nT}{2}\ln 2\pi - \frac{nT}{2}\ln \sigma^2 + T\ln|S_n(\lambda)| - \frac{1}{2\sigma^2}\sum_{t=1}^{T} \tilde{V}'_{nt}(\zeta)\, \tilde{V}_{nt}(\zeta) \qquad (8)$$

with the first order condition

$$\frac{1}{\sqrt{nT}}\frac{\partial \ln L_{n,T}(\theta)}{\partial\theta} = \begin{pmatrix} \frac{1}{\sigma^2}\frac{1}{\sqrt{nT}}\sum_{t=1}^{T}\tilde{Z}'_{nt}\,\tilde{V}'_{nt}(\zeta) \\ \frac{1}{\sigma^2}\frac{1}{\sqrt{nT}}\sum_{t=1}^{T}\left((W_n\,\tilde{Y}_{nt})'\,\tilde{V}_{nt}(\zeta) - \mathrm{tr}G_n(\lambda)\right) \\ \frac{1}{2\sigma^4}\frac{1}{\sqrt{nT}}\sum_{t=1}^{T}\tilde{V}'_{nt}(\zeta)\tilde{V}_{nt}(\zeta) = n\sigma^2 \end{pmatrix} \quad (9)$$

while the second order condition is

$$\frac{1}{\sqrt{nT}}\frac{\partial^2 \ln L_{n,T}(\theta)}{\partial\theta\partial\theta'}$$

$$= -\frac{1}{\sqrt{nT}}\begin{pmatrix} \frac{1}{\sigma^2}\sum_{t=1}^{T}\tilde{Z}'_{nt}\,\tilde{Z}_{nt} & \frac{1}{\sigma^2}\sum_{t=1}^{T}\tilde{Z}'_{nt}\,W_n\,\tilde{Y}_{nt} & \frac{1}{\sigma^2}\sum_{t=1}^{T}\tilde{Z}'_{nt}\,\tilde{V}_{nt}(\zeta) \\ * & \frac{1}{\sigma^2}\sum_{t=1}^{T}\left((W_n\,\tilde{Y}_{nt})'\,W_n\,\tilde{Y}_{nt} + \mathrm{tr}\left(G_n^2(\lambda)\right)\right) & \frac{1}{\sigma^4}\sum_{t=1}^{T}(W_n\,\tilde{Y}_{nt})'\,\tilde{V}_{nt}(\zeta) \\ * & * & -\frac{nT}{2\sigma^4} + \frac{1}{\sigma^4}\sum_{t=1}^{T}\tilde{V}'_{nt}(\zeta)\tilde{V}_{nt}(\zeta) \end{pmatrix} \quad (10)$$

where $\tilde{V}_{nt}(\zeta) = S_n(\lambda)Y_{nt} - Z_{nt}\delta$ and $\tilde{Z}_{nt} = (Y_{nt-1} - \bar{Y}_{nT-1}, W_nY_{nt-1} - W_n\bar{Y}_{nt-1}, X_{nt} - \bar{X}_{nT})$. The QMLE $\hat{\theta}_{nT}$ maximizes the function (28), satisfying the conditions of first and second order, and the estimator of quasi-maximum likelihood of $\boldsymbol{c}_{n0}$ is $\hat{\boldsymbol{c}}_{n0}(\hat{\theta}_{nT})$. Therefore, concluding the necessary estimates for the Dynamic Spatial Panel[4].

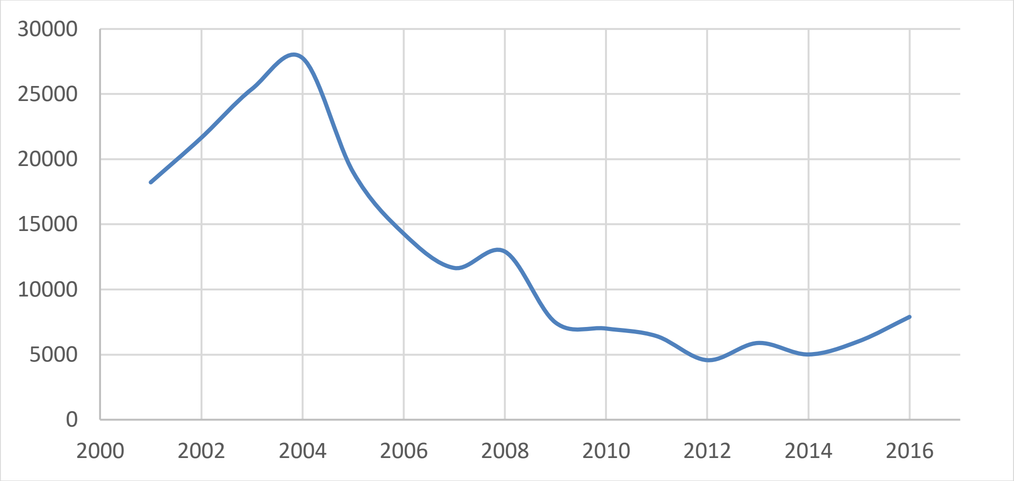
2.4 Results and Discussion

Deforestation in the Legal Amazon has significant negative impacts on the environment, affecting adjacent localities and potentially global climatic stability. Therefore, the search for its determinants are fundamental for the development of inhibitory measures.

[4] Considering the Dynamic Spatial Panel Model estimated by maximum likelihood, as proposed by Yu et al. (2008), we still do not have the Dynamic Spatial Error Model (DSEM) and Dynamic Spatial Durbin Error Model (DSDEM). Therefore, we estimated only the Dynamic Spatial Autoregressive model (DSAR) and the Dynamic Spatial Durbin Model (DSDM).

The Figure 2.2 shows the deforestation's rate in the Legal Amazon in the 2001-2016 period – cleared area in km². We can notice that deforestation reached a peak in 2004, when we had about 28,000 square kilometers (km²) of forest clearing. According to Araújo et al. (2009), the 2004 peak are related to the agricultural prospects booming due to the exchange rate depreciation and rise of agricultural commodities' prices, especially soybean. Since then, deforestation decreased considerably to approximately 8,000 km² in 2016, a drop of more than 70% (INPE, 2018).

Figure 2.2 – Deforestation in Legal Amazon in the 2001-2016 period (km²).



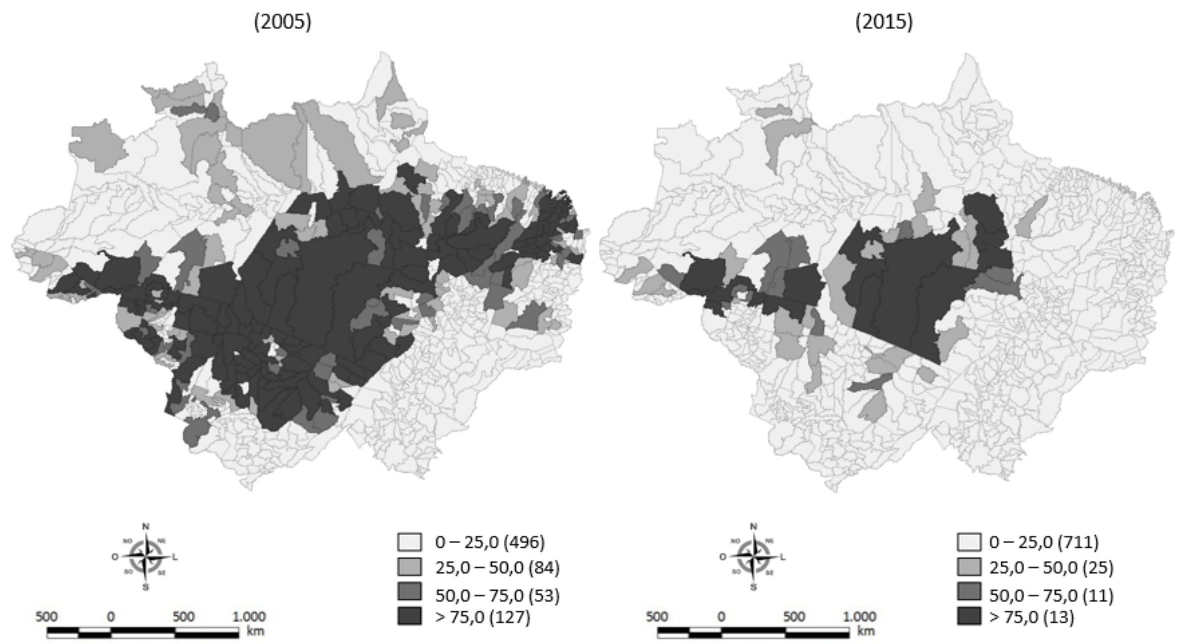
Source: research data.

Assunção et al. (2015) highlight three main factors that led to this scenario. The fall in agricultural commodities' prices after the mid-2000s, the implementation of the *Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm)* in 2004 and the agricultural credit conditionality of environmental preservation. However, the 8,000 km² of cleared area in 2016 is considerably higher than the 4,500 km² value from 2012. This scenario indicates that the "decoupling" process supported by Caviglia-Harris et al. (2016) and Silva et al. (2017) may be losing ground in the Amazon.

The Figure 2.3 shows the deforestation spatial distribution in the Legal Amazon in 2005 and 2015 among the municipalities in the region. Comparing the initial period (2005) *versus* the final (2015), there is a relatively similar spatial disposition, with the permanence of some municipalities that, *a priori*, had a preponderant participation in the deforestation in the Legal Amazon. According to Igliori (2006b), Fearnside (2007) and Araújo et al. (2009), this region is known as the "Deforestation Arc", which is characterized by the agricultural frontier expansion. However, deforestation decrease sharply in the period. For example, in 2005, approximately

35% of the municipalities cleared an area greater than 25 km², a value that decrease to only 6,5% in 2015. Considering deforestation above 75 km², we had 16,7% in the initial period compared to 1,7% ten years later.

Figure 2.3: Distribution of deforestation in the Legal Amazon in 2005[5] and 2015[6].



Source: research data.

The Moran's I statistic presented in Table 2.3 ratifies the spatial concentration for deforestation, presenting positive and statistically significant coefficients - independent of the convention matrix applied. That is, municipalities with high deforestation area are surrounded by municipalities also with high levels of degradation in both periods considered. In addition, there are a decrease in the coefficients magnitude over the years, signaling a spatial deconcentration and a decrease in the spillover from deforestation.

Theoretically, this deforestation spatial concentration process may result from spatial interactions, which can reinforce deforestation. This phenomenon are also evidenced by several empirical papers for Legal Amazon (IGLIORI, 2006; AGUIAR et al., 2007; PFAFF et al., 2007; OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; ANDRADE DE SÁ et al., 2015; JUSYS, 2016; AMIN et al., 2019).

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[5] Average of 2004, 2005 and 2006. Procedure adopted to avoid random effects of the deforestation process, which will also be adopted for the next exploratory analyzes.
[6] Average of 2014, 2015 and 2016.

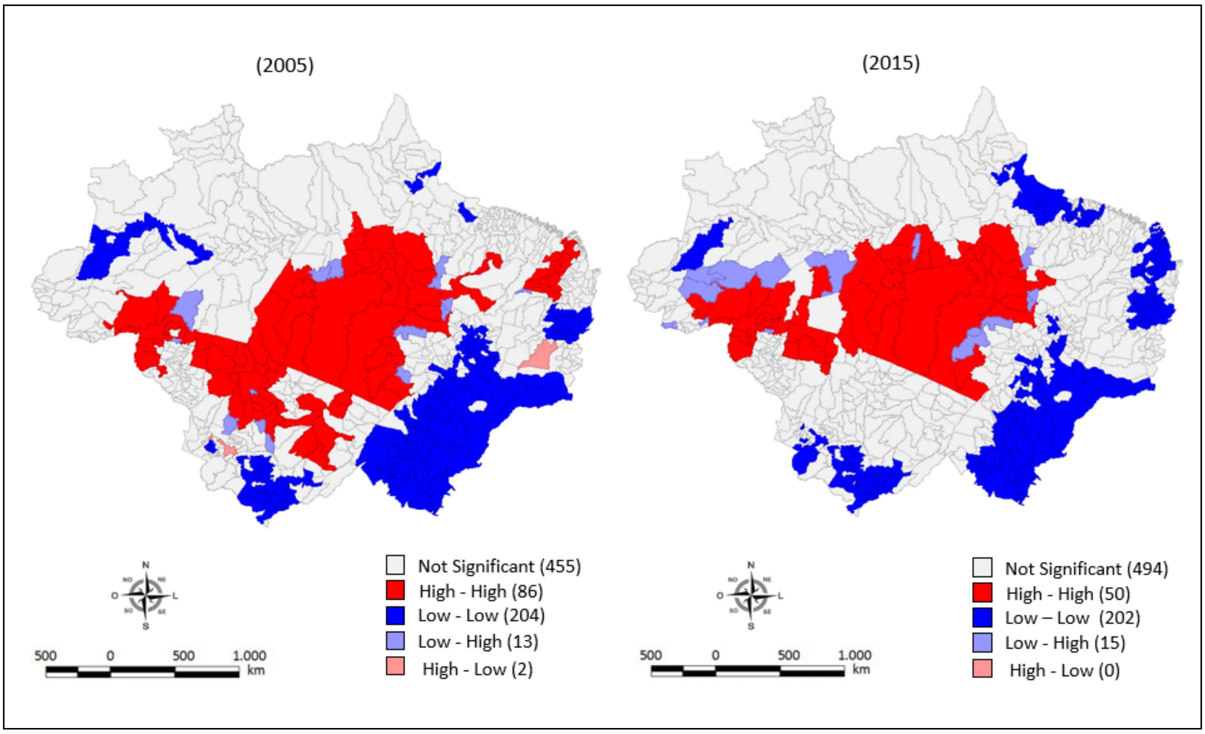
Table 2.3 - Moran's I for deforestation in the Legal Amazon in 2005 and 2015.

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
Deforestation 2005	0.48*	**0.49***	0.40*	0.38*	0.35*	0.31*
Deforestation 2015	0.46*	**0.47***	0.33*	0.37*	0.32*	0.28*

Note: * Level of significance of 1%.
Source: research data.

Figure 2.4 confirms this spatial phenomenon for deforestation in the municipalities of the Legal Amazon, with the consolidation of a large High-High cluster located in the "Arc of Deforestation". As in Figure 2.2, there is a decrease in the size of this Cluster in the municipalities in the south; while, on the other hand, there is an advance to northern locations, possibly indicating the consolidation and advancement of the agricultural frontier in the region.

Figure 2.4 – LISA map for deforestation in Legal Amazon in 2005 and 2015.



Source: research data.
Note: Empirical pseudo-significance based on 99,999 random permutations.

With the basic deforestation characteristics in the Legal Amazon identified, in terms of its spatial distribution, the next step is to find its determinants. To this end, Table 2.4 shows the Environmental Kuznets Curve results estimated with the Dynamic Spatial Autoregressive model (DSAR) and the Dynamic Spatial Durbin Model (DSDM) for the period from 2000 to 2015.

Table 2.4 – Dynamic Spatial Autoregressive model (DSAR) and Dynamic Spatial Durbin Model (DSDM) for EKC in Legal Amazon, from 2000 to 2015,

VARIABLES	DSAR (2)	DSAR (3)	**DSDM (2)**	DSDM (3)
DEFOREST $(\gamma)_{t-1}$	0.1371***	0.1372***	**0.1365*** **	0.1366***
W_DEFOREST $(\rho)_t$	1.3768***	1.3775***	**1.3237*** **	1.3244***
GDP	0.0002	-3.42E-06	**0.0003*** **	0.0001
GDP^2	-1.66E-09	3.08E-09	**-2.36E-09** **	1.57E-09
GDP^3	-	-2.49E-14	**-**	-2.07E-14
A.SUGARCANE	-0.0001	-0.0001	**-0.0002**	-0.0001
A.MAIZE	-0.0001	-0.0001	**-0.0001**	-0.0001
A.SOYBEAN	7.04E-06	9.73E-06	**2.68E-05**	2.89E-05
CATTLE	0.0001***	0.0001***	**0.0001*** **	0.0001**
FOREST.COVER	0.0010***	0.0010***	**0.0011*** **	0.0011**
DEM.DENSITY	0.0131	0.0127	**0.0064**	0.0059
SILVICULTURE	-3.85E-07	-4.08E-07	**-3.22E-07**	-3.30E-07
EXTRAC.WOOD	3.27E-05**	3.33E-05**	**3.33E-05** **	3.37E-05**
AGRIC.GDP	0.0344	0.0393	**0.1089** **	0.1126**
MAIZE.PROD	-0.0012***	-0.0011***	**-0.0009** **	-0.0009**
SOYBEAN.PROD	-0.0008	-0.0008	**-0.0005**	-0.0005
SUGARCANE.PROD	1.82E-05	1.83E-05	**-5.62E-06**	-5.42E-06
RURAL CREDIT	1.40E-08*	1.42E-08*	**1.28E-08* **	1.29E-08*
D.OUTLIER	102.5200***	102.5083***	**100.4746*** **	100.4636***
W_GDP	-	-	**-0.0007*** **	-0.0007***
W_A.SUGARCANE	-	-	**0.0007**	0.0007
W_A.MAIZE	-	-	**0.0005**	0.0005
W_A.SOYBEAN	-	-	**-4.99E-05**	-4.93E-05
W_CATTLE	-	-	**1.51E-05**	1.44E-05
W_FOREST.COVER	-	-	**-0.0007**	-0.0007
W_DEM.DENSITY	-	-	**0.0049**	0.0060
W_SILVICULTURE	-	-	**5.95E-06**	5.62E-06
W_EXTRAC.WOOD	-	-	**0.0001**	0.0001

W_AGRIC.GDP	-	-	**-0.5480*** **	-0.5456***
W_MAIZE.PROD	-	-	**-0.0008**	-0.0008
W_SOYBEAN.PROD	-	-	**-0.0040** **	-0.0039**
W_SUGARCANE.PROD	-	-	**0.0003*** **	0.0003***
W_RURAL CREDIT	-	-	**9.81E-09* **	1.00E-08*
W_D.OUTLIER	-	-	**62.9460*** **	62.8907***
Akaike	99019.06	99017.62	**98965.63**	98964.66

Source: research data.
Note: Significant at *** 1%; ** 5%. * 1%
D.OUTLIER is a dichotomous variable for the municipalities that are leverage points detected in the ESDA. They reinforce the deforestation pattern observed.[7]

Prior to the estimations, we applied the Hausman test to the fixed and random effects models (Appendix 2.B) to verify the sample's suitability to the method used. It is possible to reject the null hypothesis that there are no systematic differences in the estimated coefficients[8], making the fixed effect model the best to capture the deforestation determinants. In addition, following Baumont (2004), we chose the spatial lag matrix that generated the largest Moran's I coefficient for the fixed effect (2) model residues (Appendix 2.C) to estimate the Dynamic Spatial Panel Model, opting for the queen matrix. Moreover, we identified the presence of heteroscedasticity and in order to control the problem, we estimated the spatial dynamic models using the standard robust error of Huber/White/Sandwich (HUBER, 1967).

Next, we define which model best represents and captures the deforestation determinants. Using the Akaike information criterion, the Dynamic Spatial Durbin Model (DSDM) are the one that presented the lowest value for this adjustment criterion, making it the chosen model. On the other hand, considering the spatial dependence in the dynamic spatial models residuals (Appendix 2.D and 2.E), the Dynamic Spatial Durbin Model (DSDM) are the one that minimize the spatial effects on the model. Both facts confirms the importance in incorporating spatial spillovers to explain deforestation in dynamic-spatial model, an empirical evidence in line with Andrade de Sá et al. (2015) and Amin et al. (2019).

According to Grossman and Krueger (1995) and De Bruyn et al. (1998), the choice between the quadratic and cubic model, in the EKC context, is determined by selecting the one that presented statistical significance for the per capita income variable. Therefore, the model in its quadratic format, DSDM (2), are the most appropriate, since the cubic (3) did not presented

[7] Oliveira et al. (2011) proposed the procedure for deforestation in the EKC model for Legal Amazon, which improved econometric estimates.
[8] Chi² statistics: 212.8, with a probability of 0,000.

statistical significance. The coefficients' signs, $\beta_1 > 0$ and $\beta_2 < 0$ indicate that we have an inverted-"U" format, demonstrating that deforestation will increase until a certain threshold as the region grows economically, from which it begins to fall. This empirical evidence is in line with Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) who also found that economic development induces deforestation slowdown in the long run.

Using $\tau = -\beta_1/2\beta_2$ to calculate the EKC "turning point", where the curve reaches its maximum value, we find a value of annual per capita GDP of R$66.059,32 with 2010 as base year. This income, however, is considerably large than the Legal Amazon average of R$11.028,51 and only four municipalities in the region is above this turning point threshold. In other words, despite the fact that we got an inverted "U" curve for EKC, the majority of the region's counties are far below this turning point, which means that income growth will continue to induce deforestation on the Amazon. In addition, the per capita GDP growth presented a negative spatial spillover effect, reducing deforestation in its neighbors, a fact that can minimize the high turning point. However, even in the long run, the economic growth may not be a sufficient factor to generate biome protection, since there are other variables that also impacts deforestation. This translates into a trade-off among development and forest conservation, as supported by Igliori (2006b), Celentano et al. (2012) and Chagas and Andrade (2017).

Among the other results, we have the dependent variable temporarily lagged, DEFOREST_{t-1}, which presented a coefficient (γ) statistically significant at the 1% level, with a positive impact on deforestation. Therefore, this fact corroborates the hypotheses and empirical evidence from Andrade de Sá et al. (2015) and Amin et al. (2019) that deforestation in t is positively influenced by its value in $t-1$, and have greater importance to explain environmental degradation in the municipalities of the Legal Amazon. This scenario helps to explain the dynamics presented by deforestation in Figure 2.3 and 2.4, where it is evident that some regions that deforested the most in 2005 continued to do it in 2015, evidencing an inertial component in environmental degradation. Thus, the evidence presented here demonstrates the need and importance in incorporating the deforestation temporal inertia in the analysis of its determinants in the EKC model.

The coefficient that seeks to capture the deforestation spatial spillovers, (ρ), also showed statistical significance at 1% level, indicating that municipalities with high deforestation rates induces the increase of environmental degradation in their neighbors. This phenomenon are also evidenced by several empirical studies specifically applied to deforestation in Amazon, including: Igliori (2006), Aguiar et al. (2007), Pfaff et al. (2007), Oliveira and Almeida (2011), Oliveira et al. (2011), Andrade de Sá et al. (2015), Jusys (2016) and Amin et al. (2019). Thus, the results presented are in line with those empirical evidences and the spatial spillovers presence can also be one of those responsible for the spatial concentration verified in Figure 2.3 and 2.4. The spatial concentration phenomena occurs because certain activities are agglomerated in a given locality due to the presence of attractive (centripetal) forces such as productivity, transport costs, climate, topography and soil conditions, that induce concentration, especially from agricultural activities (KRUGMAN, 1991; WEINHOLD and REIS, 2008).

Regarding the additional explanatory variables with statistical significant coefficients, the cattle herd increase, the forest stock in the $t-1$ period, the extraction of wood, the participation of agricultural actives in GDP, the dummy for outliers and rural credit had positive impact while maize productivity presented an negative coefficient. For the statistical significant spatially lagged variables, we have the per capita GDP, participation of agricultural actives in GDP and soybean productivity with negative spillovers while the dummy outlier and rural credit had positive spillovers. There are some possible interpretations for the results presented in the EKC - DSDM (2), which we described in the next paragraphs.

The cattle herd growth in Legal Amazon is an important deforestation inductor, a fact supported by Carvalho (2007), Barona et al., (2010), Martinelli (2010), Godar et al. (2012), Alencar et al. (2015), Faria and Almeida (2016) and Nascimento (2017), who identified in this activity the main responsible for the agricultural frontier expansion in the region. However, the increase in the herd did not spillover to neighbors' municipalities, not inducing indirect environmental degradation. The remaining forest cover in previous period also helps to explain the deforestation rates patterns in Amazon: greater the proportion of native forests, higher is the environmental degradation. This evidence is in line with Oliveira et al. (2011) and shows that some municipalities may deforest less due to the simple fact that they do not have much remaining forest area to do it.

According to Bhattarai and Hamming (2001), at low economic development levels, the demand structure normally contains firewood consumption, a fact that can explain statistical significance of legally wood extraction positive impact on deforestation. However, Chimeli and Boyd (2010) and Chimeli and Soares (2017) argues that illegal logging is widely present in the Amazon, especially for high valued tropical species, which could also be a deforestation vector, amplifying the wood extraction environmental impact.

In addition, Grossman and Krueger (1991; 1995) argues that good and services growth causes a pressure on the environment, since greater natural resources use is needed to its production, what is called the scale effect. The authors emphasizes that this effect is predominant at the beginning of economic development, in which the main income generator is the agricultural sector. Indeed, the proportion of agricultural sector in GDP presented statistical significance for Legal Amazon, thus in line with Grossman and Krueger (1991; 1995) theoretical proposition. However, this phenomenon has the potential to spillover negatively to its neighbor, decreasing their deforestation rates, in other words, diminishing its negative impact on the environment.

The maize productivity growth is the only variable that has the potential to decrease deforestation directly in the Amazon. The maize production is often adopt together with soybean, in a modern crop rotation system, which increases the farmer security and profits. In this context, many municipalities have been able to increase their harvests without significant impacts on deforestation (ARVOR et al., 2011; MACEDO et al., 2012). Although soy productivity did not reduce environmental degradation directly, it has significant spatial spillovers to neighbors, diminishing its deforestation rates. Therefore, production intensification in soy and maize in an integrated crop rotation system in existing agricultural areas can be a powerful instrument to induce sustainable production growth.

Although the increase in soy cultivation area did not affect deforestation in the municipality and in its neighbors, is worth mentioning that soy has an important indirect impact in land use changes on Amazon (BARONA et al., 2010; GOLLNOW and LAKES, 2014). Due Soy Moratorium restrictions on market access of soy cultivated in recently deforested areas, the production has increased on land used previously by extensive livestock (BARONA et al., 2010; ARIMA et al., 2011; MACEDO et al., 2012; RICHARDS et al., 2012). Sugarcane despite that its production increased mainly in others regions, as in São Paulo state, it also presents a similar effect on cattle displacement (BARONA, et al., 2010; ANDRADE DE SÁ et al., 2012; JUSYS, 2017).

Therefore, the expansion of cultivated area for both soy and sugarcane causes cattle rearing displacement to counties usually in the agricultural frontier, inducing deforestation (ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013; GOLLNOW e LAKES, 2014). In summary, cattle herd growth may also encompass the indirect soy and sugarcane influence along with its own determinants. A possible solution for the problem is to incentive production intensification in existing agricultural areas, which would enable Brazil to reduce significantly its deforestation and greenhouse gas emissions and still maintain agricultural growth (COHN et al., 2014; CORTNER et al., 2019).

Although sugarcane is not a predominant crop in the region and has no important area effect, its productivity growth have positive spillover effects in its neighbors, corroborating the Assunção and Rocha (2019) affirmation that recent expansion of Brazilian ethanol production leads to direct deforestation in the Amazon.

The rural credit to the agricultural sector are historically an important occupation inductor in the Legal Amazon, being one of the main deforestation determinants by helping the agricultural frontier expands (ARAÚJO et al., 2012, ASSUNÇÃO et al., 2013; HARGRAVE and KIS-KATOS, 2013; GOLLNOW and LAKES, 2014). However, this scenario have changed after the Resolution 3,545 introduced in 2008 by the *Conselho Monetário Nacional (CMN),* when credit approval become possible only based on compliance proof with environmental regulations. According to Assunção et al. (2013), this policy instrument avoided 2,700 km² of deforestation per year. This context may explain the week statistical significance of 10% for the variable and for its spatial lagged variable. In any case, the statistical results indicates that the rural credit concession still have the potential to increase deforestation and spillover positively to its neighbors.

2.5 Final Considerations

This paper aimed to investigate the relationship between economic growth and deforestation in the Legal Amazon, considering the period from 2000 to 2015, using the theoretical approach known as the Environmental Kuznets Curve. As the main contribution to the literature, we highlight the incorporation of temporal inertia, spatial dependence and spillovers in the EKC context, using a Dynamic Spatial Panel Model. Although several studies investigated the relationship between economic growth and deforestation for the Amazon, none had incorporated together the temporal and spatial perspective in the EKC model.

Among the results, we obtained an inverted "U" format for the EKC, indicating that economic development will induce environmental preservation in the long term, a fact accelerated by spatial spillovers presence among municipalities, which supports deforestation reduction. However, we found that the majority of municipalities in Amazon are far below the turning point in the EKC model, so that economic development may act as a deforestation inductor in the following decades. In addition, we have other variables that affects deforestation and, since economic growth may not be sufficient to protect the Amazon rainforest, we need complementary means to ensure the environmental sustainability of the region.

Another important result are the confirmation of the temporal and spatial component for understanding deforestation in the region, which possibly explains the spatial agglomeration and the temporal persistence of degradation in certain municipalities, especially located in the agricultural frontier (Arc of Deforestation). These evidences indicate a spatial-temporal inertia presence for deforestation, a fact that allows more effective inhibition actions, since it makes easier to predict its occurrence in following periods due to the inertial component.

Regarding the additional explanatory variables, we can highlight the positive impact on deforestation from the cattle herd increase, forest stock in $t-1$, the extraction of wood, the participation of agricultural actives in GDP and rural credit. The agricultural participation in GDP and soybean productivity presented negative spillovers while rural credit and sugarcane productivity had positive spillovers. This empirical evidence shows that there are more deforestation determinants in Legal Amazon than only economic growth; reinforcing the need to understand their motivations and future prospects. In summary, the society cannot rely only on economic development to generate sustainability, since other factors potentially could inhibit the efforts.

The cattle herd growth, according to the literature, may also encompass the indirect soy and sugarcane influence along with its own determinants. This reflects from significant forces that land use changes causes in national and international agricultural markets, modifying relative prices that induces less profitable activities, as cattle raising, to agricultural frontiers where the land is cheaper. This empirical evidence shows the importance of considering land use dynamics and cross-agricultural activities leakages in policies targeting deforestation reduction, since crops like soy and sugarcane may indirectly affect environmental degradation in Amazon, even when located in other regions. These activities normally replaces livestock in spaces already occupied, shifting cattle production to agricultural frontier regions, where it increase deforestation.

The extraction of wood and agricultural participation in GDP, on the other hand, are related to the development scale effect, since it depends on natural resources use. The rural credit has been historically an important occupation inductor in Amazon. Even with the government recent efforts to minimize its impact on deforestation and reduce its environmental damages, the rural credit continue to cause degradation directly and through spatial spillovers. Therefore, measures aiming to improve policy instruments are still necessary to cope rural credit with legal and environmental regulations compliance

We can also mention the maize and soybean productivity as deforestation inhibitors, the first direct in the municipality where it increases and the second through spatial spillovers to its neighbors. Public policies and instruments that create incentives for implementation of technologies adapted to local conditions and adoption of more technologically advanced inputs could boost productivity, which generates greater profits to the sector, reducing its incentive to expand planted area. However, these effects are limited to maize and soy cultivation, since sugarcane productivity affect the environmental degradation in its neighbors. Therefore, productivity gains incentives cannot be defined uniformly for all agricultural activities, since each has different impacts on deforestation.

It is worth mention that the usual hypothesis advocated by various authors, along with economic and political agents, that economic growth is enough to generate environmental sustainability may not be completely true when considering the Legal Amazon. The per capita income GDP presented a high turning point, indicating that economic development will turn into a protective force just in a long term. In this context, if public policies do not address the deforestation problem in the meanwhile, the Amazon forest may present irreparable loss in its biodiversity and capability of generate ecosystem services for society.

The measures adopted after the 2004 deforestation peak for environmental protection enable considerable reduction in the cleared area without inhibiting economic growth. However, the deforestation remain at a considerable high rate and even has increased in recent years, reinforcing the need for measures that seeks sustainability. In summary, while the income do remains lower than the turning point, the Brazilian society must address the deforestation problem more actively. From the evidences found in this paper and based on the literature, we can highlight some possible alternatives. The first one is to incentive production intensification by adopting modern technology and technics, which enables higher productivity, especially focused on the main agricultural activities in Amazon: soybean, maize and cattle ranching. In addition, continue to improve the rural credit concession compliance with legal and environmental regulations while creating incentives mechanisms for productivity gains.

Finally, one important contribution of this paper is to highlight the spatial spillovers and temporal inertia importance on explaining deforestation. Policies aimed to address environmental problems on Amazon can benefit from this evidence. The spillovers and inertia components consideration could bring better understand of possible spatial interaction implications along with the temporal persistence of the adopted policies, making it more effective in coping with deforestation problems.

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APPENDICES

APPENDIX 2.A – Correlation

	GDP	A.SUGAR	A.MAIZE	A.SOYBEAN	CATTLE	FOREST	DEM.DENS	SILVIC.	WOOD	AGRIC.GDP	MAIZE.PROD	SOY.PROD	SUGAR.PROD	CREDIT
GDP	1													
A.SUGARCANE	0.0961	1												
A.MAIZE	0.2153	0.0163	1											
A.SOYBEAN	0.2344	-0.0228	0.1649	1										
CATTLE	-0.0289	-0.0057	-0.0311	0.002	1									
FOREST.COVER	-0.0212	-0.0102	-0.0221	-0.0107	0.0824	1								
DEM.DENSITY	-0.012	-0.0048	-0.0111	-0.021	-0.0221	-0.0559	1							
SILVICULTURE	0.0487	-0.0037	0.0124	0.021	-0.0088	0.1009	-0.0096	1						
EXTRAC.WOOD	0.0011	-0.004	0.0047	0.0123	0.0491	0.2606	-0.0452	0.2122	1					
AGRIC.GDP	0.1737	0.0366	0.0805	0.1413	0.0447	-0.0997	-0.1881	-0.0364	-0.0194	1				
MAIZE.PROD	0.4724	0.0479	0.1609	0.1775	0.0104	-0.0076	-0.1613	0.0163	0.0365	0.2485	1			
SOY.PROD	0.4019	0.038	0.1384	0.2216	-0.0062	-0.084	-0.0904	0.0115	0.0415	0.2316	0.6166	1		
SUGAR.PROD	0.0922	0.0882	-0.0104	-0.0097	0.0671	0.1175	-0.0729	0.0125	0.0309	0.0434	0.1762	0.0985	1	
CREDIT	0.5295	0.0247	0.1708	0.2619	0.0148	-0.0342	-0.0344	0.0482	0.0141	0.1244	0.4095	0.3633	0.0616	1

Source: research results.

APPENDIX 2.B – Pooled, Fixed Effect and Random Effect models for deforestation in Legal Amazon.

VARIABLES	POOLED (2)	POOLED (3)	FIXED EFFECT (2)	FIXED EFFECT (3)	RANDOM EFFECT (2)	RANDOM EFFECT (3)
CONSTANT	23.2649***	22.4340***	29.5915***	31.8119***	24.5116***	23.7673***
GDP	0.0003**	0.0005**	-0.0008***	-0.0012***	0.0002	0.0004
GDP^2	-2.35E-09*	-8.16E-09	4.74E-09**	1.66E-08**	-1.57E-09	-6.40E-09
GDP^3	-	3.53E-14	-	-6.35E-14	-	2.83E-14
A.SUGARCANE	0.0003	0.0003	0.0006	0.0006	0.0004	0.0005
A.MAIZE	-0.0006***	-0.0006***	-0.0006***	-0.0006***	-0.0006***	-0.0006***
A.SOYBEAN	0.0004***	0.0004***	0.0001	0.0001	0.0003***	0.0003***
CATTLE	0.0005***	0.0005***	0.0002***	0.0002***	0.0004***	0.0004***
FOREST.COVER	0.0005***	0.0005***	0.0031***	0.0031***	0.0005***	0.0005***
DEM.DENSITY	-0.0017	-0.0020	-0.0376	-0.0371	-0.0025	-0.0028
SILVICULTURE	-5.87E-06**	0.0000**	0.0000	-2.52E-06	-6.05E-06*	-6.14E-06*
EXTRAC.WOOD	0.0002***	0.0002***	0.0001***	0.0001***	0.0002***	0.0002***
AGRIC.GDP	0.1982***	0.2006***	0.2553***	0.2655***	0.2244***	0.2256***
MAIZE.PROD	-0.0021***	-0.0021***	-0.0056***	-0.0055***	-0.0028***	-0.0028***
SOYBEAN.PROD	0.0005	0.0004	-0.0023***	-0.0022***	0.0004	0.0004
SUGARCANE.PROD	2.14E-05	1.85E-05	0.0002***	0.0002***	0.0001**	0.0001**
RURAL CREDIT	6.30E-09	5.83E-09	2.50E-08*	2.51E-08***	1.01E-08	9.76E-09
D.OUTLIER	253.8052***	253.7105***	215.9399***	215.9479***	242.4429***	242.4482***
Akaike Info. Criterion	123627.6	123626.2	121329.7	121326.8	-	-

Source: research results. *Note:* D.OUTLIER is a dichotomous variable for the municipalities that are leverage points, that is, they reinforce the pattern of deforestation observed, detected in the ESDA. Significant at *** 1%; ** 5%; * 10%.

APPENDIX 2.C - Moran's I for the Fixed Effect (2) Panel Data residuals - convention matrix decision.

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
2001	**0.4769***	0.4741*	0.3743*	0.3711*	0.3227*	0.2951*
2002	**0.4706***	0.4676*	0.3707*	0.3583*	0.3168*	0.2841*
2003	**0.4815***	0.4792*	0.3781*	0.3654*	0.3213*	0.2879*
2004	**0.5034***	0.5015*	0.3920*	0.3806*	0.3412*	0.3074*
2005	**0.5129***	0.5109*	0.4000*	0.3879*	0.3470*	0.3164*
2006	**0.5119***	0.5103*	0.3979*	0.3891*	0.3485*	0.3174*
2007	**0.4702***	0.4689*	0.3690*	0.3740*	0.3344*	0.3045*
2008	**0.5182***	0.5163*	0.4108*	0.3924*	0.3532*	0.3164*
2009	**0.5198***	0.5175*	0.4126*	0.3950*	0.3555*	0.3196*
2010	0.5040*	**0.5046***	0.4052*	0.3949*	0.3601*	0.3289*
2011	**0.5120***	0.5111*	0.4167*	0.3949*	0.3623*	0.3351*
2012	**0.5334***	0.5333*	0.4392*	0.4193*	0.3830*	0.3486*
2013	0.5559*	**0.5563***	0.4651*	0.4384*	0.4081*	0.3766*
2014	**0.5392***	0.5387*	0.4445*	0.4247*	0.3897*	0.3593*
2015	**0.5574***	0.5558*	0.4630*	0.4463*	0.4085*	0.3808*

Note: * Level of significance of 1%.
Source: research data.

APPENDIX 2.D **-** Moran's I for Dynamic Spatial Autoregressive model (DSAR) residuals.

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
2002	**0.6884***	0.6856*	0.5878*	0.5734*	0.5519*	0.5103*
2003	**0.3898***	0.3906*	0.4067*	0.3175*	0.2420*	0.1895*
2004	**0.2906***	0.2962*	0.2899*	0.2625*	0.2103*	0.1628*
2005	**0.2385***	0.2391*	0.2234*	0.2113*	0.1802*	0.1584*
2006	**0.4940***	0.4950*	0.4633*	0.4265*	0.4153*	0.3395*
2007	**0.2457 ***	0.2454*	0.1937*	0.1575*	0.1611*	0.1508*
2008	**0.2970***	0.2998*	0.2902*	0.2174*	0.2167*	0.1512*
2009	**0.3137***	0.3179 *	0.2623*	0.2349*	0.2128*	0.1810*
2010	0.3338*	**0.3369***	0.2167*	0.2471*	0.2246*	0.1802*
2011	**0.2883***	0.2894*	0.2224*	0.2040*	0.1732*	0.1543*
2012	**0.4854***	0.4884*	0.3835*	0.3805*	0.3443*	0.2980*
2013	**0.2070***	**0.2070***	0.1894*	0.1828*	0.1758*	0.1435*
2014	**0.2816***	0.2859*	0.2415*	0.2345*	0.2059*	0.1784*
2015	**0.2327***	0.2376*	0.1726*	0.1760*	0.1525*	0.1449*

Note: * Level of significance of 1%.
Source: research data.

APPENDIX 2.E **-** Moran's I for the Dynamic Spatial Durbin Model (DSDM) residuals.

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
2002	**0.6540***	0.6512*	0.5634*	0.5450*	0.5209*	0.4770*
2003	**0.3728***	0.3736*	0.3912*	0.3654*	0.2274*	0.1758*
2004	**0.2717***	0.2769*	0.2695*	0.2389*	0.3412*	0.1371*
2005	**0.2576***	0.2586*	0.2365*	0.2229*	0.1840*	0.1690*
2006	**0.5263***	0.5279*	0.4863*	0.4578*	0.4438*	0.3728*
2007	**0.2947***	0.2937*	0.2296*	0.1947*	0.1945*	0.1823*
2008	**0.2841***	0.2876*	0.2901*	0.2114*	0.2096*	0.1468*
2009	**0.3017***	0.3059*	0.2559*	0.2222*	0.2023*	0.1660*
2010	0.3646*	**0.3670***	0.2522*	0.2665*	0.2434*	0.1959*
2011	**0.3166***	0.3179*	0.2353*	0.2177*	0.1852*	0.1641*
2012	**0.5118***	0.5145*	0.3984*	0.3941*	0.3541*	0.3030*
2013	0.2117*	**0.2185***	0.1989*	0.1901*	0.1824*	0.1458*
2014	**0.3384***	0.3430*	0.2887*	0.2816*	0.2523*	0.2160*
2015	**0.2640***	0.2694*	0.2027*	0.2003*	0.1723*	0.1559*

Note: * Level of significance of 1%.
Source: research data.

3. The Environmental Impacts of the Agricultural Frontier Expansion in the Cerrado

3.1 Introduction

The Cerrado is the richest savannah in the world, being of great importance for the balance of the global ecosystem. However, its intensive occupation, which began in the 1970s, has caused serious damage to the biome, making it a hotspot of the world's biodiversity[9], with high endemism and the threat of irreparable environmental losses (MYERS et al., 2000). The Cerrado is located essentially in the central part of Brazil, occupying about 25% of the national territory, with an area of approximately 2,039,243 km², covering 1,389 Brazilian municipalities (IBAMA, 2010).

Due to the expansion of the agricultural frontier in the Cerrado, there is an increase in the pressure for the opening of new agricultural areas, which induces the environmental degradation of the region (GIBBS et al., 2015; BRAGANÇA, 2018; ARAÚJO et al. 2019). According to Araújo et al. (2019), agricultural frontier are a region dominated by natural vegetation that is facing intensive agriculture-related land occupation.

In 2002, for example, the biome had 43.6% of deforested area and, in 2010, the value increased to 47.8%. Thus, in this short period, we had 4% of forest clearing. Considering year 2010, the annual rate of deforestation are 0.3%, the highest for all biomes present in the Brazilian territory. In terms of territorial extension, the clearing in Cerrado also exceeds the cleared area of the Amazon rain forest. Nevertheless, the Cerrado biome have been overlooked when compared to the attention given to the Amazon region. These factors led to a progressive depletion of its natural resources, making the biome the second that more suffered anthropic alterations in Brazil, after the Atlantic Forest (IBAMA, 2010; BEUCHLE et al., 2015).

[9] Refers to 25 biologically rich areas in the world that have lost at least 70 % of their original habitat (MYERS et al., 2000).

The current deforestation of the Cerrado occurs due to the establishment of new frontiers for agricultural production, such as Matopiba[10], which is the main region of the current Brazilian agricultural frontier and has presented a rapid economic growth (BORGES and SANTOS, 2009; DIAS et al., 2016; BRAGANÇA, 2018).

In addition, there are several underutilized lands in the region that can be incorporated into the most dynamic areas of the Cerrado, with the adoption of higher productivity techniques that are already available in other places. Moreover, there are many areas of Matopiba that have a considerable amount of Cerrado native forests, which can also be incorporated, as the Brazilian agricultural frontier expands (BATISTELLA and VALLADARES, 2009; STUDTE, 2008; BOLFE et al, 2016; NOOJIPADY et al., 2017; ARAÚJO et al. 2019). This context may result in rapid deforestation of Cerrado. In 2010, for example, among the ten municipalities with the largest deforested area, all were located in Matopiba (IBAMA, 2010).

The factors mentioned have enabled the Matopiba to present increasing levels of production, especially in soybean culture, and local economic growth (BOLFE et al, 2016; ZANIN and BACHA, 2017; BRAGANÇA, 2018; ARAÚJO et al. 2019). To illustrate this, according to Araújo et al. (2019), the Matopiba had a significant growth in soy production, from 260,624 t in 1990 to 10,758,927 t in 2015, an increase of 4.028% in the period.

However, according to Assunção and Bragança (2015) and Bragança (2018), the recent dynamics presented by Matopiba, in fact, is part of a historical process of the agricultural frontier expansion in the Brazilian Cerrado, which began in the 1960s and 1970s. This expansion has been mainly due to the implementation of technologies adapted to local conditions, as the accommodation of soy cultivation in tropical areas for acid and poor soils, which allows an increase in productivity for the agricultural production of the region (SPEHAR, 1994; KIIHL and CALVO, 2008; ASSUNÇÃO and BRAGANÇA, 2015; MUELLER and MUELLER, 2016).

The low price of land and the easy adoption of mechanized and large-scale agriculture have attracted labor along with investments in capital, which intensified their occupation, resulting in an expressive growth in local production, mainly of grains like soybeans and maize (SPEHAR, 1994; MIRANDA et al., 2014; ASSUNÇÃO and BRAGANÇA, 2015; BRAGANÇA, 2018; ARAÚJO et al. 2019).

[10] This term refers to the initial syllables of the states that compose this region: Maranhão, Tocantins, Piauí e Bahia. The main criterion used by Embrapa in its delimitation was the presence or not of the Cerrado in these states (IBAMA, 2010).

An important effect of the recent Cerrado occupation is the cattle ranching replacement, characterized with low capital intensity, by soybean cultivation that usually adopts more technologically advanced inputs, with greater potential to generate profits (MONTEIRO et al., 2012; ASSUNÇÃO and BRAGANÇA, 2015). In addition, Assunção and Bragança (2015) found evidence that the decline in cattle ranching, despite being lower than the soybean advance, occurred especially in municipalities that had greater natural abilities and adequate infrastructure for technological innovations adoption related to soy cultivation.

The land use changes in Cerrado resulted in restrictions on the beef supply, which caused an increase in its price in the national and international markets. This fact induced an increase in production with livestock displacement to municipalities of the Cerrado relatively unfit for soybean cultivation – especially due soil heterogeneity conditions - and for agricultural frontier regions in the Legal Amazon[11] (BRAGANÇA, 2014; ASSUNÇÃO and BRAGANÇA, 2015) . This is an important indirect impact due to land use changes, and may lead to deforestation in Brazil (LAPOLA et al., 2010; BARONA et al., 2010, ARIMA et al., 2011; MACEDO et al., 2012, ANDRADE DE SÁ et al., 2013, RICHARDS et al., 2014; GOLLNOW and LAKES, 2014)

In this context, the present paper aims to verify if there is a relationship between economic development, - which is correlated with the increase in agricultural production (BRAGANÇA, 2018) - and the Cerrado biome deforestation, with a special focus on the Matopiba region, due to agricultural frontier expansion.

The basic hypothesis to be tested comes from the work of Grossman and Krueger (1991; 1995). The authors state that at low levels of development, economic growth leads to an increase in environmental degradation due to a scale effect. However, from a certain level this logic would reversed, with the increase of material well-being leading to a decrease of environmental degradation, when demand composition and technological effects are greater than scale one. The representative curve of this relationship, according to the authors, would present an inverted "U" shape, known in the literature by the Environmental Kuznets Curve (EKC).

However, some problems are not considered in many EKC estimations, at least not altogether. Among them, we can cite mainly three: (i) inadequate proxy utilization (mainly per capita income) to represent economic development (HILL and MAGNANI, 2002; JHA and BHANU MURTH, 2003; STIGLITZ et. al., 2009; KUBISZEWSKI et. al., 2013; NEVE and HAMAIDE, 2017). (ii) relevant variable omission (LIEB, 2003; STERN, 2004; CARSON,

[11] Legal Amazon covers 20% of Cerrado (ASSAD, 2016).

2010; STERN, 2017); and (iii) heterogeneity in the sample (LIST and GALLET, 1999; DE BRUYN, 2000; LIEB, 2003; STERN, 2017). Although there are several papers that tried to control the mentioned problems, we do not found studies that consider all the problems at the same time.

A methodological contribution of this work, besides the verification of the impacts of the economic development on the Cerrado deforestation, is the attempt to consider all the problems simultaneously. The strategy adopted consists of: (i) replace per capita income as proxy for a socioeconomic development multidimensional index created with factorial analysis; (ii) consider the existence of spatial dependence, together with additional variables that captures the agricultural frontier expansion in the Cerrado; (iii) estimate the EKC with spatial regimes for heterogeneity control purposes.

This paper have four sections, including this introduction. In the second, we have an overview on the agricultural frontier expansion in Cerrado, while in the third section is the theoretical reference on the Environmental Kuznets Curve. In the fourth section, the methodology and the database are detailed. The results and discussion are in the fifth section, followed by the final considerations.

3.2 The Agricultural Frontier Expansion in Cerrado

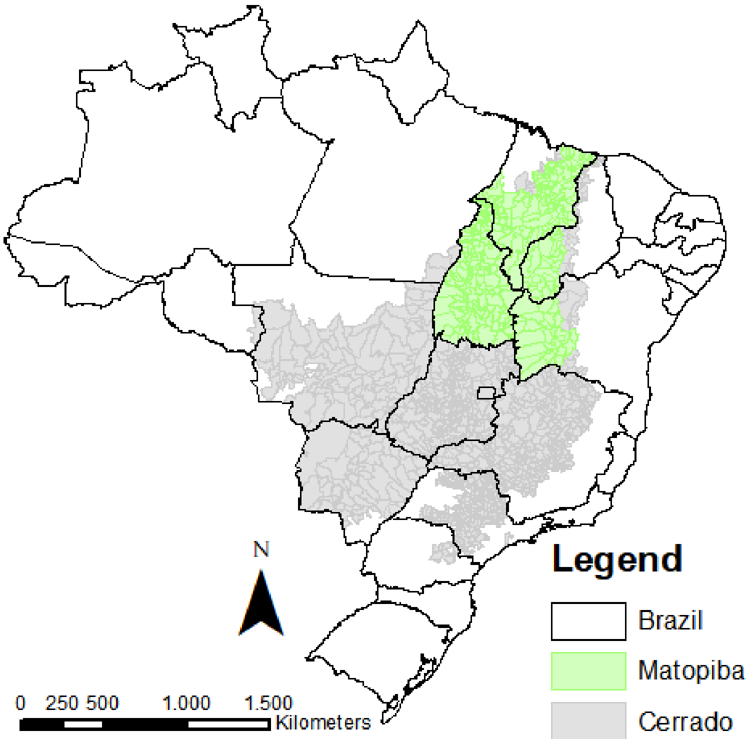
The Cerrado is located essentially in the central region of Brazil, occupying about 25% of the national territory, with an area of approximately 2,039,243 km², covering 1,389 Brazilian municipalities. In addition, the biome is the richest savanna in the world and of much importance to the balance of the global ecosystem. However, its intensive occupation, especially after the 1970 with the advancement of the Brazilian agricultural frontier, has caused serious damage to the biome, with many irreparable environmental losses (MYERS et al., 2000). The biome is present in several Brazilian states, with distinct proportions: Goiás with 97% of the total of its territory; Maranhão presented 65%, Mato Grosso do Sul, 61%; Minas Gerais, 57%; and smaller portions in the states of Mato Grosso, 40%; Piauí, 37%; Sao Paulo, 33%; Bahia, 27%; Paraná, 2%; and Rondônia with 0.2% (IBAMA, 2010).

The Matopiba, composed by the states Maranhão, Tocantins, Piauí and Bahia, are the main region of the current Brazilian agricultural frontier, which is presenting rapid economic growth. (BOLFE et al, 2016; DIAS et al., 2016; NOOJIPADY et al., 2017; BRAGANÇA, 2018). Recognizing the region's strategic importance for Brazilian agribusiness, the country's government issued Decree No. 8,447 on May 6, 2015, establishing an Agricultural

Development Plan for Matopiba, which seeks to guide federal projects and actions of agricultural and livestock activities specifically for the region (BRASIL, 2015). Figure 3.1 brings the location that the Cerrado and the Matopiba occupy in the Brazilian territory.

The *Empresa Brasileira de Pesquisa Agropecuária* (Embrapa) elaborated the Matopiba demarcation, having as its main criterion the presence or not of the Cerrado in the four states, as well as other factors, such as socioeconomics elements. The demarcation resulted in 337 municipalities from 31 microregions with an area of 73 million hectares. The state with the highest percentage in the region is Tocantins which has 37.95% of the area (139 municipalities), followed by Maranhão with 32.77% (135 municipalities), Bahia with 18.06% (30 municipalities) and, finally, Piauí with 11.21% (33 municipalities) (EMBRAPA, 2017). According to the Ministério da Agricultura (2017), the Matopiba region reached an 11% share in the total produced by Brazilian agribusiness in 2015.

Figure 3.1 –Cerrado and Matopiba Location in Brazil



Source: research data.

The Brazilian government played an active role in the occupation and expansion of the agricultural frontier in the Cerrado. This role began in the 1970 with the military governments, especially after the *II Plano Nacional de Desenvolvimento (PND)*. The Government had as its main objective the technical and political control in terms of Brazilian territory occupation. In practice, the occupation incentive of the Cerrado, especially the Central-West, was through the advancement of the Agricultural Frontier in the region (BECKER, 2001). The basic instrument used was the subsidized rural credit offer, combined with the implementation of an infrastructure that enabled the territory occupation, especially for the production of commodities destined for export. Such incentives and measures resulted in rapid changes in land coverage and use in the region (PIRES, 2000; ASSUNÇÃO and BRAGANÇA, 2015; BRAGANÇA, 2018).

Soybean, originally cultivated in southern Brazil, are the main crop that led to the agricultural frontier expansion in the Cerrado, especially after the 1960s. Initially, soy cultivation was inadequate for the region due to the characteristics of the Central part of Brazil, which are overcome after Government investments in agricultural research aimed to adapt this crop to the tropical climate and to the soil of the Cerrado, naturally acidic and poor in nutrients. (SPEHAR, 1994; KIIHL and CALVO, 2008; ASSUNÇÃO and BRAGANÇA, 2015; MUELLER and MUELLER, 2016; ARAÚJO et al., 2019). In the 1970s, for example, the Brazilian Central-West accounted for approximately 5% of the national soybean production in the 1960s, a percentage that jumped to more than 40% in the 1990s (ZANIN and BACHA, 2017).

Colonization projects that granted land rights and subsidies in Cerrado, associated with the construction of a basic infrastructure, especially roads, allowed the displacement of farmers to the region, intensifying the territory occupation. There is a close relationship between migration and the opening of roads, which enable the creation of access corridors to the region. These, in turn, induce the agricultural frontier expansion and possibly native areas deforestation because the road network expansion allows access to previously isolated areas, affecting its environmental degradation rhythm. Nevertheless, papers analyzing the roads impacts in the Brazilian deforestation are concentrated exclusively on the Legal Amazon (NESPTAD et al., 2001; SOARES-FILHO et al., 2004; PFAFF et al., 2007; FEARNSIDE et al., 2007; WALKER et al., 2013).

The colonization projects lasted from approximately 1940 to 1980, a period characterized by a considerable increase in the Cerrado occupation, especially in the Central-West region (ALSTON et al., 1996; JEPSON, 2006; SANTOS et al., 2012). According to Zanin and Bacha (2017), the considerable migration of soybean farmers from the South region of Brazil explains considerable proportion of soybean cultivation increase in the Cerrado, as well as in other regions of the country. In other words, we have an interconnection between the advance of soy in the Cerrado and the migration of farmers from the South region. Zanin and

Bacha (2017) found evident that this phenomenon is still underway, with Matopiba being the main attraction region in recent periods.

Table 3.1 brings the distribution and percentage of each type of land use and cover in in the Cerrado from 1985 to 2015. Considering pasture, agriculture and pasture/agriculture, they presented a joint growth in land use of 10% in the period, which highlights the importance that agriculture and livestock has in the Cerrado occupation. However, this fact increase the pressure to open new areas intended for agricultural production, reflected in a reduction of 11% in the native forest area in the biome, a value that is practically similar to the joint growth of agriculture and pasture. This fact corroborates the hypothesis that the main driver of deforestation in the Cerrado is the agricultural frontier expansion. To better visualize this phenomenon, Figure 3.2 shows the annual evolution of native forests, agriculture and pastures in the Cerrado region.

Table 3.1 - Land use and cover in the Cerrado from 1985 to 2015.

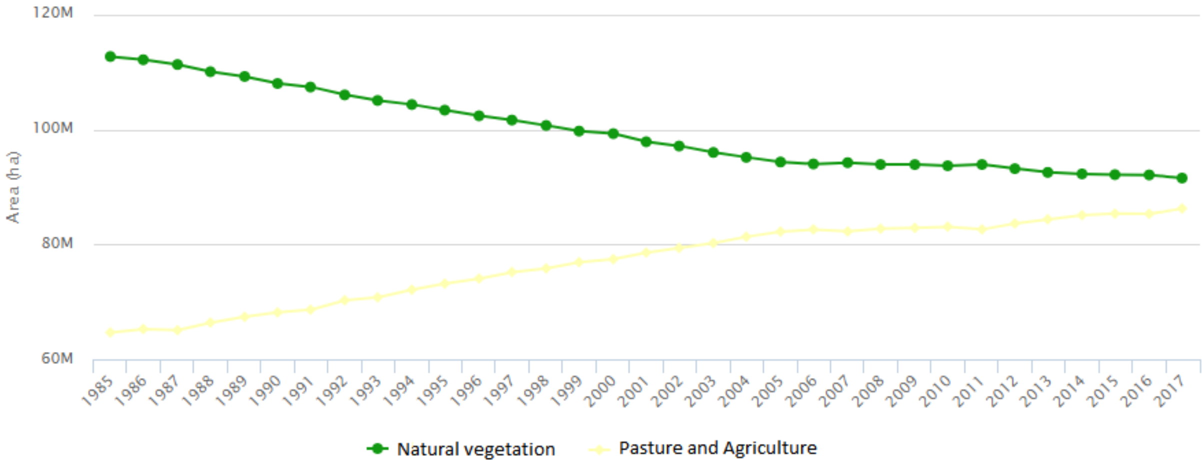
Class	1985		1995		2005		2015	
	Hectares	(%)	Hectares	(%)	Hectares	(%)	Hectares	(%)
Forest	112.736.620,67	0,56	103.397.324,69	0,51	94.372.623,95	0,46	92.163.330,48	0,45
Pasture	36.999.133,48	0,18	49.501.478,93	0,24	52.993.574,51	0,26	48.784.659,34	0,24
Agriculture	5.370.055,78	0,03	8.964.408,84	0,04	15.440.277,94	0,08	23.429.564,97	0,12
Pasture/Agricult*	22.297.905,12	0,11	14.734.388,63	0,07	13.820.613,12	0,07	13.162.889,26	0,06
Forestry	515.637,12	0,00	1.087.997,60	0,01	995.899,44	0,00	2.355.195,93	0,01
Water	1.189.881,00	0,01	1.217.313,33	0,01	1.535.092,89	0,01	1.568.446,22	0,01
Others	23.854.356,94	0,12	24.060.678,08	0,12	23.805.508,26	0,12	21.499.503,92	0,11
Total	202.963.590,11		202.963.590,11		202.963.590,11		202.963.590,11	

Source: Mapbiomas (2019)

Note: * This class corresponds to land use between agriculture and/or pasture that are not precisely identified. Its value declines over the period due to the improvement of the satellite images and methods used to gather such information.

We can note that the decline in the biome's native forests showed a faster pace between 1985 and 2005, concomitantly with significant growth in the area devoted to agriculture and pasture. After 2005, on the other hand, both presented a considerable reduction in their respective rates, indicating a relative stabilization in the land use and cover in the Cerrado. In addition, Table 3.1 shows that, between 1995 and 2005, the area growth rate devoted to agriculture and pasture are approximately 6%, while the reduction in native forests are 5%. On the other hand, in the period of 2005 and 2015, agriculture and pasture grew by only 1%, with native forests also declining by 1%. This dynamic indicates a possible close connection between changes in land use and deforestation in the Cerrado, given the negative correlation between both growth rates.

Figure 3.2 - Land use and cover between natural vegetation and pasture-agriculture in the Cerrado Biome from 1985 to 2017.

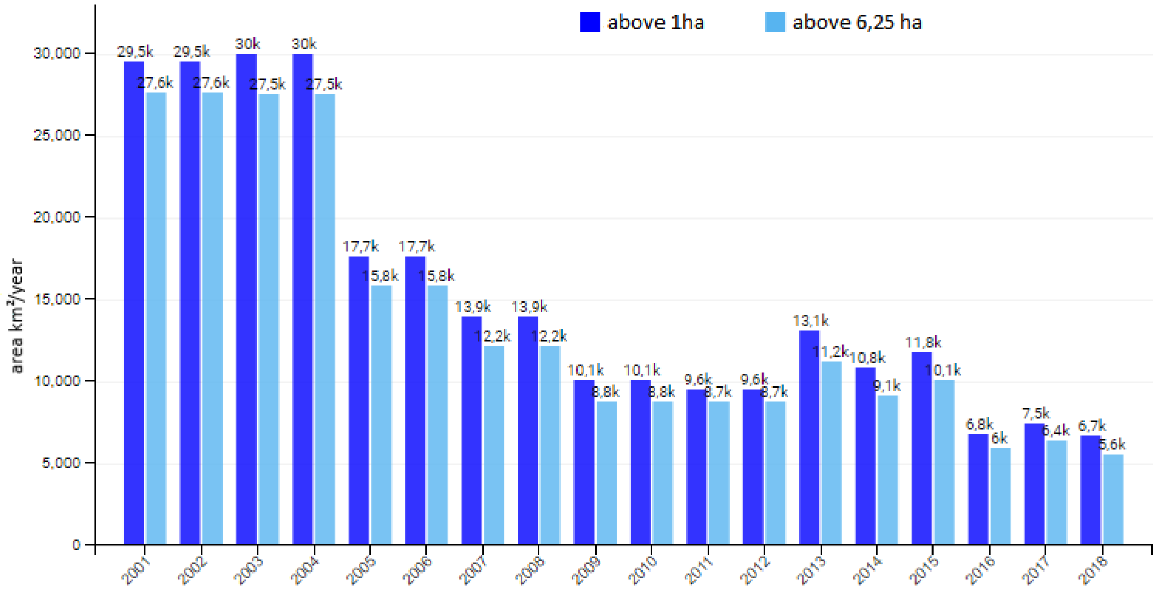


Source: Mapbiomas (2019).

To verify how this dynamics translated into actual deforestation of the biome, Figure 3.3 shows the annual values, in area per km², of the Cerrado deforestation between 2001 and 2017. We can note that in the period prior to 2005, the cleared area presented a rate of approximately 30,000 km² per year, while in the later period this value decreased considerably, reaching a level of less than 7,000 km² in 2018. In addition, deforestation in the period occurred predominantly in areas larger than 6.25 hectares, which could be due to the agricultural frontier expansion in the biome that occurred mainly in large agricultural properties. (BOLFE et al., 2016; ZANIN and BACHA, 2017).

In addition to the advancement and modernization of agriculture, the exploitation of the forest for removing firewood for the production of coal is an inducing factor of the environmental degradation of the region. These factors have led to a progressive depletion of the natural resources of the Cerrado, making this biome the second that suffered more changes due to anthropogenic actions in Brazil, after the Atlantic forest. Despite this, conservation units protect only 7.44% of its territory, which has served to aggravate the intensive use of its natural resources (SANTOS et al., 2009; BORGES and SANTOS, 2009; VIANA and BAUCH, 2009; IBAMA, 2010).

Figure 3.3 – Cerrado deforestation between 2001 and 2018.



Fonte: TerraBrasilis – Cerrado (2019).

Despite this context, according to Soares-Filho et al. (2014) and Noojipady et al. (2017), changes in the Brazilian Forest Code (FC) legislation in 2012 may induce more deforestation in the Cerrado region, especially in Matopiba, due to the no longer mandatory protection of ‘hill top’ areas in rural properties. In addition, according to Noojipady et al. (2017), the Forest Code established minimum amounts of reserves in private properties, being 35% for the Cerrado portion belonging to the Legal Amazon and only 20% for the rest of the biome, which are smaller than the current reserves in many rural properties of the region. For comparison purposes, rural properties located in the Amazonian biome should have 80% in legal reserves, a considerably higher value. In other words, the legislation itself, through the Forest Code, can become an important environmental degradation vector in the Cerrado biome.

The Soy Moratorium (SoyM), an industry effort to reduce deforestation in Amazon stemming from soy production after 2006, despite being successful in its goal, may have cause spillover effects on the Cerrado biome. This effort consisted of restrictions on market access to soybeans cultivated in recently deforested areas. However, the SoyM, along with the FC, led to an increased in the area cultivated in other regions, such as the Cerrado. This is an important spillover effect from the Amazon region leading the deforestation of Cerrado due the smaller restrictions applied to this region, in a ‘cross-biome leakage’ (MACEDO et al., 2012; GIBBS et al., 2015; NOOJIPADY et al., 2017).

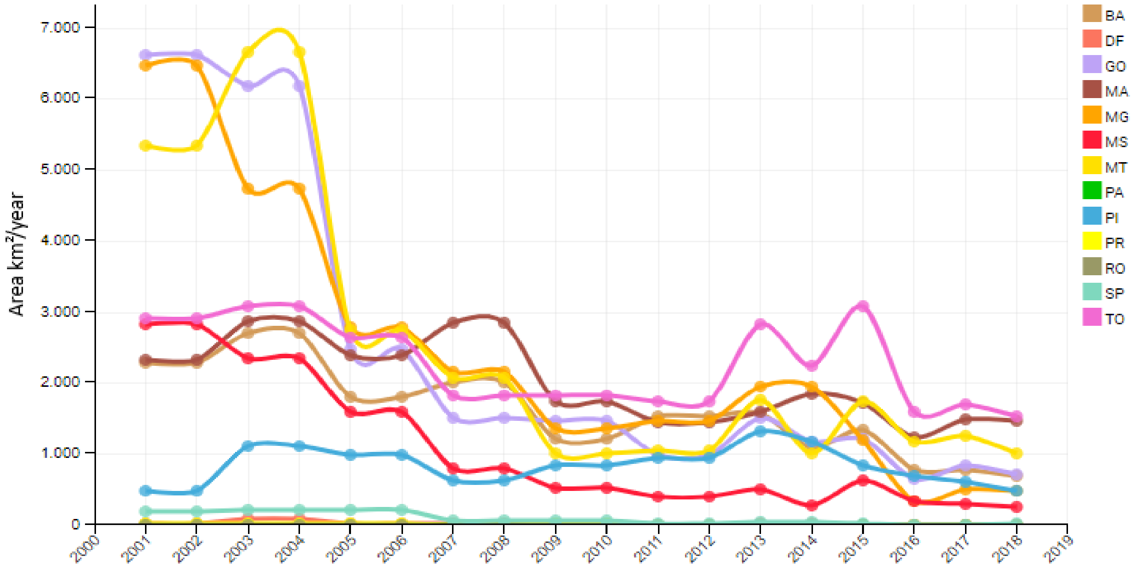
In fact, Noojipady et al. (2017) points out that the soybean restriction in Amazonia, associated with SoyM and FC, is the reason why the growth of this crop are concentrated in the

Cerrado, with a considerable part occurring due to forest areas reduction in rural properties in the region. To illustrate this phenomenon, according to Gibbs et al. (2015), among the 14.2 million unprotected forest suitable for soybean cultivation in the Cerrado, approximately 2 million hectares can be deforested legally under the FC. In addition, about 23% of the soybean expansion in the biome between 2007 and 2013 occurred in forest areas, a figure that reaches 40% when considered Matopiba.

According to Bragança (2018), the agriculture expansion in the Cerrado has been also reallocating the rural organization of the region, with cropland inducing a decrease in cattle ranching. Barona et al. (2010), Arima et al. (2011), Macedo et al. (2012) and Richards et al. (2012) found evidence that this process is also occurring in the Legal Amazon. The authors argue that the increase in soybean production in Amazon, as well as in the Cerrado, has induced the advance of cattle raising to agricultural frontiers and, consequently, inducing deforestation. In addition, we can mention the work of Barona et al. (2010), Andrade de Sá et al. (2012) and Jusys (2017), who found evidence that an increase in sugarcane production for biodiesel production in the state of São Paulo, and to a lesser extent in other regions, also shifted livestock towards the agricultural frontiers, together with other non-fuel crops. In fact, Freitas Júnior and Barros (2018) confirms this advancement to the agricultural frontiers in Amazon and Cerrado, which presented a considerable higher cattle herd growth in the 1990-2015 period, when compared to others Brazilian regions. Therefore, changes in land use in the Cerrado impact not only this region, but also indirectly, and possibly the deforestation, in the Amazon rainforest.

In area terms, the state that presented greater deforestation of Cerrado are Sao Paulo, with about 90% of the total. Then we have Mato Grosso do Sul with 75.87%, Federal District, 70.63%, Paraná, 70%, Goiás, 65.11%, Minas Gerais, 56.84%, Mato Grosso, 42.83%, Bahia, 36.45%, Tocantins, 26.4%, Maranhão, 22.85, Piauí, 15.1%, and, finally, Rondônia with 2.88% (IBAMA, 2010). The Figure 3.4 brings the Cerrado total deforestation by state in the period from 2000 to 2018.

Figure 3.4 - Deforestation in each Cerrado State in the period from 2000 to 2018.



Source: TerraBrasilis – Cerrado (2019).

Although the states belonging to the Matopiba are those with the smallest area deforested, the current Cerrado deforestation has been located mainly in these unoccupied areas due to the establishment of new agricultural frontiers (BORGES and SANTOS, 2009; SILVA, 2013; ARAÚJO et al., 2019). We can verify this fact through Figure 3.4, which demonstrates the deforestation persistence in Matopiba states, especially after 2005. To reinforce this perception, Table 3.2 brings the ten municipalities that presented the largest deforested areas in the Cerrado in 2010. Among the ten municipalities with the largest deforested area in 2010, all are located in the states belonging to Matopiba region.

Table 3.2 – Cerrado municipalities that presented greater deforestation in 2010.

Municipality	State	Suppression (km2)	Area (%)
Baixa Grande do Ribeiro	PI	394,29	5,05%
Uruçuí	PI	203,48	2,41%
Formosa do Rio Preto	BA	143,92	0,89%
São Desidério	BA	119,85	0,81%
Mateiros	TO	93,06	0,97%
Barreiras	BA	88,39	1,12%
Balsas	MA	85,24	0,65%
Santa Quitéria	MA	73,88	3,85%
Codó	MA	69,91	1,60%
Riachão das Neves	BA	68,81	1,18%

Source: IBAMA (2010)

In this context, the Brazilian Government has been adopting measures to combat and inhibit the deforestation in the Cerrado. In 2009, for example, it released the *Plano de Ação para Prevenção e Controle do Desmatamento e das Queimadas no Bioma Cerrado (PCCerrado),* which aims to reduce continuously and permanently the deforestation rate, as well as forest fires and wildfires in the Cerrado. In 2014, the second phase of the plan was launched for guiding the actions to be taken, in addition to ratifying the importance of the natural resources conservation on the region.

An essential element of the plan is the *Política Nacional de Mudanças Climáticas*, Law nº 12.187/2009, which seeks the reduction of greenhouse gas emissions in the atmosphere. In addition, it established as a goal the reduction of at least 40% of the deforestation rate in the biome. In addition, the Brazilian government launched a program to monitor deforestation annually in the Cerrado, using Landsat satellite-derived spatial data (ARAÚJO et al., 2019).

The Matopiba intensive occupation for agricultural production began in the 1980, and this process is not yet completed. This is due to the existence of many underutilized land, which adopt low productivity production techniques. The region owns conditions that facilitate this occupation process, such as: good climate for agriculture, flat land that enables the adoption of land productivity enhancing machinery, cheap labor, easy-to-fix soils and low price land. In addition, many spaces have not yet been occupied, where native forests of the Cerrado prevail. Therefore, this availability makes it possible to incorporate these regions into the most dynamic areas of Matopiba, as the agricultural frontier advances. (BATISTELLA and VALLADARES, 2009; STUDTE, 2008; BOLFE et al., 2016; DIAS et al., 2016; NOOJIPADY et al., 2017; BRAGANÇA, 2018; ARAÚJO et al., 2019).

According to Bolfe et al. (2016) and Bragança (2018), the increase in the use of high-capacity land, combined with the adoption of productivity-enhancing technologies, has enabled the Matopiba to present significant increases in its production levels and consequently economic growth. However, according to Garcia and Vieira Filho (2018), approximately 68% of the agricultural expansion in the region between 2002 and 2014 resulted from conversion of native areas. In fact, according to Borges and Santos (2009) and Noojipady et al. (2017), the Cerrado current deforestation has been located mainly in these sparsely occupied areas, as is the Matopiba case, due to the establishment of new agricultural frontiers, especially soybean.

In 2017, for example, the region accounted for approximately 11% of the national soy production, a figure that may increase in the future as the agricultural frontier in the region expands (ZANIN and BACHA, 2017; ARAÚJO et al., 2019). Therefore, the existence of underutilized and/or not yet occupied land, together with the agricultural frontier expansion and the economic development of the Matopiba, may maintain the deforestation process in the region in the following years. To make matters worse, Garcia and Vieira Filho (2018) point out that due to inadequate soil management, which causes their progressive degradation, resulted in approximately 9 million and 591 thousand hectares of area with moderate and high degree of desertification, respectively.

The agricultural frontier expansion in Matopiba, however, faces some natural challenges, especially at transitioning areas with the Caatinga biome. According to Silva et al. (2016), a transition area normally presents diverse ecosystems, climatic conditions and lower natural fertility. The soybean, for example, is not suitable in regions with annual average rainfall below 1000mm, which occur in Cerrado areas near the semi-arid. In other words, the annual average rainfall acts as a natural barrier for the agricultural frontier expansion, a scenario that could be reversed with the development of new varieties of soy that supports rainfall between 1000 - 800 mm. However, this technological innovation could boost deforestation along with agricultural production in Matopiba (ARAÚJO et al., 2019).

In terms of population, the Matopiba has about 6 million inhabitants, and 35% resides in the rural area, considerably above the Brazilian average of 15.3%. Among the region states, the most populous is the Maranhão with 57.6% of the total, followed by Tocantins with 25.30%, Bahia with 12.72% and 4.75% in Piauí (IBGE, 2010). In relation to the income, the region presented in 2010, a per capita income of only 40% compared to the Brazilian average, R$8,000 in Matopiba against a value of R$19.878,00 for Brazil. However, if considered only Tocantins and Bahia, the percentage would go up to approximately 60%, indicating a per capita income spatial heterogeneity between the regions that comprise the Matopiba (BOLFE et. al, 2016).

Considering current Cerrado deforestation in recent years, especially in the Matopiba, and the importance of the theme, the present paper aims to verify the determinants of this degradation, especially in the current Brazilian agricultural frontier. In addition, we seek to identify what the role of agricultural activities have in this process. The next section, we deal with the theoretical framework for the Environmental Kuznets Curve (EKC) used in this paper.

3.3 The Environmental Kuznets Curve (EKC)

Grossman and Krueger (1991), analyzing the environmental impact of the creation of NAFTA (North American Free Trade Agreement), identified an inverted “U” relationship with economic growth initially damaging the environment up to a point on which development contributes to environmental preservation. This relationship, named the Environmental Kuznets Curve., according to the authors, has three effects: scale, composition and technical. The scale effect refers to the environmental impact caused by production growth; while the composition effect is the change that occurs in the composition of the goods and services produced. The technical effect is due to technological advances that increase productivity and/or make production less polluting. The composition and technical effects can be large enough to mitigate the scale effect, leading to the reversal of the relationship between income growth and environmental degradation.

Despite the evidence for the existence of an EKC, some authors, such as De Bruyn et al. (1998), argue that this relationship would not be sustainable in the long term. This would occur due to the existence of another inflection point in which economic growth would lead again to an increase in environmental degradation. Therefore, the relationship between development and environment in the long term in the form of "N" and not in the format of an inverted "U".

Considering deforestation as a variable of environmental degradation, used in this paper, there is no consensus on the existence of a traditional EKC in an inverted “U format. Shafik and Bandyopadhyay (1992), in a pioneering investigation, and Shafik (1994), for example, have not found statistically significant relationships between deforestation and economic growth. On the other hand, analyzing this relationship for three continents, Africa, Latin America and Asia, Cropper and Griffiths (1994) found statistically significant results for the first two.

Bhattarai and Hammig (2001) conducting a similar study for the three continents found statistically significant results for all between growth and forest cover, with an inverted "U" relationship. According to the authors at low levels of development, the structure of demand as, for example, the consumption of firewood, cause deforestation. On the other hand, as economic growth occurs, such demand structure tends to change, moving to goods that affect less the environment. In addition, income growth induces an increase in replanting efforts, which ends up reversing the deforestation process in the long run. On the other hand, Koyuncu and Yilmaz (2009) found that the increase in demand for arable land also has a significant impact on deforestation along economic growth.

Due to the controversial results in the literature on the EKC format, Chiu (2012) argues that it is necessary to perform an analysis for each locality of interest, since it is not possible to infer causality from studies in other regions.

For Brazil, some studies sought to identify the existence of the Environmental Kuznets Curve (EKC) using deforestation. However, practically all studies are for Legal Amazon, with only one paper in the literature looking for an EKC in the Cerrado. Therefore, the present paper, because it seeks to better understand the relationship between economic development and deforestation in this biome, is an important contribution to the literature

Among the papers for Legal Amazon, we have a controversial empirical evidence, which varies according to the analyzed year or method adopted. For example, Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) found evidence of an inverted "U" relationship while Araújo et al. (2009) and Jusys (2016) captured an EKC in "U"; and Oliveira et al. (2011) and Oliveira and Almeida (2011) identified a relationship in the "N" format.

For the Cerrado, on the other hand, the paper by Colusso et al. (2012) are the only one to estimate an EKC for this biome, seeking the relationship between economic growth and deforestation for the region. The authors estimated several spatial models, which corroborated significant results for an "N" shaped curve for the Cerrado, indicating that, in the long run, the economic growth is not sufficient to prevent the biome deforestation.

Analyzing the papers for Brazil, the results are not conclusive in relation to an EKC existence for the country biomes. Therefore, additional studies are necessary to reach a definitive conclusion. In any case, the results point to the existence of an "N" relationship with economic growth in Brazil, a fact that we seek for Cerrado in this paper.

3.3.1 Methodological Considerations and Advances in the EKC Estimation

The EKC model, according to Stern (2017), has been the main method used to verify the relationship between economic development and environmental degradation. However, the relationship proposed by EKC, according to Stern (2004), is an essentially empirical phenomenon, despite having some econometric problems. Among them, the author refers to the possibility of relevant variables omission, since many studies include only the linear, quadratic and cubic form of per capita income to verify the relationship with environmental degradation, without considering other possible influences. This omission may lead to spurious regressions, in which the coefficients are significant, but the causal relationship does not exist. Stern (2017) states that additional variables inclusion is important to explain degradation and avoid such problem.

There are studies that seek to incorporate additional variables into the EKC model, but most of them are highly correlated with per capita income. Therefore, besides the problem of omission, these models also started to suffer from multicollinearity, invalidating the estimates statistical inferences due to the effects on the coefficients variance. Therefore, it is not possible to make robust inferences and conclusions derived from the estimations of these models due to their poor specifications, invalidating most of the work done with EKC (LIEB, 2003; STERN, 2004; CARSON, 2010; STERN, 2017).

A recurrent problem in works involving EKC involving omission of relevant variable, according to Maddison (2006), is the non-consideration of the spatial location influence. The spatial interactions existence in forest conversion and land use changes may occur due to centripetal forces, generated by productivity differences, transport costs, climate, topography and soil conditions that can cause significant regional differences; attract productive activities, especially agricultural and livestock (MADDISON, 2006; WEINHOLD and REIS, 2008; ROBALINO and PFAFF, 2012).

We have many papers in the literature as Maddison (2006), Colusso et al. (2012), Kenne and Deller (2013), Wang et al. (2013), Hao et al. (2016) and Qing et al. (2016) that identified and included space as an important variable to explain environmental degradation. Especially for Brazil, we have Igliori (2006), Aguiar et al. (2007), Pfaff et al. (2007), Oliveira and Almeida (2011), Oliveira et al. (2011), Andrade de Sá et al. (2015), Jusys (2016) and Amin et al. (2019) for Legal Amazon and Colusso et al. (2012) for Cerrado that also captured spatial spillovers from deforestation. In general, the results indicate that spatial dependence control improves the estimation results for the environmental degradation determinants.

In addition, many studies developed in Brazil for deforestation identified that explanatory variables inclusion, such as rural credit, population density, forest stock, and cattle herd size, are significant to explain the relationship with deforestation, reducing the variable omission problem.

Another relevant problem in the EKC model is the use of per capita income as a proxy for economic development. According to Neve and Hamaide (2017), this variable is not the most adequate to verify the relationship with environmental degradation, since per capita income only partially captures the region development. Thus, Hill and Magnani (2002), Jha and Bhanu Murth (2003), Kubiszewski et al. (2013) and Neve and Hamaide (2017) recommend using a variable that is more related to general well-being than just economic performance. The authors cite, for example, that inequality in income distribution may not bring welfare to society, excluding a portion of the population from the benefits of economic growth, which could affect the environmental preservation. Hill and Magnani (2002) and Jha and Bhanu Murth (2003) sought to avoid this problem by using the Human Development Index (HDI) as proxy for development, thus replacing the per capita income variable. The authors also found that the substitution improved the environmental degradation prediction, suggesting that the HDI may be better able to capture the relationship with the environment than per capita income.

From Hill and Magnani (2002) and Jha and Bhanu Murth (2003) pioneering works, other authors, such as Constantini and Monni (2008), Constantini and Martini (2010), Lamb and Rao (2015), Neve and Hamaide (2017), sought to replace the per capita income by the HDI, or similar indicators. However, the authors do not directly considered the models poor specification or the multicollinearity problems. In order to solve both, some researchers started using multivariate statistical methods, specifically factorial analysis, to include relevant explanatory variables in the EKC model while minimizing the multicollinearity problem. As an example, we can cite the works of Araújo et al. (2009) and Zaman et al. (2016) who used this method to synthesize highly correlated variables in an index that are later included as an explanatory variable in the model. According to the authors, there are a considerable reduction in the omitted-variable bias and in the occurrence of multicollinearity.

The Paudel and Shafer (2009) approach, on the other hand, is pioneer in the factorial analysis adoption in the context of the EKC, because the authors, besides treating the model poor specification and the multicollinearity, also sought to develop a better proxy for the economic development, replacing the per capita income. The authors considered that the quality of the institutions, especially the social ones, that are closely related to social and economic development. Therefore, using the factorial analysis, they synthesized several social variables in an index that could serve as a proxy more suitable for the EKC estimation. The index are also included in the model in its linear, quadratic and cubic form, seeking to capture the various possible formats for EKC.

Finally, we can cite the heterogeneity problem present in most of the samples used in the EKC estimation. In general, the empirical papers assume that all spatial units are homogeneous, estimating a coefficient representing the entire sample. Thus, according to Lieb (2003), the estimates can be biased and inconsistent, invalidating possible conclusions of the EKC model. Even in the case of regressions with panel data, which allows a differentiated intercept for each sample element, the coefficient slope is still the same for all. List and Gallet (1999) and De Bruyn (2000), for example, identified that in most of the work involving EKC, each sample element tends to present a different coefficient and turning point. In addition, Chimeli (2007) demonstrated theoretically that heterogeneity across countries fail to produce robust estimates for the EKC. In summary, the factors mentioned make fragile many of the inferences using the EKC (LIEB, 2003; STERN, 2017).

Seeking to control the heterogeneity problem present in the sample, many authors estimated the EKC with geographically weighted regression (GWR). This methodology allows the estimation of a coefficient for each geographical point. Tanaka and Matsuoka (2008) are the first authors who applied the GWR methodology to estimate the EKC, aiming to control the heterogeneity problem. The authors sought to verify the relationship between economic development and environmental degradation between the China provinces, obtaining better results when compared with global estimation. From then on, several works sought to apply this methodology in the context of EKC. (JAIMES et al., 2010; OLIVEIRA and ALMEIDA, 2011; MOON and FARMER, 2012; CARR et al.. 2012; ZHANG and QIN, 2013; WANG et al. 2014; VIDERAS, 2014; JUSYS, 2016; KIM et al., 2017; SHENG et al., 2017; KIM et al., 2017; BIN ZU and LIN, 2017; WEI et al., 2018). Specifically to deforestation, we can cite the works of Jaimes et al. (2010), Oliveira and Almeida (2011), Moon and Farmer (2012), Carr et al. (2012), Jusys (2016) and Sheng et al. (2017).

Although many previously identified works have sought to control spatial heterogeneity, while including additional variables to the EKC model (reducing omission of relevant variable), none of them controlled these factors along with spatial dependence. Therefore, this paper seeks to fill this gap in the literature on the subject, estimating an EKC model with spatial regimes, an alternative way of controlling the sample heterogeneity, along with the spatial dependence and additional explanatory variables inclusion. In addition, we replace the per capita income as proxy for economic development by a social and economic development indicator, created with factorial analysis, improving the deforestation explanation while avoiding the problem of multicollinearity.

3.4. Methodology

3.4.1 Factor analysis

The methodology used to create the Socioeconomic Development Index (SDI), used as proxy for economic development in the estimation of Environmental Kuznets Curve, comes from multivariate statistics, specifically from factor analysis, due to the multidimensional nature of economic development. This technique make it possible to include a large number of variables that can explain deforestation in the Cerrado, avoiding the bias of poor model specification and at the same time controlling the multicollinearity problem, since the method allows synthesizing the variables into orthogonal factors. The procedure are based on the Jha and Bhanu Murth (2003), Paudel and Shafer (2009), Araújo et al. (2009), Zaman et al. (2016), Khan et al. (2016), Almeida et al. (2017) and Rasli et al. (2018), who used the methodology in the EKC context.

The factorial analysis is characterized as a multivariate statistics method that aims to summarize information of p variables, for example, which are correlated with each other, in a number of k variables (with $\mathrm{k} < \mathrm{p}$, both finite and $\mathrm{k}, \mathrm{n} \in \mathbb{N}$). These new variables are called factors, which are obtained with the minimum loss of information possible.

The factorial analysis model [12] used in this work, is defined as follows: a) Let X_{px1} be a random vector; b) with mean $\mu = (\mu_1, \ldots, u_p)$; c) by standardizing the variables X_i, we have $Z_i = \left[\frac{X_i - \mu_i}{\sigma_i}\right]$ with $i = 1, 2, \ldots, p \in \mathbb{N}$; d) P_{pxp} is the correlation matrix of the random vector $Z = (\,Z_i)$. By using P_{pxp}, the factorial analysis model is represented as follows:

$$\begin{array}{lll} Z_1 = & l_{11}F_1 + \cdots + l_{1k}F_k & + \varepsilon_1 \\ \vdots & \vdots & \vdots \\ Z_p = & l_{p1}F_p + \cdots + l_{pk}F_k & + \varepsilon_p \end{array} \tag{1}$$

or in matrix notation by:

$$D(X - \mu) = LF + \varepsilon \tag{2}$$

where

$$L = L_{pxk} = \begin{bmatrix} l_{11} & \cdots & l_{1k} \\ \vdots & \ddots & \vdots \\ l_{p1} & \cdots & l_{pk} \end{bmatrix}$$

so F is a random vector containing k factors, which seek to summarize the p variables; ε is a random error vector, which contains the portion of Z_i which was not explained by the F_j factors ($j = 1, 2, \ldots, k \in \mathbb{N}$); L is a matrix of parameters l_{ij} (loadings), to be estimated, which will represent the degree of linear relationship between Z_i and F_j.

To perform the model's estimation (1) some assumptions are required: i) $E[F_{kx1}] = 0$, the factors have a mean equal to zero; ii) $Var\,[F_{kx1}] = I_{kxk}$, orthogonal factors with unitary variances; iii) $E\left[\varepsilon_{px1}\right] = 0$, errors with a mean equal to zero; iv) $Var\left[\varepsilon_{pxp}\right] = \psi_{pxp} \Rightarrow Var\left[\varepsilon_j\right] = \psi_j$ and $Cov\left(\varepsilon_i, \varepsilon_j\right) = 0,\ \forall\, i \neq j$, that is, orthogonal errors and possibly with

[12] For more information on the methodology adopted, see Mingoti (2005).

different variances; v) $Cov\left(\varepsilon_{px1}, F_{kx1}\right) = E[\varepsilon F'] = 0 \Leftrightarrow \varepsilon_{px1}\ e\ F_{kx1}$ are linearly independent. Hence, P_{pxp} can be reparameterized as

$$P_{pxp} = LL' + \psi \qquad (3)^{13}$$

So the main objective of the factorial analysis is to decompose the correlation matrix of p variables, P_{pxp}, in L_{pxk} and ψ_{pxp}, remembering that L_{pxk} is the matrix representing the l_{ij} equation coefficients of (1) and ψ_{pxp} is the matrix of errors ε_p also from (1), both need to be estimated by the factorial analysis model. In addition, there are some implications that deserve to be mentioned because they will be analyzed in the present paper: 1) $Var\ (Z_i) = \sum_{j=1}^{k} l_{ij}{}^2 + \psi_i \Longrightarrow$ Variance is decomposed into two parts, being the first ($\sum_{j=1}^{k} l_{ij}{}^2$) called Commonality, which represents the variability of Z_i explained by the k model factors from (6); the second (ψ_i) is called Uniqueness, variability coming from the random error ε_i; 2) $PEV_{F_j} = \frac{\sum_{i=1}^{p} l_{ij}^2}{tr(P_{pxp})}$, defined as total proportion explained by the factor F_j (PEV).

The first step of the estimation is the definition of the number k (with $< p$) of factors to compose the equation (1). This should be accomplished after the estimation of the correlation matrix P_{pxp}, through the sample correlation matrix $\hat{P}_{pxp}$, which is symmetrical because it is a correlation matrix. The n roots characteristics of the matrix $\hat{P}_{pxp}$ are obtained with the characteristic equation of the det($\hat{P}_{pxp} - \lambda I) = 0$. The roots are also known as eigenvalues of the matrix, denoted by λ_i. Ordering them in descending order, we obtain P_{pxp}, that will be used in defining the number of factors. This, in turn, will be determined by the criterion proposed by Kaiser (1958), that is, k will be equal to the number of eigenvalues $\lambda_i \geq 1$. The P_{pxp} is a diagonal matrix with elements $p_{ij} = \lambda_i\ if\ i = j\ or\ p_{ij} = 0\ if\ i\ \neq j$ and tr(P_{pxp}) = p, so a reduction in the size of the matrix to $k < p$ will be made until the variance explained by λ_i is at least equal to the variance of the original variables X_i.

After the determination of K, the matrices L_{pxk} and ψ_{pxp} should be estimated. The method here used to obtain EDI will be the principal components (PC), that works as follows: it is necessary to find the normalized autovectors, $\hat{e}_i = \left(\hat{e}_{i1}, \dots, \hat{e}_{ip}\right)$, corresponding to each eigenvalues $\lambda_i \geq 1$ with $i = 1, 2, \dots, k$. The matrices L_{pxk} e ψ_{pxp} will be estimated by:

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[13] Because $P_{pxp} = Var(Z) = Var\ (LF + \varepsilon) = Var\ (LF) + Var\ (\varepsilon) = LIL' + \psi = LL' + \psi$ with I being the identity matrix.

$$\hat{L}_{pxk} = \left[\sqrt{\lambda_1}\hat{e}_1 \dots \sqrt{\lambda_k}\hat{e}_k\right] \quad e \quad \hat{\psi}_{pxp} = diag\left(\hat{P}_{pxp} - \hat{L}_{pxk}\hat{L}'_{pxk}\right) \tag{4}$$

So, using the estimates of (4), we have:

$$\hat{P}_{nxn} = \hat{L}_{pxk}\hat{L}'_{pxk} + \hat{\psi}_{pxp} \tag{5}$$

That is, the sample correlation matrix in fact can be decomposed into two parts, one representing the l_{ij} equation coefficients (1) and another the error term ε_i. The next step, after the estimation (4) and (5), will be the calculation of the scores for each sample element $m, m = 1, 2, \dots, n$ (with m finite and m ∈ ℕ).

For the particular case of this work, suppose the set $I_n = \{p \in \mathbb{N}; \text{p} \leq 1397\}$ and the set well-order and upper bounded $\mathcal{M} = \{1, 2, \dots .1397\} \subset \mathbb{N}$ of the Cerrado municipalities, so there's a bijection $f: I_n \longrightarrow \mathcal{M}$, with cardinality $(\overline{\overline{\mathcal{M}}}) = 1397$ call counting of $\mathcal{M}$. Therefore, for each $m = f(p)$ there will be scores on the factor j, that is, $\forall\ m \in \mathcal{M}, \exists \hat{F}_{jm}$ that represents the scores of the municipality m in the factor j, which can be represented as:

$$\hat{F}_{jm} = \sum_{i=1}^{p} w_{ji} Z_{im} \tag{6}$$

where Z_{im} are the observed values of the standard variables for the m-th sample element; w_{ji} are the weights of each variable Z_i in factor F_j. The scores coefficients w_{ji} is obtained, in turn, by estimates using the regression method.

Often, the factors F_j exhibit $\hat{l}_{ij}$ with similar numerical magnitude making the interpretation difficult. In these situations, it is recommended to perform an orthogonal rotation of the original factors to obtain an easy-to-interpret structure. That way, F_j is a vector such that $F_j \in \mathbb{R}^p$ (p = number of variables and $j = 1, \dots, k$) and a linear transformation $T: \mathbb{R}^p \longrightarrow \mathbb{R}^p$, That is, that keeps the factors in the same dimension, such that T_{kxk} is an orthogonal matrix with $TT' = T'T = I$, That is, it maintains multiplication between any factor as being zero. Let $\hat{L}_{pxk}$ be an estimate of the matrix L_{pxk}, then the matrix $\hat{L^*}_{pxk} = \hat{L}_{pxk}T_{kxk}$ is the matrix with the loadings ($\hat{l}_{ij}$) Linearly transformed by orthogonal rotation[14]. Although any orthogonal matrix satisfies the T transformation, the ideal is to choose a T so that each $\hat{l}_{ij}$ show a great absolute value for just one of the factors. Therefore, the variables Z_i is divided into groups, facilitating their respective interpretations. There are several methods in the literature for that purpose. The present work adopts the Varimax criterion developed by Kaiser (1958), which seeks a configuration in which each factor has a small number of factorials scores with high absolute values and a large number with small values. The Varimax criterion seeks to maximize the following equation:

$$V = \frac{1}{p}\sum_{j=1}^{k}[\sum_{i=1}^{p}(\tilde{l}_{ij}^{2})^{2} - \frac{1}{p}(\sum_{i=1}^{p}\tilde{l}_{ij}^{2})^{2}] \quad (7)$$

where $\widetilde{l_{ij}}$=($\tilde{l}_{ij}^{*}/\hat{h}_i$), with $\hat{h}_i$ being the the square root of the commonality of the variable Z_i. Then the criterion selects the $\widetilde{l_{ij}}$ that maximize V, reaching the desired setting.

Finally, two measures will be carried out to check the quality of the adjustment of the factorial analysis model. The first of these is the criterion of Kaiser-Meyer-Olkin (KMO), which is a measure based on the following coefficient:

$$KMO = \frac{\sum_{i\neq j} R_{ij}^2}{\sum_{i\neq j} R_{ij}^2 + \sum_{i\neq j} Q_{ij}^2} \quad (8)$$

where R_{ij} is the sample correlation between the variables X_i and X_j; Q_{ij} is the partial correlation between the variables X_i and X_j while the others (p-2) are kept constant. The model will prove appropriate for $KMO > 0{,}8$, if it is inferior, the factorial analysis model is not indicated for the data set. The second adjustment measure used is the *Bartlett* sphericity test that seek to test the following assumptions: $H_o: P_{pxp} = I_{pxp}$ $against$ $H_a: P_{pxp} \neq I_{pxp}$, where P_{pxp} is the theoretical correlation matrix and I_{pxp} is the identity matrix. The test statistic T is given by:

[14] $\widehat{L^*}_{pxk}$ after the application of the linear transformation $T: \mathbb{R}^p \longrightarrow \mathbb{R}^p$ will also be a solution for the factorial analysis model: $(\hat{L}_{pxk}T_{kxk})(\hat{L}_{pxk}T_{kxk})' = \hat{L}_{pxk}T_{kxk}T'_{kxk}\hat{L}'_{pxk} = \hat{L}_{pxk}\hat{L}'_{pxk}$

$$T = -[n - \frac{1}{6}(2p + 11)][\sum_{j=1}^{p} \ln(\hat{\lambda}_i)] \quad (9)$$

where $\hat{\lambda}_i$ are the eigenvalues of the sample correlation matrix $\hat{P}_{pxp}$. The statistic T has a chi-squared distribution with $\frac{1}{2}p(p-1)$ degrees of freedom. So the farther away from one are the eigenvalues ($\hat{\lambda}_i = 1$), higher tends to be the statistic T, that is, the more a few eigenvalues can explain the total variance, the higher will be T, indicating the suitability of the factorial analysis model.

After the processes mentioned above, the factorials scores will be distributed as follows: $X \sim N(\mu, \sigma^2)\ with\ \mu = 0\ and\ \sigma^2 = 1$. So if $X_{jm} > 0$ (factor score j to the municipality m), then the element m suffers positive influence of the factor j. If $X_{jm} < 0$, then the contrary is valid. In this way, factorials scores will indicate whether a particular factor will contribute positively or negatively to explain economic development.

The Socioeconomic Development Index (SDI) are calculated from the factorials loads, as Soares (2011), because they reflect the influences of the variables used in the factorial analysis model at the development level. So the SDI for every Cerrado municipality m can be represented by:

$$SDI_m = \sum_{j=1}^{k} \frac{\lambda_j}{tr(P_{nxn})} F_{jm} \quad (10)$$

where, SDI_m is the index of the municipality m; λ_j is the j-th root characteristic of the correlation matrix; k is the number of factors chosen; F_{jm} is the factorial load of the municipality m, from factor j; $tr(P_{nxn})$ is the trace of the correlation matrix P_{nxn}.

For the purpose of facilitating the comparison between the indexes, a transformation has been performed so that the values are restricted to the range from 0 to 100:

$$\overline{SDI_m} = \frac{(SDI_m - SDI_{min})}{(SDI_{max} - SDI_{min})} \times 100 \quad (11)$$

where SDI_{min} is the smallest index found in (10) and SDI_{max} is the largest index found, both taking into consideration the entire sample of municipalities. Finally, the choice of the variables that will compose the index (Chart 3.1) are based not only on economic elements, but also on several social factors that influence the well-being of society.

Chart 3.1 – Variables used in the factorial analysis model and their respective sources.

Variables		Source
Income_pc	Per capita income	ATLAS[15]
Higher_education	Population with higher education (%)	IBGE[16]
HDI_E	HDI_E – Human Develop. Index - Educational Dimension	ATLAS
HDI_L	HDI_L – Human Develop. Index – Life Expectancy Dimension	ATLAS
Labor_market	Formalization of the labor market (%)	ATLAS
Fertility_rate	Fertility rate	ATLAS
Child_mortality	Child mortality	ATLAS
Illiterate_pop	Illiterate population (%)	ATLAS
Primary_school	Population (over 18 years) without elementary school (%)	IBGE
Gini	Gini coefficient	ATLAS
Extremely_poor	Proportion of extremely poor people	ATLAS
Electricity	Population in households with electricity (%)	ATLAS

Source: research data.

The approach follows Hill and Magnani (2002), Jha and Bhanu Murth (2003), Paudel and Shafer (2009), Kubiszewski et al. (2013) and Neve and Hamaide (2017) that recommend using variables more related to general well-being than just economic performance. We follow Paul and Shafer (2009) approach, which adopted factorial analysis in the context of the EKC to develop a better proxy for the economic development, replacing the per capita income. All the variables refer to the year 2010.

3.4.2 Cluster Analysis

The cluster analysis aims, in the present paper, to seek the existence of heterogeneous groups, with regard to their rates of deforestation and socioeconomic development. The basic hypothesis is that municipalities with high development are those that present the lowest deforestation rates, according to Grossman and Krueger (1991; 1995). Therefore, cluster analysis will help identify this pattern between the Cerrado municipalities.

[15] Atlas of Human Development (2013).
[16] Demographic Census (2010).

Suppose the countable and upper bounded set[17] $\mathcal{M} = \{1, 2, \ldots .1397\} \subset \mathbb{N}$ formed by m Cerrado municipalities. The main objective of cluster analysis is to create subsets (groups) $G_1, \ldots, G_n \subset \mathcal{M}$ of municipalities at the same time as $G_1 \cap G_2 \ldots G_{n-1} \cap G_n = \emptyset$, that is, if $m_1 \in G_1$, then $m_1 \notin G_2 \cup G_3 \ldots G_{n-1} \cup G_n$ [18]. In addition, a function c (*cluster*) is defined such that each element of a group possesses characteristics that are the most similar as possible, According to a criterion to be defined, when compared to the other elements of the group. At last, $\forall\, m$ the function c defines a group and $G_1 \cup G_2 \ldots G_{n-1} \cup G_n = \mathcal{M}$, that is, the union of all created groups results in the same cardinality as the original set $\mathcal{M}$.

The function c is defined by following a criterion based on measures of similarity and dissimilarity (MINGOTI, 2005). Let m be the number of sample elements and p the number of random variables of the characteristics of m, the goal is to group in n groups. For each sample element m, there is a vector of measurements X_m defined by: $X_m = \left[X_{1m}, \ldots, X_{pm}\right]'\ with\ m = 1, \ldots, 1397$, where X_{ij} represents the observed value of the variable i measure in the element j. So you can define some measure of similarity or dissimilarity to serve as a selection criterion, such as: Euclidean distance, Weighted distance, Distance from Minkowsky, among others. The one used here will be the Euclidean distance measurement, as defined below [19]:

$$d(X_l, X_k) = \sqrt{[(X_l - X_k)'(X_l - X_k)]}, \quad \text{where} \quad l \neq k. \tag{12}$$

The techniques for building clusters are basically defined in hierarchical and non-hierarchs, and the present paper will use the hierarchical[20]. The hierarchical grouping method consists of (function c) in starting with as many groups as elements, that is, with $n = m$. From there, each sample element will be grouped up to the limit ($\lim_{n \to \infty} c\,(n) = 1$) so $n = 1$. The final choice of the number of groups in which m is divided will be based on the observation of the chart Dendrogram, that shows all the agglomerations carried out of $n = m$ until $n = 1$.

[17] That is, it is finite and there is a bijection $f\colon \mathbb{N} \longrightarrow \mathcal{M}$, with f being the enumeration of the elements of.$\mathcal{M}$ (LIMA, 2014).

[18] Setting $f\colon G_n \longrightarrow \mathcal{M}$ as a injective function and being $G_n \subset \mathcal{M}$, then G_n is also characterized as a countable and finite set.

[19] The remaining distances are weighted distance defined by:$d(X_l, X_k) = \sqrt{[(X_l - X_k)'A(X_l - X_k)]}$, with A being the desired weighting; and the distance from Minkowsky: $d(X_l, X_k) = [\sum_{i=1}^{p} w_i |X_{il} - X_{ik}|^{\lambda}]^{1/\lambda}$, with w_i being the weighting.

[20] The non-hierarchical techniques will be omitted, for further information, see Mingoti (2005, pag. 192).

Among the various existing hierarchical grouping methods [21], the *Complete Linkage Method* is the one that will be employed to define the clusters between deforestation and economic development for the m Cerrado municipalities. This method is defined by the following rule: The similarity criterion between two clusters is defined by the elements that are "less similar" to each other, that is, clusters will be grouped according to the largest distance between them: $d(C_1, C_2) = max\ \{d(X_l, X_k), with\ l \neq k\}$.

3.4.3 Exploratory Spatial Data Analysis (ESDA) and Spatial Econometrics

The ESDA are techniques used to capture effects of spatial dependence and spatial heterogeneity. For this reason, it is of great importance in the model specification process, since if the ESDA indicates that there is some type of spatial process, it must be incorporated into the model or treated in the correct way to avoid econometric problems such as bias and inconsistency in the parameters. ESDA is also able to capture spatial association patterns (spatial clusters), indicate how the data are distributed, occurrence of different spatial regimes or other forms of spatial instability (non-stationarity), and identify outliers (ANSELIN, 1995)

The Moran's *I*, which are a statistics that seeks to capture the degree of spatial correlation between a variable across regions. The expected value of this statistic is *E(I) = -1/(n-1)* being that values statistically higher or lower than expected indicate positive or negative spatial autocorrelation respectively. Mathematically, it can represent the statistic by:

$$I = \frac{n}{S_o} \frac{\sum_i \sum_j w_{ij} z_i z_j}{\sum_{i=1}^{n} z_i^2} \qquad (13)$$

where n is the number of regions, S_0 is a value equal to the sum of all elements of matrix W, z is the normalized value for deforestation in the present paper.

However, the Moran's I statistic, according to Anselin (1995), can only capture the global autocorrelation, not identifying the spatial association at a local level. Therefore, complementary measures were developed that aim to capture local spatial autocorrelation, that

[21] Among them: a) *Single Linkage Method* In which the similarity between two conglomerates is defined by the two elements more similar to each other, $d(C_1, C_2) = min\ \{d(X_l, X_k), with\ l \neq k\}$. ; b) *Average Linkage Method* That deals with the distance between two conglomerates as the average of the distances, $d(C_1, C_2) = \sum_{l \in C_1} \sum_{k \in C_2} (\frac{1}{n_1 n_2})\ d(X_l, X_k)$.

is, that seek to observe the existence of local spatial clusters. The main one is the LISA (Local Indicator of Spatial Association) statistic.

For an indicator to be considered LISA, it must have two characteristics: (i) for each observation it should be possible to indicate the existence of spatial clusters that are significant; ii) the sum of local indicators, in all places, should be proportional to the global spatial autocorrelation indicator. The present work will estimate the local Moran I statistic (LISA), which can be represented mathematically as:

$$I_i = z_i \sum_{j-1}^{J} w_{ij} z_j \tag{14}$$

where z_i represents the variable of interest of the standardized region i, w_{ij} is the spatial weighting matrix element (W) and z_j is the value of the variable of interest in the standardized region j. The local Moran I (LISA) can represent four spatial clusters: High-High (AA), Low-Low (BB), High-Low (AB) and Low-High (BA). The most analyzed is the High-High cluster, which indicates that a region with a high value for the analyzed variable is surrounded by regions with similar values.

In univariate spatial autocorrelation, existing spatial dependence is found in relation to a variable with itself lagged in space. In addition, there is a way to compute a correlation indicator in the context of two variables, ie to find out if a variable has a relation with another variable observed in neighboring regions. Formally, the calculation of Moran's I in the context of two variables is done following the equation:

$$I^{yx} = \frac{n}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j (x_i - \bar{x}) w (y_i - \overline{y)}}{\sum_i (x_i - \bar{x})^2} \tag{15}$$

Like the univariate Moran I, if the bivariate has a positive value, this indicates that there is a positive spatial correlation. If the value is negative, it indicates negative spatial dependence. On the other hand, if the value is not statistically different from zero, this will indicate that there is no spatial relationship between the variables.

In an econometric model, it is possible to incorporate the spatial component through spatially lagged variables. It is possible to propose a general spatial model that, by imposing restrictions on the parameters, can achieve the desired specifications. Such a model can be represented mathematically as follows:

$$y = \rho W y + X\beta + WX\tau + \xi \quad (16)$$

with

$$\xi = \lambda W \xi + \varepsilon$$

where X is the matrix of explanatory variables; β is the vector $k \times 1$ of regression coefficients; ε is the error term with mean zero and constant variance. The remaining terms are analyzed in the next paragraphs.

The Spatial Autoregressive Model (SAR) is obtained by imposing the following constraints on the model (16): $\rho \neq 0$, $\tau = 0$ and $\lambda = 0$. In this paper, the SAR model will seek to identify if the deforestation rate of a given municipality is influenced by the value of its neighbors, determined according to a spatial weight matrix. If $\rho > 0$ and significant, there is evidence of positive spatial autocorrelation, while a significant $\rho < 0$ indicates the presence of negative spatial autocorrelation. The above model will suffer from the problem of endogeneity of the lagged variable, then, it must be estimated through instrumental variables, and the instruments used are the lagged explanatory variables (WX).

The Spatial Error Model (SEM), in turn, emerges if $\rho = 0$, $\tau = 0$ and $\lambda \neq 0$, that is, when spatial dependence manifests itself in the error term. The estimation by OLS is not adequate, since the bias in the error term makes the estimations of the model parameters inefficient. Therefore, according to Kelejian and Prucha (1999), the SEM model must be estimated by maximum likelihood (MV) or by the generalized method of moments (MGM). The Spatial Lag of X model (SLX) occurs when $\rho = 0$, $\tau \neq 0$ and $\lambda = 0$, it seeks to capture the presence of spatial spillover from the explanatory variables. The model does not present the problem of endogeneity, and it is therefore possible to estimate by Ordinary Least Squares.

The Spatial Durbin Model (SDM) and the Spatial Durbin Error Model (SDEM) are a combination of the previous models. SDM is obtained if $\rho \neq 0$, $\tau \neq 0$ and $\lambda = 0$ while the SDEM occurs if $\rho = 0$, $\tau \neq 0$ and $\lambda \neq 0$.

The model selection, however, does not occur arbitrarily, since spatial effects may manifest in one or more forms. There are certain procedures to identify the presence of spatial effects, as well as to choose the best modeling for them. According to Florax et al. (2003), the best way to proceed is by following the steps: (i) estimate by ordinary least squares (OLS) using conventional econometrics. (ii) Perform the lagrange multiplier tests[22], one for the SAR model (MLp) and another for the SEM model (MLe). (iii) If the tests are both non-significant, there is no spatial dependence on the residues, then the OLS model is adequate. (iv) If the two focused tests are significant, the appropriate model will be the one for which the test had a higher statistical significance.

These models are not capable of incorporating spatial heterogeneity, but in many cases, the elements may not be homogeneous, being subdivided into heterogeneous groups. So the existing relationships are not structurally stable throughout space. These existing differences are expressed in different coefficients for each group. Therefore, the global β found in the classical regression model is not representative of the relationships analyzed. The EKC, according to Lieb (2003), List and Gallet (1999) and De Bruyn (2000), often suffers from the problem of heterogeneity, a fact that makes spatial regime estimation methodology adequate to control the problem[23].

According to Almeida (2012), the use of spatial econometric models, together with spatial regimes, is capable of simultaneously controlling spatial dependence and heterogeneity. Each regime is estimated using a subset of the data, controlling the heterogeneity through different interceptions and inclinations for each group. This makes the methodology is adequate for this paper because is capable of controlling the problem of structural instability in the parameters of regression. In general, it is possible to represent a model with g spatial regimes

$$\begin{bmatrix} y_1 \\ \vdots \\ \vdots \\ y_g \end{bmatrix} = \begin{bmatrix} X_1 & 0 & \dots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & X_g \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \vdots \\ \beta_g \end{bmatrix} + \begin{bmatrix} \xi_1 \\ \vdots \\ \vdots \\ \xi_1 \end{bmatrix} \qquad \xi \sim Normal\ (0, \Omega) \tag{17}$$

or, synthetically, by:

$$y^* = X^* \beta^* + \xi^* \tag{18}$$

[22] The lagrange multiplier test seek to verify if there is spatial autocorrelation in OLS residues (FLORAX et al., 2003).
[23] The GWR methodology can also address this issue and it's widely adopted by the EKC deforestation literature (JAIMES et al., 2010; OLIVEIRA and ALMEIDA, 2011; MOON and FARMER, 2012; CARR et al., 2012; JUSYS, 2016; SHENG et al., 2017). We estimate the deforestation determinants for Cerrado using the GWR methodology, however, the major part of the results was not significant and the Akaike information criterion even increase, indicating that this approach worsen the results. One possible explanation for this is the presence of just two heterogeneous regions in Cerrado, one being the Matopiba, current agricultural frontier in the biome, and another with the remaining municipalities that was occupied decades before.

where y^*, $X^*\beta^*$ and ξ^* are the expression vectors. Therefore, the equation (16), together with the spatial regimes, are:

$$y^* = \rho W y^* + X^*\beta^* + W X^*\tau + \xi^* \qquad (19)$$
$$\xi^* = \lambda W \xi^* + \varepsilon$$

So that the specific models are obtained by establishing restrictions on the model parameters (18).

The use of spatial regimes in the econometric models should not be used if it does not contribute to the adequacy of the model when compared to the global model. Therefore, it is necessary to perform a test, known as the Spatial Chow test, to verify if the regimes is better to explain the phenomenon. The test consists of comparing the sum of the squares of the error of the global model in relation to the square of the residues of the regime models. The Spatial Chow test are:

$$C = \left\{\frac{(e_r' e_r - e_{IR}{}' e_{IR})/k}{(n - 2k)}\right\} \qquad (20)$$

Where e_r is the error of the restricted model in estimated by MQO; e_{IR} the error for the unrestricted form, with the whole sample. The null and alternative hypotheses, on the other hand, are, respectively,

$$H_0: y = X\beta + \varepsilon$$

$$(21)$$

$$H_1: y = \begin{bmatrix} X_1 & 0 & \dots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & X_m \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \vdots \\ \beta_m \end{bmatrix} + \varepsilon$$

the test follows an F distribution with k and $(n - mk)$ degrees of freedom. In the case of spatial structural stability, we will have $H_0: \beta_1 = \cdots = \beta_m$, so the coefficients for each spatial regime will be similar, resulting in the similarity with the global model. Otherwise, the coefficients will be different, capturing the heterogeneity contained in the sample, inducing the non-acceptance of the null hypothesis.

3.4.4 Data

Deforestation is the proxy for environmental degradation used in this paper. The data comes from the *Projeto de Monitoramento do Desmatamento por Satélite (PRODES),* an official deforestation monitoring system carried out by the *Instituto Nacional de Pesquisas Espaciais (INPE).* The project consider the hectares of vegetation cleared regardless of the purpose. We consider 2010 as a reference year for deforestation, as well as for all the explanatory variables. This year are choose in this paper due to the wide availability of variables related to the level of socioeconomic development of the municipalities, coming from the Demographic Census and the Altas of Human Development, important to make the Socioeconomic Development Index (SDI). In addition, there are no available data for deforestation after 2011[24].

In accordance with the literature, we used the SDI as an economic development proxy, considering that per capita income does not capture all dimensions of development, limiting its ability to explain environmental degradation in the EKC model. (HILL and MAGNANI, 2002; JHA and BHANU MURTH, 2003; STIGLITZ et. al., 2009; KUBISZEWSKI et. al., 2013; NEVE and HAMAIDE, 2017). The SDI are also included in its squared and cubic version in the econometric modeling, in order to verify the existence of other formats for the EKC (GROSSMAN and KRUGMAN, 1991, 1995; DE BRUYN et al., 1998).

The Table 3.2 brings the description of all variables that we used in the econometric modelling. Its inclusion aimed to improve the EKC model specification, as well as better represent structurally the region and explain deforestation in the Cerrado. This procedure follows the Stern (2004; 2017) recommendation, which states that the inclusion of additional variables is important to explain environmental degradation, avoiding poor specification and spurious regressions - recurrent in the EKC models.

In addition to the variables directly linked to the agricultural frontier expansion in the Cerrado, we also consider some geographic and structural variables for control purpose, due to their importance indicated by the literature. Among them, we used some vector data to construct variables specifically to this empirical design: ROADS, RAINFALL, SOIL, FEDERAL.RES, STATE.RES and INDIGN.RES. We construct the measures using the spatial joint tool in the GIS software (ArcMap 10.3). Some explanations about these variables, however, are worth mentioning.

[24] It is worth mentioning that in August 2018, the PRODES-INPE updated its deforestation database to year 2018. However, at this point, the paper methodology and its main estimations were already defined.

Chart 3.2 – Variables description.

Abbreviation	Description	Unit	Source
DEFOREST	Deforested area	ha	PRODES/ INPE
SDI	Socioeconomic Development Index (SDI)	count	-
SDI^2	SDI Squared		-
SDI^3	SDI Cube		-
RURAL CREDIT	Total rural credit	R$ (BRL)	BACEN
DEM.DENSITY	Demographic density (inhabitants/km2)	km^2	SIDRA/IBGE
AGRIC.GDP	Agricultural participation in GDP	%	SIDRA/IBGE
CATTLE	Cattle herd size	count	SIDRA/IBGE
CROP	Total area for permanent and temporary planting	ha	SIDRA/IBGE
EXTRAC.WOOD	Extraction of wood (charcoal, firewood)	m^3	SIDRA/IBGE
SUGARCANE	Sugarcane Productivity	kg/ha	SIDRA/IBGE
MAIZE	Maize Productivity	kg/ha	SIDRA/IBGE
SOYBEAN	Soy Productivity	kg/ha	SIDRA/IBGE
ROADS	Roads extension	km	MAPBIOMAS
RAINFALL	Average annual precipitation	mm	CPRM
SOIL	Good or regular soil suitability for farming	binary	MMA/IBGE
FEDERAL.RES	Federal Reserve	binary	CSR
STATE.RES	State Reserve	binary	CSR
INDIGEN.RES	Indigenous Reserve	binary	CSR
FOREST.COVER	Remaining forest cover	%	MAPBIOMAS

Source: research data.

The SOIL variable was construct using the *Mapa de Potencial Agrícola do Brasil,* complied by the *Instituto Brasileiro de Geografia e Estatística (IBGE)* and made available by the *Ministério do Meio Ambiente (MMA).* The Brazilian territory are classified according to the agricultural potential of its soils, considering factors such as: fertility, physical and morphological characteristics, main limitations and topography. The effort resulted in five basic classifications: i) good; (ii) regular; iii) restricted; iv) unfavorable; and (v) inadvisable. Merging the agricultural potential map with the Cerrado map, we identified the predominant type of soil that exists in the municipalities of this biome. Finally, we created a binary variable, in which the number 1 are assigned to municipalities with i) good or regular soil and 0 for the others. The basic purpose of this procedure is to verify if municipalities with greater agricultural potential soils have higher rates of deforestation. In an indirect way, it will be possible to identify if the

Brazilian agricultural frontier expansion in Cerrado, caused by the conversion of forests into arable areas, is occurring in municipalities with greater agricultural potential.

The RAINFALL is composed of average annual precipitation data (1977 to 2006), from the national hydrometeorological network, compiled by the *Serviço Geológico do Brasil (CPRM)* and made available by the Pluviometric Atlas of Brazil. The ROADS refers to the extension in kilometers of state and federal highways in a given municipality. The data vector was made available by the Mapbiomas project, using data provided by the Brazilian government. Finally, we obtained information on protected areas, which generated the variables FEDERAL.RES, STATE.RES and INDIGN.RES, from the *Centro de Sensoriamento Remoto da Universidade Federal de Minas Gerais (CSR-UFMG)*. Joining the Cerrado municipalities with the protected area shape files, it was possible to obtain the presence or not of these areas for each municipality, considering only those created until 2010. From this, we created three binary variables to designate the three predominant forms of reserves: federal, state or indigenous.

3.4.5 Descriptive Statistics

Gallet (1999), Lieb (2003) and Stern (2017) argues that the heterogeneity present in most of the samples used in the EKC estimation can invalidated the results. In general, the literature assume that all spatial units are homogeneous, estimating a coefficient representing the entire sample. In order to investigate the possibility of this problem in this paper, Table 3.3 reports the descriptive statistics, for Matopiba and for the Non-Matopiba municipalities of the Cerrado, for the variables used in the EKC model

We can notice that there are considerable differences between the variables. Deforestation, for example, is on average four times larger in Matopiba when compared to other municipalities in the Cerrado. Such difference could be the result of Matopiba having approximately 60% of remaining forest cover, twice compared to the rest of the Cerrado. On the other hand, Matopiba has comparatively half of the socioeconomic development. This fact could characterize the regions as belonging to different parts of the Environmental Kuznets Curve and, as supported by Grossman and Krueger (1991; 1995), regions with lower levels of development tend to degrade the environment relatively more.

In addition, all the remaining variables also showed some degree of difference between the two regions, except for the annual average precipitation. Therefore, the presence of heterogeneity in the Cerrado biome can invalidated the results, due biased and inconsistent estimation. One possible way to solve this problem is to use methods that estimate different coefficients for each region (LIEB, 2003; STERN, 2017). The estimation by spatial regimes, adopted in this paper, precisely seek to circumvent this problem.

Table 3.3 – Descriptive statistics of Matopiba and Cerrado.

Variable	Mean		Standard Deviation		Minimum		Maximum	
	Non-Matop.	Matopiba	Non-Matop.	Matopiba	Non-Matop.	Matopiba	Non-Matop.	Matopiba
DEFOREST	4.167042	16.14699	8.506893	26.3755	0	0	103.53	227.34
SDI	50.33009	26.87199	13.49983	12.8613	0.05	0	100	74.34
RURAL CREDIT	2.95E+07	1.16E+07	9.66E+07	3.79E+07	0	0	2.58E+09	4.85E+08
DEM.DENSITY	67.54312	13.2597	366.3196	18.60841	0.33	0.23	7387.69	180.79
AGRIC.GDP	25.83889	30.08705	16.63562	14.88851	0	0.62	78.46	74.86
CATTLE	74634.61	44609.33	130844.6	47192.23	0	1300	1930475	423650
CROP	24104.89	12510	60644.1	37912.34	0	0	875851	441164
EXTRAC.WOOD	6843.948	21849.96	36877.5	73749.18	0	0	871166	749060
SUGARCANE	52677.16	22380.72	31524.31	21809.96	0	0	136666.7	100000
MAIZE	3897.004	2126.088	1925.994	1713.858	0	276.67	9433.33	8770.33
SOYBEAN	1501.552	1036.023	1370.847	1321.249	0	0	4266.67	3449.67
ROADS	24.71304	36.97518	18.17881	22.37455	0	0	135	119.3
RAINFALL	1428.891	1465.512	219.0353	295.7933	700	800	2250	2100
FOREST.COVER	0.3018216	0.602651	0.2014908	0.1997072	0.01	0.04	0.97	0.98

Source: research results.
Note: Non-Matop. refers to the remaining 1,060 municipalities, excluding those in the Matopiba region (337).

Another problem recurrent in the EKC is the multicollinearity, which can affect the coefficients variance, invalidating the statistical inferences. According to Lieb (2003), Carson (2010) and Stern (2004; 2017), most of the additional variable included in the model are highly correlated with per capita income. Despite the fact that we construct an Index to substitute the per capita income as proxy for economic development, this problem could remain. To check this possibility, the Appendix 3.A, 3.B and 3.C shows the correlation between the variables used for the all the Cerrado, Matopiba and for the non-Matopiba municipalities in Cerrado, respectively. From them, we can notice no extremely high correlations that could compromise the EKC model estimation, with the exception of the variable CROP and RURAL.CREDIT for Matopiba[25]. Therefore, the creation of the index of socioeconomic development was able to mitigate the problem of correlation between the proxy and other explanatory variables.

[25] In other words, there are a strong relation between the amount of rural credit destined for the region and the cultivated area.

3.4.6 Empirical Design

In the particular case of this paper, as mentioned above, the deforested area of the Cerrado of municipalities are the dependent variable. As explanatory variable, we used the Socioeconomic Development Index (SDI) to verify its relation to the level of deforestation. In addition, to better verify the relationship, De Bruyn et al. (1998) argues that is necessary include its squared and cube version. Thus, the equations that we estimated are as follows

$$DEFOREST_i = \beta_0 + \beta_1 SDI_i + \beta_2 SDI^2{}_i + \beta_3 SDI^3{}_i + \beta_k Z_i + \varepsilon_i \quad (22)$$

where $DEFOREST$ is the area of the municipality that was cleared.; SDI is the Socioeconomic Development Index; i refers to the municipality; where Z is the matrix of k additional explanatory variables included in the model (described in section 3.4.4). The model (22) seeks to verify the relationship between deforestation and development. The inclusion of the term in its squared form, attempts to verify the existence of a quadratic relationship while the cube term intended to capture if there is an N-shaped format between deforestation and development.

The Environmental Kuznets Curve format is related to the signals and significance presented by the coefficients $\beta_1, \beta_2\ and\ \beta_3$ In the model (22), tt is a sufficient condition a linear format when occurs a significant $\beta_1 > 0$, while β_2 and β_3 are not significant. For the inverted U-shape, it is sufficient to $\beta_1 > 0$, $\beta_2 < 0$ and statistically significant with β_3 not. The case $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$, with all statistically significant, it is a necessary and sufficient condition for the "N" shape.

In order to better specify the econometric model, we incorporated additional explanatory variables in the econometric model. The forest conversion and land use changes may present spatial interactions that result in significant spillovers, influencing the economic agent decision. This spatial spillover may occur due to the presence of centripetal forces, generated by productivity difference and transport costs that can cause significant regional differences; attracting productive activities, especially agricultural and livestock (MADDISON, 2006; WEINHOLD and REIS, 2008; ROBALINO and PFAFF, 2012). On other words, the presence of spatial spillovers may be one important factor inducing the economic agents to push the agricultural frontier expansion. Therefore, we represent the spatial spillovers in model (22) as

$$DEFOREST_i = \beta_0 + \beta_1 SDI_i + \beta_2 SDI^2{}_i + \beta_3 SDI^3{}_i + \beta_k Z_i + \tau WS + \varepsilon_i \quad (23)$$

where S is a vector containing elements that represents the agricultural frontier expansion, which is: sugarcane, maize and soy productivity; roads extension, cattle herd size and total area for planting. The spatial dependence matrix W, which represents the structural configuration between the regions, will capture the presence of spatial spillovers in the variables related to the agricultural frontier expansion. The inclusion of additional spillovers, as from the deforestation, will be determined by following Florax et al. (2003).

3.5 Results and Discussion

The factorial analysis model application for the 12 socioeconomic variables described in section 3.4.1 allowed the extraction of two factors with characteristic roots larger than one ($\lambda_i \geq 1$). The Table 3.4 shows the factors obtained, after the orthogonal rotation with the Varimax method, with their respective characteristic roots, as well as the explained and accumulated variance. The two factors are able to explain approximately 78.51% of the twelve selected variables variance, indicating that they managed to summarize them relatively well, especially considering that they are socioeconomic variables.

According to Hair et al. (2009), a cumulative variance greater than 60% is satisfactory, especially in social sciences. Therefore, we can conclude that the factors have been able to summarize relatively well the variables. In other words, the factors obtained can represent the socioeconomic development of the Cerrado municipalities.

Table 3.4 – Characteristic root, variance explained by factor and accumulated variance.

Factor	Characteristic root	Variance explained by the factor (%)	Cumulative variance (%)
F1	7.049	54.22	54.22
F2	3.157	24.29	78.51

Source: research data.

The Kaiser-Meyer-Olkin (KMO) test presented a value of 0,9072 what shows that the set of variables have a sufficiently high correlation for the use of the method. In addition, Bartlett's sphericity test proved statistically significant[26], that is, it rejected the null hypothesis

[26] Chi-square: 2.4310,139; Degrees of freedom: 66; p-valor: 0,000

that the correlation matrix is equal to the identity matrix. Therefore, from both tests, we can support that the sample is suitable for the factorial analysis method. Table 3.5 presents the factorials loads of each factor, as well as the uniqueness of each variable. The interpretation of the results are given as follows: for each variable, we considered the factor loads above 0.600 (in absolute value), which are highlighted in bold.

Table 3.5 – Factorials loadings and commonality

Variables	Factorials loadings		Uniqueness
	F1	F2	
Income_pc	**0.9262**	-0.1750	0.1116
Higher_education	**0.9043**	0.0220	0.1817
HDI_E	**0.8168**	-0.3605	0.2029
HDI_L	**0.7907**	-0.4167	0.2012
Labor_market	**0.7468**	-0.4438	0.2453
Fertility_rate	**-0.5881**	0.5036	0.4005
Child_mortality	**-0.7354**	0.5465	0.2429
Illiterate_pop	**-0.8074**	0.4780	0.1197
Primary_school	**-0.8898**	0.2193	0.1601
Gini	-0.0833	**0.9029**	0.1777
Extremely_poor	-0.6249	**0.6498**	0.1230
Electricity	0.3260	**-0.6843**	0.4254

Source: research data.

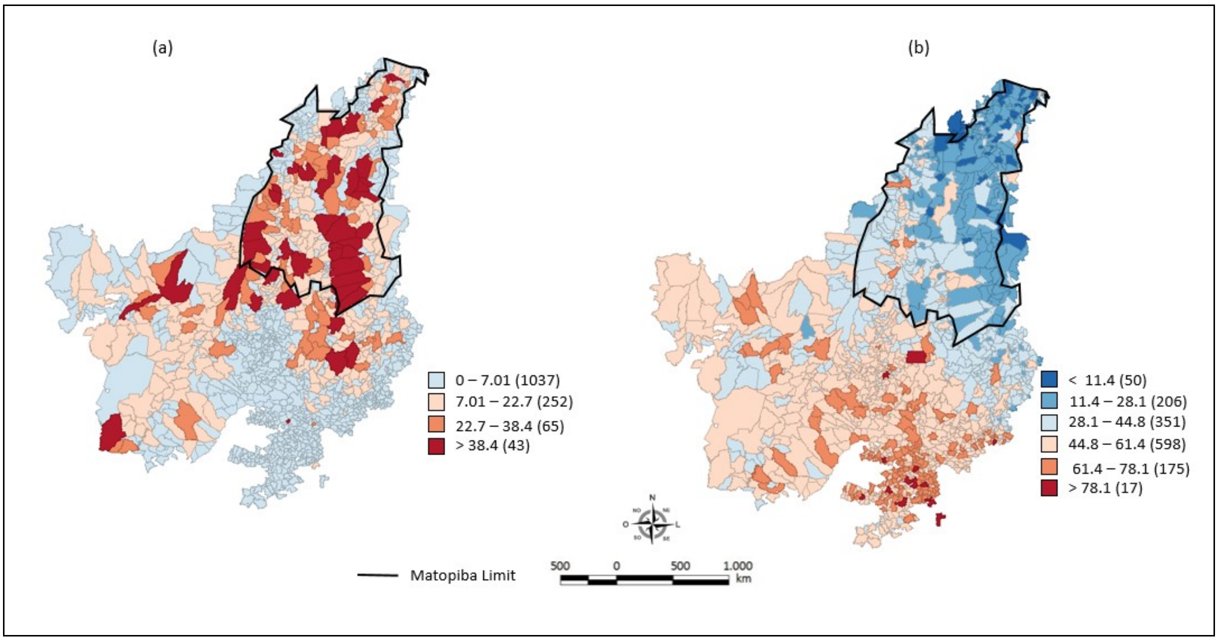
Factor 1 is related to nine of the twelve variables used. In addition, it presents a positive relation with five of them and negative with the remaining four. Among the positive ones, we have: Income_pc, per capita income; Higher_education, population with higher education (%); HDI_E, Human Development Index - Educational Dimension; HDI_L, Human Development Index – Life Expectancy Dimension; Labor_market. The variables mentioned are related to the economic and social development level, the higher the values, more the municipality is characterized as a locality that provides good material and social conditions for its population.

The variables related negatively to Factor 1, on the other hand, are: Fertility_rate; Child_mortality; Illiterate_pop, Illiterate population (%); Primary_school, Population (over 18 years) without elementary school (%). Therefore, high values for these variables are related to underdeveloped localities, thus justifying the inverse impact in relation to those of the previous paragraph. Therefore, Factor 1, by capturing essentially economic and social characteristics, we called the *Indicator of Socioeconomic Development* of the Cerrado municipalities.

Factor 2, in turn, is related to three of the twelve variables used in the factorial analysis model, two with a positive impact: Gini, Gini coefficient, and, Extremely_poor, proportion of extremely poor people. Moreover, one with negative impact: Electricity, Population in households with electricity (%). Thus, high values (in absolute terms) for these variables are related to undesirable characteristics. Therefore, we have a Factor 2 that is negatively correlated with the economic and social development level of the municipalities. Therefore, we called the Factor 2 as *Indicator of Socioeconomic Underdevelopment,* with municipalities with a high value for this indicator, presenting a lower development.

After the estimation of the factorial score for each Cerrado municipality, we built the Socioeconomic Development Index (SDI) as specified in the methodology. Figure 3.5 shows the spatial distribution of deforestation (Figure a) and the SDI (Figure b). The municipalities with high cleared area (Figure a) are concentrated in the Matopiba region, especially in western Bahia, the central area of the Matopiba region and, finally, the northern part of Maranhão. Araújo et al. (2019) argue that these regions, especially the first two, have undergone an intense modernization of their agricultural activity, especially in soy cultivation, resulting in significant increases in its production and yield after 2000s. According to the authors, this phenomenon may be one of the explanations for the recent deforestation in the region.

Figure 3.5 - Distribution of deforestation (a) and SDI (b) for the municipalities of Cerrado.



Source: research data.

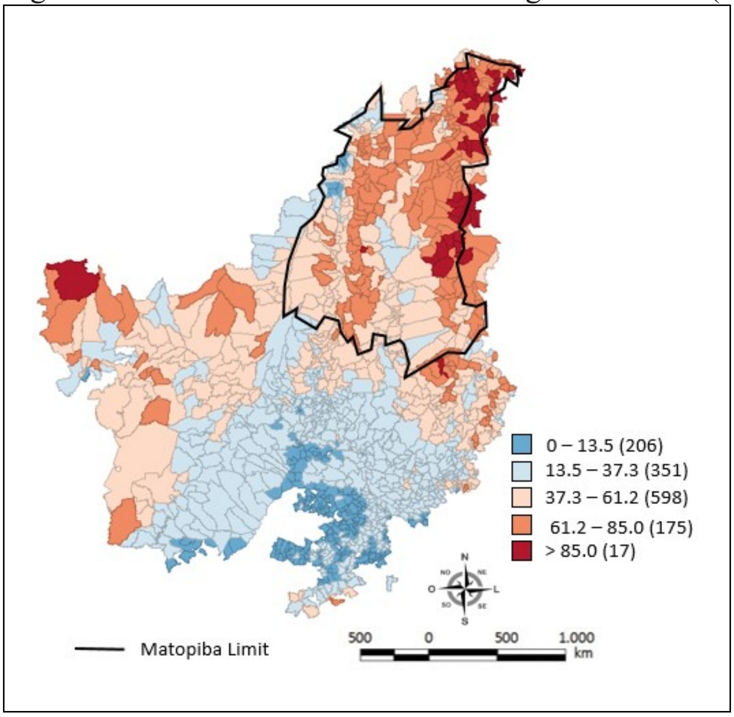
We can also identify, although with less intensity, regions of the Mato Grosso and Mato Grosso do Sul states that have deforested significant parts of their natural area. The cultivation of soybeans and cattle raising are advancing on both states, a fact that may have resulted in deforestation of their native forests (FREITAS JÚNIOR and BARROS, 2018; ARAÚJO et al., 2019). On the other hand, municipalities with low deforestation are located mainly in the states of São Paulo, Paraná and parts of Minas Gerais and Goiás. These states are among those who have deforested their forests the most (IBAMA, 2010; MAPBIOMAS, 2019). Therefore, their low rates of deforestation may be a result of them having fewer forest areas.

Considering the SDI (Figure b), there is a division of the Cerrado into two areas with different levels of development; municipalities with high socioeconomic development are located essentially in the states of São Paulo and in southern regions of Minas Gerais. On the other hand, underdeveloped municipalities are located mainly in the states that make up the Matopiba region, as well as parts of northern Minas Gerais. These corroborate Bolfe et al. (2016) and Bragança (2018), which identified in Matopiba, a region with lower socioeconomic development compared to the other parts of the Cerrado. Despite this, the authors emphasize that, due to the advancement of the agricultural frontier, the region has presented higher economic growth rates, a fact that has diminished the disparities in recent years.

A possible explanation for the spatial distributions of deforestation and development may be the occupation and colonization process of Cerrado. The developed regions, which matches those with lower rates of deforestation, are concentrated in parts of the Central-West and Southeast. These, in turn, were the first to receive the migratory waves of the Cerrado in the 1940s, encouraged by the concessions of land rights, subsidies and the construction of a basic infrastructure, especially roads (ALSTON et al., 1996; JEPSON, 2006; SANTOS et al., 2012). According to Zanin and Bacha (2017), this phenomenon is still underway, with Matopiba being the main migratory destination in Cerrado after 2000s.

To verify the relationship between development, deforestation and forest cover, Figure 3.6 shows, in percentage terms, the forest remnants of the Cerrado biome. Through it, we can see that most of the municipalities with more than 60% of their territory covered by forest areas are located in Matopiba or adjacent regions. This phenomenon may relate to the mentioned migratory process in Cerrado, in addition to being a transitional area to the Caatinga biome. According to Silva et al. (2016), a transition area normally presents diverse ecosystems, climatic conditions and lower natural fertility. Araújo et al. (2019) argues that soybean cultivation, the main driver of Matopiba occupation, is suitable only in areas with annual average rainfall above of 1000mm, which does not occur in Cerrado areas near the semi-arid region. The authors affirm that the future of agricultural expansion in this region depends on the development of new varieties of soy that supports rainfall between 1000 - 800 mm and, if this occurs, we can expect profound land use changes with reductions in forest cover.

Figure 3.6 – Distribution of the remaining forest cover (%) in Cerrado.



Source: research data.

The spatial concentration of deforestation and development is visible in Figure 3.5, indicating the existence of patterns, which may result in spatial dependence and heterogeneity. To verify this hypothesis, Table 3.6 presents the Moran's I statistic for these variables, according to several spatial matrices conventions. We confirm the existence of spatial dependence for both variables, all values were positive, and statistically significant regardless of the convention adopted, indicating that deforestation and / or SDI tend to be surrounded by municipalities with similar values.

Table 3.6 **-** Moran's I for deforestation and for SDI in the Cerrado.

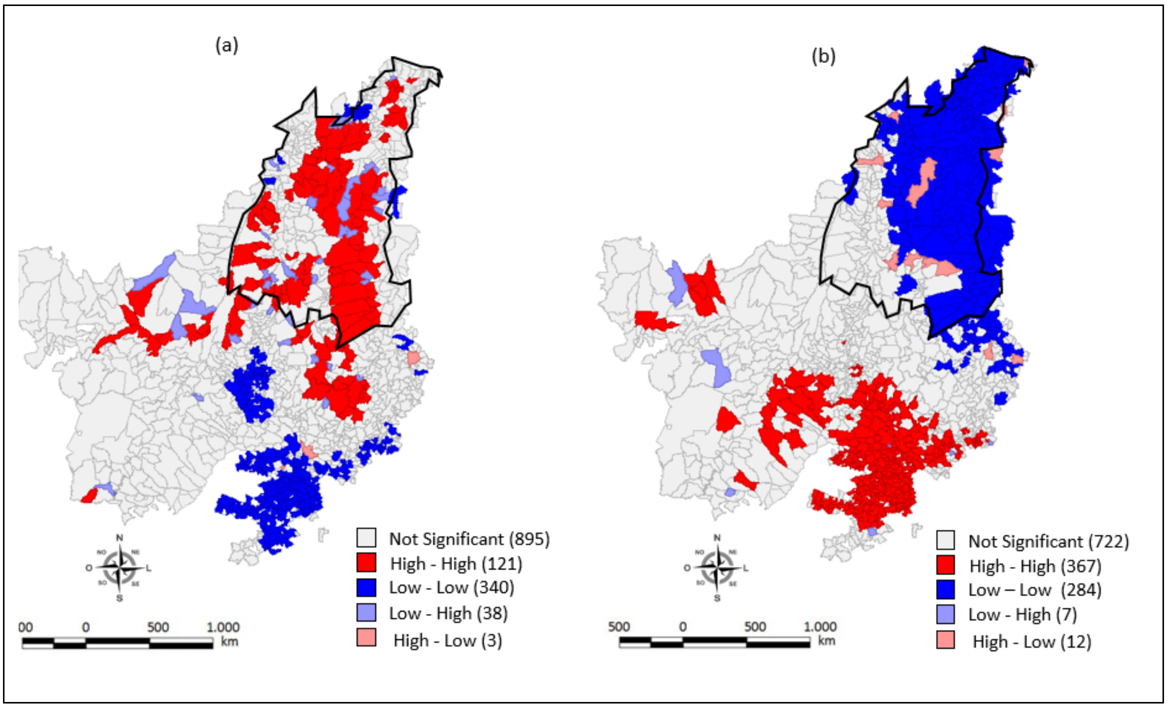
	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
Deforestation	0.31*	**0.32***	0.26*	0.22*	0.25*	0.21*
Index - SDI	0.54*	0.54*	**0.56***	0.55*	0.55*	0.56*

Source: research data. *Note*: * Level of significance of 1%.

Theoretically, this spatial concentration of the deforestation process may result from spatial spillovers, resulting from productive links and from human and physical capital concentration. For deforestation, this phenomenon was also evidenced by several empirical studies in Brazil, as Igliori (2006), Aguiar et al. (2007), Pfaff et al. (2007), Oliveira and Almeida (2011), Oliveira et al. (2011), Andrade de Sá et al. (2015), Jusys (2016) and Amin et al. (2019) in Legal Amazon; and Colusso et al. (2012) for Cerrado.

Figure 3.7 shows the LISA maps of spatial clusters for deforestation and SDI. Two significant clusters for deforestation (Figure a) are identified in the Cerrado region, one Low-Low and another High-High. The low deforestation cluster is located in the Southeast part of the map, composed of municipalities of the states of Sao Paulo and parts of Minas Gerais and Goiás. The high deforestation clusters, on the other hand, are concentrated especially in Matopiba, in two autocorrelated blocks: one in western Bahia and the other in the central part of the region. In addition, we have some extensions of these clusters, especially in west of Tocantins and Northwest of Minas Gerais. The clusters presented a similar spatial pattern than the one in Figure 3.2.

Figure 3.7 – LISA map for deforestation in Cerrado (a) and for SDI (b).



Source: research data.
Note: Empirical pseudo-significance based on 99,999 random permutations.

One important aspect is that the spatial clusters identified for the deforestation rate are not located in the same regions as the clusters for the socioeconomic development. The

Matopiba, for example, presents a spatial concentration for deforestation at the same time that is a region with low SDI, while the opposite occurs for the Southeast region. This fact is in line with the EKC hypothesis, that there is a negative relation between environmental degradation and economic development (GROSSMAN and KRUEGER, 1991; 1995). However, as we observed in Figure 3.6, the forests availability in the municipality may also be one an important responsible for this phenomenon, a fact that we investigated more deeply in the EKC model.

Table 3.6 presents the univariate Moran's I for the variables that are used in the econometric model, as well as the bivariate Moran's I in relation to deforestation. The purpose of bivariate statistics is to check whether some specific attributes of neighboring municipalities are autocorrelated spatially with deforestation in the Cerrado municipalities.

Table 3.7 - Univariate and bivariate Moran's I for the variables used in the empirical design.

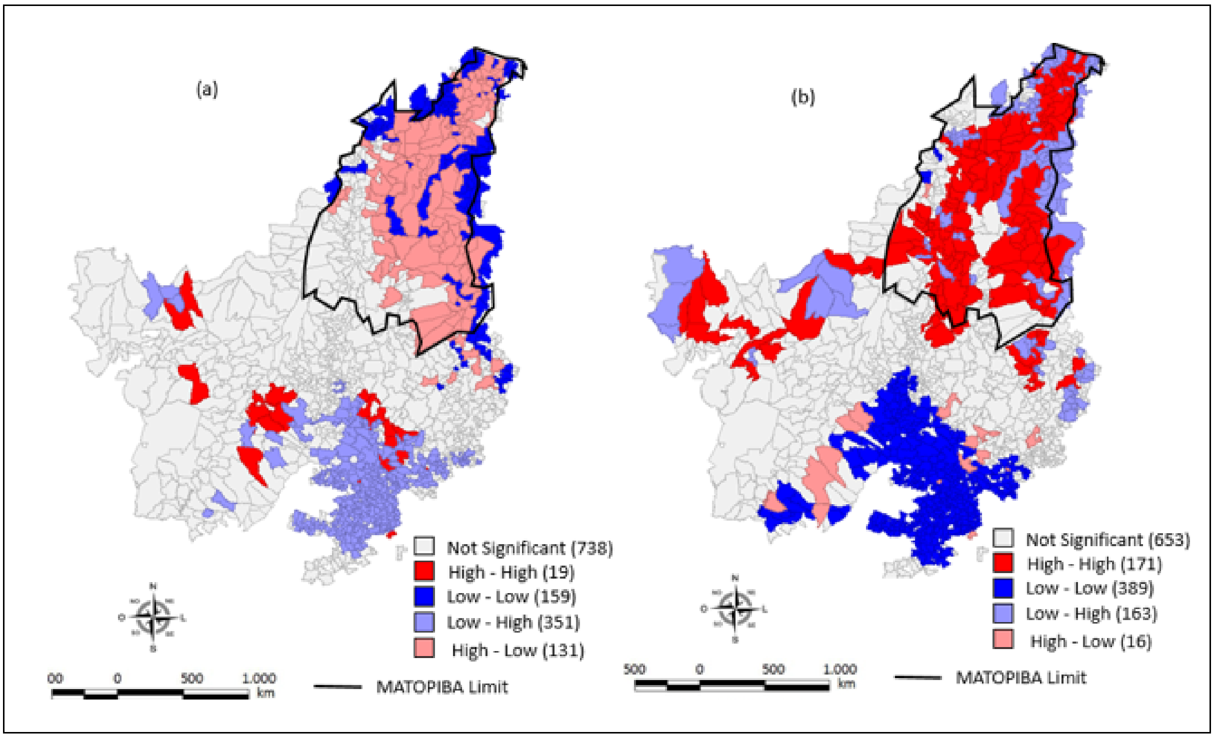
Variable	Cerrado		Matopiba		Non-Matopiba	
	Univariate	Bivariate	Univariate	Bivariate	Univariate	Bivariate
DEFOREST	0.3976*	-	0.3176*	-	0.3791*	-
SDI	0.7726*	-0.2484*	0.5651*	**0.0020**	0.6839*	-0.1699*
RURAL CREDIT	0.0603*	**0.0187**	0.4277*	0.3157*	0.0408	**0.0036**
DEM.DENSITY	0.2502*	-0.0515*	0.3686*	-0.1532*	0.3278*	-0.0593*
AGRIC.GDP	0.3077*	0.1329*	0.3069*	0.1165*	0.3687*	0.1719*
CATTLE	0.5713*	0.0616*	0.4949*	**0.0702**	0.5786*	0.2140*
CROP	0.5174*	0.0814*	0.4339*	0.3144*	0.5240*	0.0953*
EXTRAC.WOOD	0.3436*	0.1007*	0.4346*	**0.0555**	0.1417*	0.0588*
SUGARCANE	0.6343*	-0.1611*	0.3894*	0.2078*	0.6006*	-0.2119*
MAIZE	0.7382*	-0.0766*	0.5901*	0.3535*	0.7229*	-0.0630*
SOYBEAN	0.5470*	0.0692*	0.4818*	0.2566*	0.5633*	0.0597*
ROADS	0.3837*	0.1384*	0.2086*	0.0908*	0.3146*	0.01609*
RAINFALL	0.3155*	0.0753*	0.4227*	**0.0132**	0.4002*	0.0958*
FOREST.COVER	0.8657*	0.2780*	0.7701*	**0.0597**	0.8671*	0.2511*

Source: research data.
Note: Empirical pseudo-significance based on 99,999 random permutations; * Level of significance of 1%.
Non-Matopiba refers to the remaining 1,060 municipalities, excluding those in the Matopiba region (337).

We can notice that the spatial autocorrelation, in both univariate and bivariate Moran's I, change when the Cerrado is divided into the Matopiba and Non-Matopiba. This relationship means that the spatial patterns are different according to the region considered, a fact that corroborates the previous descriptive analysis. For example, the relationship between deforestation and socioeconomic development variable is negative and significant in the municipalities located at the Non-Matopiba region while in Matopiba there are no significant spatial relation. This phenomenon indicates that if we consider all the Cerrado counties in the econometrics estimation, the heterogeneity in the sample can invalidated the results, (GALLET, 1999; LIED, 2003; STERN, 2017).

Seeking to break this relationship spatially, Figure 3.8 presents the results for the Bivariate LISA for the deforestation in relation to the SDI (a) and forest cover (b). As expected, the low-high (LH) and high-low (HL) spatial clusters, in figure (a), showed a greater number of significant municipalities, compared to low-low (LL) and high-high (HH), with 73.03% against 26.93%, respectively.

Figure 3.8 – Bivariate LISA map for Deforestation and SDI (a); Forest Cover (b) in Cerrado.



Source: research data.

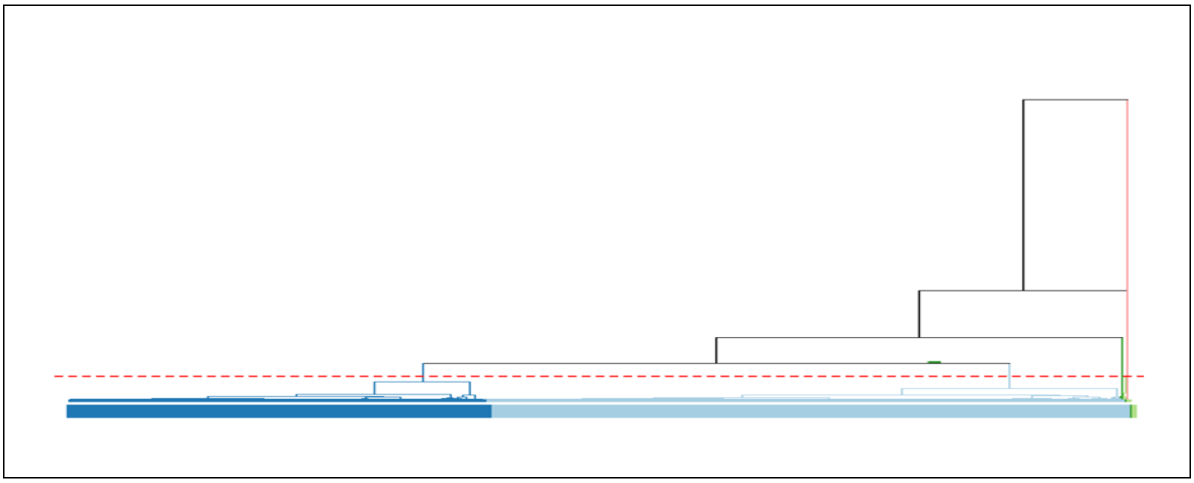
In addition, the low-low configuration has most of the spatial clusters of positive association, with only seventeen municipalities setting up with high deforestation rate and high development. Therefore, the bivariate spatial cluster presents: (i) an inverse relationship between the variables; (ii) or a low value for both. In the first case (i), the relationship is in line with the EKC hypothesis that high environmental degradation is associated with low development (and vice versa). In the second one (ii), it is also in line with EKC, as municipalities with low SDI may have a small scale effect, a fact that leads to a weak economic dynamism as well as to a non-environmental degradation (GROSSMAN and KRUEGER, 1991; 1995).

However, the bivariate relationship between deforestation and forest cover, in figure (b), have 75,77% being low-low (LL) or high-high (HH), indicating that deforestation is spatially related with the forest cover magnitude in the Cerrado municipalities. In addition, we can see a clear spatial pattern with majority of the HH clusters occurring in the Matopiba region, the current agricultural frontier in Cerrado, and the LL clusters are mostly in the southern part of the Cerrado, which was occupied decades before. Therefore, the differences in socioeconomic development may not be the only explanation for the environmental degradation. In other words, developed municipalities may deforest less because they do not have much remaining forest area to do it.

Spatial clusters are significant only when they assume a certain pattern, with municipalities necessarily having to be a neighbor's of each other. In cluster analysis, on the other hand, the neighborhood relation is not necessary; two municipalities may be located on opposite sides of the Cerrado, but still belong to the same cluster. According to Mingote (2005), the multivariate technique groups the information according to some criterion; then not disregarding information as it occurs in the spatial context. In this paper, we used the Complete Linkage Method, which classifies according to a criterion of dissimilarity, that is, it groups municipalities with high development and low deforestation (and vice versa).

We used the clusters analysis as a complementary methodology, once this technique is able to capture relationships that the ESDA cannot. In Figure 3.9, we have the Dendrogram for deforestation and the Socioeconomic Development Index (SDI), which shows the agglomerations carried out. Initially, each information is as an isolated group and, then, it grouped according to the chosen criterion, until there is only one large group with all the information. The Dendrogram shows all these combinations from the beginning to the end. According to Mingote (2005), the selection of how many groups is *ad hoc* with the researcher seeking to find groups that contain as similar information as possible. In this paper, we selected five clusters. Two clusters managed to capture most of the municipalities of the Cerrado with the remaining three being located on the far right of the Dendrogram, represented by a small number of counties.

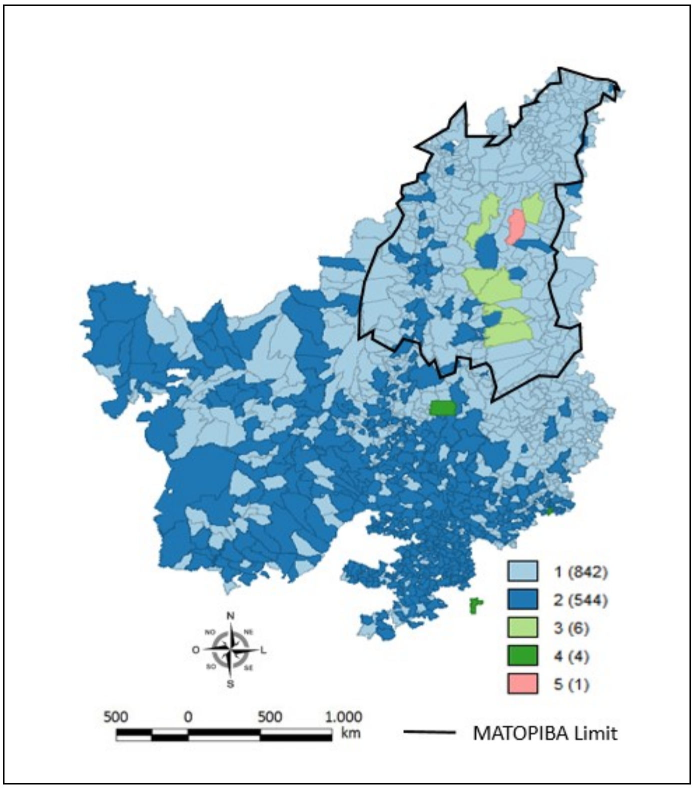
Figure 3.9 - Dendrogram.



Source: research data.

The clusters distribution and the number of municipalities in each group are in Figure 3.10. Two groups captured most of the Cerrado municipalities, with the others having just a few members. The largest one is Cluster 1, which has 842 municipalities (60.27% of the total) while the second, the Cluster 2, has 544 municipalities (38.94% of the total). Therefore, both has approximately 99.21% of the total, which represents the great majority of the municipalities belonging to the Cerrado biome.

Figure 3.10 – Clusters distribution.



Source: research data.

To better verify the characteristics of each Cluster, Table 3.8 shows the mean value for deforestation and the Socioeconomic Development Indicator (SDI) in each group as well as for all the biome. Cluster 1 presented a below-average value for SDI and, at the same time, above-average value for deforestation rate. The Cluster 2 presented an inverse figure, having high socioeconomic development and low deforestation. Therefore, high deforestation are linked to municipalities with low socioeconomic development (and vice versa), corroborating the EKC hypothesis.

Table 3.8 – Deforestation and SDI mean for the five clusters

Variables	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cerrado
Deforestation	4,78	2,41	122,32	1,20	394,29	4,63
SDI	24,36	45,83	29,98	91,30	15,24	32,93
Municipalities	842	544	6	4	1	1397

Source: research data.

In addition, because they represent 99.21% of the Cerrado municipalities, in fact this dynamic represents the major reality of the biome. In any case, Cluster 3 and 5 are have municipalities with deforestation rates considerably above the region average, with lower levels of socioeconomic development. These municipalities are mainly located in the Matopiba, especially western Bahia, possibly indicating the impacts of the agricultural frontier expansion in the region. According to Araújo et al. (2019), the western Bahia have undergone an intense modernization of their agricultural activity, especially of soy, which resulted in forest conversions and land use changes. On the other hand, Cluster 4 is composed by municipalities that with high development and low rates of deforestation.

Therefore, both the spatial and clusters analysis indicate the presence of spatial concentration and that high socioeconomic development may relate to a low environmental impact in the Cerrado. To verify this hypothesis more rigorously, in the next subsection, we estimate the Kuznets Environmental Curve for Cerrado.

3.4.1 Environmental Kuznets Curve (EKC)

First, we estimate the EKC model in its quadratic and cubic version using the OLS method; in order to verify which functional form is the most adequate, following the approach propose by Grossman and Krugman (1991; 1995) and De Bruyn et al. (1998). In addition, according to Almeida (2012), this procedure is necessary to verify the existence of spatial dependence on the model residues. Table 3.9 presents the estimations results.

Table 3.9 –Global EKC model.

Variables	OLS (2)	OLS (3)	SLX (2)	SLX (3)
CONSTANT	-8.1048***	-17.8776***	-10.1952***	-19.7822***
SDI	-0.0240	1.0490***	0.0920	1.0996***
SDI^2	-0.0020*	-0.0316***	-0.0032***	-0.0312***
SDI^3		0.0002***		0.0002***
RURAL CREDIT	0.0001***	0.0001***	0.0001**	0.0001**
DEM.DENSITY	-0.0005	-0.0015	0.0003	-0.0005
AGRIC.GDP	0.0446	0.0401	0.0785***	0.0724***
CATTLE	3.20E-06	6.20E-06	1.24E-05**	1.52E-05***
CROP	3.15E-05***	3.50E-05***	4.81E-05***	0.0001***
EXTRAC.WOOD	1.47E-05*	1.21E-05	1.33E-05*	1.12E-05
SUGARCANE	1.98E-05	2.62E-05*	-2.00E-06	6.00E-07
MAIZE	0.0015***	0.0017***	0.0020***	0.0020***
SOYBEAN	0.0003	0.0003	5.95E-04	0.0005
ROADS	0.0203***	0.0174***	0.0206***	0.0184***
SOIL	2.2768**	2.4019***	2.5744***	2.6374***
FEDERAL.RES	5.8092***	5.4499***	6.4388***	6.0453***
STATE.RES	-0.8429	-1.1403	-0.8285	-1.1086
INDIGEN.RES	-5.1895***	-4.7489**	-4.7571**	-4.2164**
RAINFALL	-0.0003	-0.0001	-3.56E-05	0.0002
FOREST.COVER	0.1783***	0.1688***	0.1813***	0.1770***
W_CATTLE			-1.57E-05**	-1.48E-05**
W_CROP			-3.00E-05***	-2.87E-05**
W_SUGARCANE			4.17E-05*	4.95E-05**
W_MAIZE			-0.0010**	-0.0008*
W_SOYBEAN			0.0002	0.0003
W_ROADS			-0.0033	-0.0049
Akaike Info. Criterion	11248.717	11225.874	11224.636	11204.532
Jarque-Bera	174236.608***	164027.394***	155522.006***	148789.036***
Koenker-Basset Test	134.088***	134.371***	152.307***	153.445***

Moran's I	0.2971***	0.2853***	0.2945***	0.2842***
ML ρ (lag)	216.937***	207.043***	310.574***	293.991***
MLR ρ (robust lag)	2.924*	0.759	24.226***	27.174***
ML λ (error)	291.576***	268.890***	286.390***	266.818***
MLR λ (robust error)	77.563***	62.606***	0.042	0.001

Source: research results.
Note: Significant at *** 1%; ** 5%; * 10%.

The OLS (2) and SLX (2) had no statically significance for SDI, indicating that the relation proposed by Grossman and Krueger (1991; 1995) may not occur in the Cerrado biome. On the other hand, both the OLS (3) and SLX (3) presented statistical significance for the SDI variable in its linear, quadratic and cube format at 1%. Therefore, this empirical result implies that the EKC for Cerrado have an "N" format as supported by De Bruyn et al. (1998). This means that although municipalities with low level of economic development have higher rates of deforestation, as economic and social indicators progress, the tendency is to reduce this degradation. However, in the long-run, the increase in socioeconomic development may induce the environmental degradation to return. This result corroborate the one found by Colusso et al. (2012) who also identified an "N" relationship in the EKC model for the Cerrado.

In addition, the best model according to the Akaike information criterion is the SLX (3), which incorporates a cubic relationship between SDI and deforestation and the spatial spillovers from the agricultural frontier expansion. This will be the base model for the following analyses. Furthermore, from the Jarque-Bera test it was possible to reject the null hypothesis of normality in the residuals with a significance level at 1%. Regarding the variance, the Koenker-Bassett test reject the homoscedasticity hypothesis, indicating the presence of a non-constant variance in the residuals.

Among the other variables in SLX (3), we have a significant relationship for rural credit, percentage of agriculture in GDP, cattle herd, crop area, maize productivity, roads extension, soil suitability, presence of federal and indigenous reserve and the percentage of forest cover. All the variables, except the indigenous reserve, presented a positive sign, indicating that their increase causes environmental degradation in Cerrado. The spillovers from agricultural frontier expansion, in the other hand, the cattle herd, crop area and maize productivity presented a significant negative impact on deforestation while the sugarcane productivity has a positive spillover, inducing environmental degradation.

However, we can notice in Table 3.9 that the models do not have a stability in its coefficients in terms of magnitude and statistical significance. According to Almeida (2012), this fact can be a reflection of spatial heterogeneity present in the data, which leads to structural instability of the parameters of the regression. Put another way, the structural instability in the parameters of the models is a sign of the presence of spatial heterogeneity in the Cerrado, a fact that may invalidate the results found, especially in the EKC context (LIST and GALLET, 1999; LIEB, 2003; STERN, 2017). Therefore, the model with spatial regimes may be suitable for this purpose because it can control the spatial heterogeneity.

In addition, since deforestation, agricultural and geographic variables usually suffers from spatial interactions, the Moran's I statistic presented a statistical significance of 1% as expected, which indicates the presence of spatial autocorrelation in the model residuals. In this context, the estimates may not be consistent, which requires the adoption of specific econometric methods to address the presence of spatial effects (IGLIORI, 2006; MADDISON, 2006; ALMEIDA, 2012). In addition, we identify with the ML test that both the dependent variable and the error variable suffers from spatial dependence, since they presented statistical significance of 1%. On the other hand, when using the robust lagrange multiplier test, only the lag term is statistically significant.

By adopting the approach proposed by Florax et al. (2003), we consider the spillovers from deforestation as the pattern that is the most representative of the spatial autocorrelation in the model residuals. Therefore, we estimate the Spatial Durbin Model (SDM) in order to control the spatial dependence. In this paper, the SDM model will incorporate the spatial spillover of deforestation and of the agricultural frontier expansion.

Although the models in Table 3.9 indicates spatial heterogeneity, which invalidate global coefficients, we estimate all the spatial models to better verify the robustness of the results found. The spatial models and their respective results are in Appendix 3.E. Following Baumont (2004), we chose the spatial lag matrix that generated the largest Moran's I coefficient for the SLX (3) residues (Appendix 3.D) to estimate the spatial models, opting for the rock matrix. Moreover, due to the non-normality of the residuals and the presence of heteroscedasticity, we used the Generalized Method of the Moments by Kelejian and Prucha (1999), together with the robust error of White (1980) for the SAR and SDM models. For the SEM and SDEM models, in the other hand, we adopted the robust error of Keleijan and Prucha (2010). Both methods aim to control the presence of heteroscedasticity.

The variables aimed at capturing spatial dependence, both the lag of the dependent variable (ρ) and the error term (λ), were significant at 1%, corroborating the Lagrange Multiplier tests in the models of Table 3.9. Despite this, according to Florax et al. (2003), the robust ML in SLX (3), the deforestation spatial lag (ρ) is best suited to capture the presence of spatial autocorrelation in the model residues.

Among the other results, we highlight the SDI that presented statistical and the same relationship as the previous models in Table 3.9 in all spatial models. However, the spatial models also presented unstable coefficients, indicating that the spatial dependence incorporation do not solve the heterogeneity problem. To investigate this issue more rigorously, before the estimation of models with spatial regimes per se, it is necessary to perform the Spatial Chow test. This test is responsible for identifying the presence of structural instability in the parameters of the model. The Table 3.10 brings the stability analysis of coefficients and models.

Table 3.10 - Diagnostics of Individual stability for SLX models with spatial regimes.

Variables	SLX (2)	SLX (3)	ª SLX (2)	ª SLX (3)
Constant	2.171	2.220	1.994	2.087
SDI	3.710*	1.907	3.196*	1.929
SDI^2	7.432***	1.302	6.987***	1.394
SDI^3	-	0.248	-	0.331
RURAL CREDIT	0.771	0.772	-	-
DEM.DENSITY	2.349	2.942*	2.988*	3.815*
AGRIC.GDP	0.403	0.336	0.943	0.801
CATTLE	2.089	2.119	3.569*	3.601*
CROP	4.353**	4.385**	19.758***	19.711***
EXTRAC.WOOD	0.001	0.003	0.004	0.021
SUGARCANE	1.593	1.520	1.470	1.403
MAIZE	2.005	1.996	1.686	1.694
SOYBEAN	3.484*	3.497*	3.553*	3.569*
ROADS	1.956	1.873	2.178	2.043
SOIL	1.622	1.397	1.952	1.705
FEDERAL.RES	1.711	1.747	1.590	1.636
STATE.RES	0.279	0.222	0.159	0.109
INDIGEN.RES	0.001	0.001	0.001	0.002
RAINFALL	5.459**	5.236**	5.236**	5.052**
FOREST.COVER	1.202	1.716	1.153	1.681

W_CATTLE	0.010	0.013	0.081	0.092
W_CROP	2.121	2.038	2.858*	2.670
W_SUGARCANE	3.944**	3.828*	4.179**	4.140**
W_MAIZE	1.693	1.727	0.873	0.914
W_SOYBEAN	0.1570	0.183	0.071	0.100
W_ROADS	1.0610	0.750	1.829	1.345
Spatal Chow Test	143.7990***	149.3320***	146.579***	151.179***

Source: research results.
Note: Significant at *** 1%; ** 5%; * 10%.
[a] SLX model without the rural credit variable.

In order to verify if the results found by the OLS method and spatial models for EKC are due to the spatial heterogeneity, we considered the EKC in its quadratic and cubic form. In addition, the rural credit are excluded from the models [a] SLX (2) and [a] SLX (3) since we identified high correlation, in Appendix 3.C, between rural credit and crop area for Matopiba what could diminish its instability. The spatial Chow test, necessary to verify the suitability of spatial regimes, was significant at 1% for all models. In other words, the models in Table 3.9 and Appendix 3.E are be adequate due the presence of spatial heterogeneity.

The instability diagnostic indicates some structurally unstable coefficients: SDI, SDI² DEM.DENSITY, CATTLE, CROP, SOYBEAN, RAINFALL and W_SUGARCANE. In summary, these variables are statistically different, depending on the region. The regional differences for socioeconomic development, demographic density, crop area and soybean/sugarcane productivity are close related to agricultural frontier expansion in Cerrado. For example, we have states such as São Paulo, Paraná, Minas Gerais, Goiás and Mato Grosso do Sul that initiated its occupation and migration process in the 1940s, while in Maranhão, Tocantins, Piauí and Bahia it starts only after the 1980s and is still undergoing. (SPEHAR, 1994; ALSTON et al., 1996; JEPSON, 2006; KIIHL and CALVO, 2008; SANTOS et al., 2012; ASSUNÇÃO and BRAGANÇA, 2015; MUELLER and MUELLER, 2016; ZANIN and BACHA, 2017; ARAÚJO et al., 2019).

This fact brings the need to estimate the spatial models with regimes and consider the regional differences in order to avoid econometric problems. Therefore, the next step was to estimate the SAR model for EKC in their quadratic and cubic form with spatial regimes, seeking to control the spatial dependence and spatial heterogeneity concomitantly. In order to do that, we used two regimes; the first considering all the municipalities that belong to the Matopiba region, while the second is composed by the remaining localities that have the Cerrado as their vegetal composition. Due the non-normality of the residuals and inconstant variance, we estimate the models using the Generalized Method of Moments proposed by Kelejian and Prucha (1999) and the robust error of White (1980). Table 3.11 presents the SDM models estimations with spatial regimes.

Table 3.11 –SDM model with spatial regimes.

Variables	Spatial regimes			
	Matopiba (2)	Matopiba (3)	**Non-Matopiba (2)**	Non-Matopiba (3)
Constant	**-14.4423****	-16.0579**	**-5.6960****	-4.2993
SDI	**0.5799****	0.7946	**0.1424****	0.0684
SDI^2	**-0.0113*****	-0.0191	**-0.0016****	-0.0001
SDI^3	**-**	0.0001	**-**	-9.50E-06
RURAL CREDIT	**-**	-	**0.0001**	0.0001
DEM.DENSITY	**-0.0681***	-0.0734*	**0.0004**	0.0006
AGRIC.GDP	**-0.0315**	-0.0300	**0.0473*****	0.0446***
CATTLE	**0.0001****	0.0001**	**1.36E-05***	1.39E-05*
CROP	**0.0004*****	0.0004***	**1.50E-06**	1.00E-06
EXTRAC.WOOD	**-5.00E-06**	-5.20E-06	**-4.20E-06**	-3.50E-06
SUGARCANE	**4.88E-05**	4.78E-05	**-1.21E-05**	-1.25E-05
MAIZE	**0.0021**	0.0021	**0.0002**	0.0002
SOYBEAN	**0.0018***	0.0018*	**-0.0001**	-0.0001
ROADS	**0.0351*****	0.0345***	**0.0186*****	0.0185***
SOIL	**-0.5184**	-0.5223	**1.4034*****	1.2776**
FEDERAL.RES	**6.5641***	6.6130*	**1.8302**	1.7959
STATE.RES	**1.2458**	0.9969	**-0.4809**	-0.4435
INDIGEN.RES	**-1.1909**	-1.1765	**-0.9864**	-0.9611
RAINFALL	**0.0019***	0.0020*	**-0.0005**	-0.0004
FOREST.COVER	**0.1016****	0.1030**	**0.0472****	0.0366*
W_CATTLE	**-5.70E-06**	-5.10E-06	**-1.25E-05****	-1.26E-05**
W_CROP	**-0.0002***	-0.0001	**-8.00E-07**	2.00E-07
W_SUGARCANE	**0.0001****	0.0001*	**1.56E-05**	1.93E-05
W_MAIZE	**-0.0022**	-0.0022	**-0.0002**	-0.0002

W_SOYBEAN	**0.0004**	0.0005	**-1.38E-05**	1.59E-05
W_ROADS	**-0.0368***	-0.0363*	**-0.0099****	-0.0134***
ρ	**0.2939***	0.2795*	**0.5026*****	0.6178***
Anselin-Kelejian	**0.004**	0.002	**1.667**	7.873***

Source: research results.
Note: Significant at *** 1%; ** 5%; * 10%.
Non-Matopiba refers to the remaining 1,060 municipalities, excluding those in the Matopiba region (337).

Note that the coefficients differ in terms of statistical significance and magnitude for two estimated spatial regimes, indicating that the Cerrado in fact suffers from structural instability. This corroborates the statements of Borges and Santos (2009) and Silva (2013), who identified in Matopiba the new Brazilian agricultural frontier, characterized by significant changes in land use, which resulted in higher levels of environmental degradation when compared to the others localities of the Cerrado. In fact, The Matopiba municipalities are the ones that deforested the most in the year of analysis and is a region a agricultural frontier (IBAMA, 2010).

According to Grossman and Krueger (1991; 1995) and De Bruyn et al. (1998), the choice between the quadratic and cubic model is determined by selecting the one that presented statistical significance for the economic development proxy. Therefore, since only the quadratic models (Matopiba (2) and Cerrado (2)) have statistically significant proxies with coefficients ,$\beta_1 > 0, \beta_2 < 0$, we have an inverted-"U" relationship between deforestation and socioeconomic development for both regions in the biome.

The results differs from Colusso et al. (2012) and from the Global EKC models estimated by OLS (Table 3.9) that identified an "N" relationship when analyzing the whole biome. However, both not considered the existence of spatial heterogeneity in Cerrado, which can led to structural instability in the parameters, resulting in bias and inconsistent estimations (LIST and GALLET, 1999; LIEB, 2003; ALMEIDA, 2012; STERN, 2017).

Therefore, the spatial regimes is a methodological advance in the EKC estimation for the biome, by making it possible to obtain results more consistent, what may explain the shift to an inverted-"U" relationship. This empirical evidence supports the Grossman and Krueger's (1991; 1995) Environmental Kuznets Curve hypothesis. In other words, at low levels of socioeconomic standards, development growth initially causes a scale effect by increasing natural resources use, which leads to deforestation. However, after a "turning point"[27], the

[27] A region where the curve reaches its maximum value. According to Stern (2017), we can obtained the "turning point" with: $\tau = -\beta_1/2\beta_2$

composition and technical effects became large enough to mitigate the scale effect, reducing environmental degradation.

The Table 3.12 shows the turning point for Matopiba and Cerrado regimes, as the SDI mean, standard deviation and the percentages of municipalities above the turning point in the EKC. We can notice a difference in the turning points between the regions, indicating that socioeconomic development do not affect both in the same magnitude. This empirical evidence corroborates the argument from List and Gallet (1999), De Bruyn (2000) and Stern (2017), which argues that most of the estimations involving EKC tends to present different coefficient and turning point within the sample.

Table 3.12 – EKC turning point, SDI mean, standard deviation and percentage of municipalities with SDI above the turning point in the Environmental Kuznets Curve.

	EKC Turning Point	SDI Mean	Stand.Dev.	% Municip. Above
Non-Maatopiba*	44.5	50.33	13.49	72.30%
Matopiba	21.80	26.87	12.84	60.54%

Source: research data.

In addition, we have approximately 40% and 28% of municipalities that did not reach its maximum environmental degradation in Matopiba and Cerrado*, respectively, due socioeconomic development. In other words, despite the fact that we got an inverted “U” curve for EKC for both regimes, there are municipalities that are below this turning point, which means that socioeconomic growth will continue to boost Cerrado deforestation in those places. However, even in the long run, the socioeconomic development may not be a sufficient factor to generate biome protection, since there are other variables that impacts deforestation.

The coefficients ρ (Rho) of all the models were significant, indicating the presence of spatial spillover of deforestation among the Cerrado municipalities, a similar result to that found by Colusso et al. (2012). However, we can notice that the spillovers from deforestation is smaller in the Matopiba region when compared to the others municipalities of Cerrado. This fact indicates that spatial interactions in forest conversion and land use changes are not similar along the biome, which may occur due differences in crop productivity, transport costs, climate, topography, soil conditions and occupation stage. (MADDISON, 2006; WEINHOLD and REIS, 2008; ROBALINO and PFAFF, 2012; ASSUNÇÃO and BRAGANÇA, 2015; MUELLER and MUELLER, 2016; ZANIN and BACHA, 2017; ARAÚJO et al., 2019). In addition, we have variables with statistical significance that captures spillovers from the agricultural frontier expansion, reinforcing the importance of spatial interactions in explaining deforestation.

The SDM approach, by incorporation relevant spatial spillovers related to deforestation and the agricultural frontier expansion, are able to control the presence of spatial dependence. The Anselin-Kelejian test was not significant and do not reject the hypothesis of spatial autocorrelation absence in the models residuals. Therefore, the methodology adopted permitted to control satisfactorily the spatial dependence and heterogeneity, diminishing the bias and inconsistency often present in the EKC models (LIST and GALLET, 1999; DE BRUYN., 2000; LIEB 2003; STERN, 2004; MADDISON, 2006; CARSON 2010; STERN, 2017).

The roads extension have a positive impact in deforestation for both regimes, while spillover negatively to its neighbors, decreasing environmental degradation. The road network expansion allows access to previously isolated areas by creating corridors to the region. In addition, it reduces transportation costs, which allows the agricultural frontier to expand by intensifying the migration and occupation of the territory, affecting its deforestation rhythm. (WEINHOLD and REIS, 2008; NESPTAD et al., 2001; SOARES-FILHO et al., 2004; PFAFF et al., 2007; FEARNSIDE et al., 2007; WALKER et al., 2013; ZANIN and BACHA, 2017; ARAÚJO et al., 2019).

However, those effects acts as an centripetal force, attracting human and economic resources from neighbors regions, especially for agricultural activities, generating spatial agglomeration, which explains the negative spillover. (KRUGMAN, 1991; WEINHOLD and REIS, 2008). The spatial attracting elements helps to explain the greater value (in absolute terms) presented for Matopiba regime, since those forces are stronger due the stage of agricultural frontier expansion and colonization process in the region. This empirical evidence are an important contribution to the literature on deforestation in the Cerrado, since there are no papers that address directly this issue for the region.

The cattle herd is also an important deforestation inductor in both regimes. This phenomenon are explained mainly by land use changes due the soy and sugarcane cultivation advancement in recent periods in Brazil, which adopts more technologically advanced inputs, with greater potential to generate profits. This have been leading to a displacement of cattle ranching to agricultural frontier regions with lower land prices, causing the Cerrado and Amazon deforestation. (LAPOLA et al., 2010; BARONA et al., 2010, ARIMA et al., 2011; MACEDO et al., 2012, ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013, RICHARDS et al., 2014; GOLLNOW and LAKES, 2014; JUSYS, 2017; BRAGANÇA, 2018). In the non-Matopiba Cerrado, the cattle herd has a negative spillover to its neighbors, revealing the presence of centripetal spatial forces; while in Matopiba region, cattle did not presented spatial spillovers.

In addition, after 2006, we had the Soy Moratorium, an industry effort that restrict the access to the market of soybean from recently deforested areas in Amazon, which aggravate the cattle displacement. The effort, despite being successful in its goal, induced the soy production to increase on land previously used by extensive livestock in both biomes or by converting forest areas in the Cerrado, due its smaller restrictions, in a ‘cross-biome leakage’ (MACEDO et al., 2012; GIBBS et al., 2015; NOOJIPADY et al., 2017).

These Facts also help to explain the crop area and soybean productivity statistical positive significance on deforestation in the Matopiba (2). Gibbs et al. (2015) and Noojipady et al. (2017) argues that crop expansion – the soy cultivation in particular – is occurring in a considerable part due forest area reduction on rural properties, especially at the agriculture frontier, reflecting the restrictions imposed to the expansion in Amazon. According to Garcia and Vieira Filho (2018), 68% of the agricultural expansion in Matopiba was due to the conversion of native areas. However, the crop area presented statistical significance and a negative spillover in the Matopiba. Considering Gibbs et al. (2015), Noojipady et al. (2017) and Zanin and Bacha (2017) empirical evidences, municipalities with greater rural proprieties area, infrastructure and agricultural activities attracts crop expansion, diminishing its neighbor’s deforestation, facts that help to explain the negatively spatial spillovers from crop.

The sugarcane productivity, on the other hand, presented significant positive spatial spillover in Matopiba. The increase in the national and international demand for biodiesel have been the main responsible for the high profitability that induces the production and productivity growth of sugarcane cultivation (ANDRADE DE SÁ et al., 2013; GOLLNOW and LAKES, 2014). Therefore, although sugarcane is not a predominant crop in Matopiba, the recent expansion of Brazilian ethanol production is also leading to direct deforestation in the region. In addition, the sugarcane non-impact in the Cerrado regime supports Andrade de Sá et al. (2012) and Jusys (2017), who found evidence that its production is increasing on São Paulo, and adjacent states, in previous occupied areas, not directly affecting deforestation.

The remaining forest cover in the municipality are statistical significant for both regimes, indicating that higher deforestation is associated with greater proportion of native forests. This fact makes logical sense, since some municipalities may deforest less simples because they do not have much remaining forest area to do it. In addition, higher proportion of forests are related to regions where the agricultural activities, basic infrastructure and migratory attraction did not reach its full potential yet (BOLFE et al., 2016; ZANIN and BACHA, 2017;

ARAÚJO et al, 2019). In other words, these factors growth translates into the agricultural frontier expansion, which are the main environmental degrader in Cerrado (ASSUNÇÃO and BRAGANÇA, 2015; GARCIA and VIEIRA, 2018). According to Cohn et al. (2014), agricultural intensification can be viable solution to the problem, since it spare land from deforestation and maintain agricultural production growth. Assunção and Bragança (2015) highlights that technological innovation adoption are important in the intensification process and helps to attenuate environmental pressures.

Regarding soil suitability, we have statistical significance only for the Cerrado regime, which corroborates the Bragança (2014) and Assunção and Bragança (2015) arguments that soil conditions are essential for agricultural production in Cerrado. Better suitability translated into higher productivity and profitability when compare to unfit soils, which induces deforestation. However, soil characteristics in Matopiba region, where the environmental degradation is bigger in recent periods, do not affect land use changes. In other words, deforestation occur independent if the soil is indicated or not for agricultural production, corroborating Bolfe et al (2016) evidences that a considerable part forest conversion on Matopiba did not occur on soils with agricultural suitability.

The rainfall variable presented significance for Matopiba regime, indicating that higher annual average rainfall induces deforestation in the region. According to Silva et al. (2016), the agricultural frontier expansion in Matopiba faces natural challenges in transitioning areas with the Caatinga biome, where the annual average rainfall ranges between 1000 - 800 mm, which acts a natural barrier. Araújo et al. (2019) emphasizes that the development of drought resistant crops or pasture could outline this problem, but they also highlight that this innovation could boost deforestation. The remaining municipalities in Cerrado do not face such a rainfall shortage, thus not acting as a natural barrier.

According to IBAMA (2010), the Cerrado biome has only 7.44% of its territory as conservation units, which has served to aggravate deforestation. Although the Cerrado regime reserves did not presented statistical significance, indicating that the reserves presence do not affect deforestation, which corroborates the affirmation in some sense. However, in Matopiba regime, the Federal Reserve presented a significant positive impact, contradicting the idea that conservation units acts as inhibitor deforestation. This demonstrates a need for expanded government supervision over conservation areas in Matopiba, since the status granted to the areas do not serve as inhibitors of deforestation.

Grossman and Krueger (1991; 1995) argues that good and services growth pressure the environment, since increase in natural resources use is needed for its production, causing a scale effect. The authors emphasizes that this effect is predominant at the beginning of economic development, in which the main income generator is the agricultural sector. Indeed, the agricultural sector proportion in GDP presented statistical significance for the Cerrado regime in line with Grossman and Krueger (1991; 1995) theoretical proposition. In other words, municipalities that depends more from the agricultural sector presents higher deforestation rates. The Matopiba regime, on the other hand, did not presented statistical significance for this variable; a possible explanation is that almost all municipalities in the region has agricultural as the main sector, deferentially from the Cerrado regime, which has regions where other sectors is predominant.

However, the Matopiba regime presented statistical significance for the demographic density variable, which captures another effect proposed by Grossman and Krueger (1991; 1995): the composition in the goods and services produced. This effect occurs with the displacement of agricultural sector to the industrial and service sectors, which uses less natural resources and is strong for the latter. The changes in the goods and services composition production is accompanied by an increase in demographic density because the industrial and service sector is predominant urban and associated with economic development and dynamism, which attracts migratory waves and reduces mortality, increasing demographic density.

When using spatial models with the dependent variable lagged, it is worth mentioning the fact that, according to Lesage e Pace (2009), the explanatory variables effects are not fully provided by their respective coefficients β_k. This fact occurs due spatial interactions between the municipalities, which induces an indirect marginal effect spillover. The total impact that a variable exerts on deforestation, therefore, must also consider these indirect effects, which are calculated with the equation: $(1-\rho)^{-1}\beta_k$. Table 3.13 shows the total marginal effects on deforestation calculated for the explanatory variables from Table 3.12 for both regimes.

The greater deforestation spillover, ρ (Rho), presented by the Cerrado regime, resulted in a considerable marginal indirect effect. Therefore, its consideration is important to understand the real environmental impacts with spatial interactions from the deforestation determinants. In this spatial context, socioeconomic development causes environmental degradation with different magnitude, implying a new turning point. Using the total effect on Table 3.13, the Cerrado regime turning point goes from 44.50 to 46.19 while the Matopiba regime, on the other hand, changes from 21.80 to 25.66.

Table 3.13 – Direct, indirect and total marginal effect provided by the spatial interaction in the regimes of the SDM model.

Variables	Direct Effect		Indirect Effect		Total Effect	
	Matopiba	Non-Matopiba	Matopiba	Non-Matopiba	Matopiba	Non-Matopiba
Constant	-14.4423	-5.6960	-6.0127	-5.7563	-20.4550	-11.4523
SDI	0.5799	0.1424	0.2414	0.1439	0.8214	0.2864
SDI²	-0.0113	-0.0016	-0.0047	-0.0016	-0.0160	-0.0031
RURAL CREDIT	-	0.0000	-	0.0000	-	0.0000
DEM.DENSITY	-0.0681	0.0004	-0.0284	0.0004	-0.0965	8.47E-04
AGRIC.GDP	-0.0315	0.0473	-0.0131	0.0478	-0.0446	0.0952
CATTLE	0.0001	1.36E-05	3.50E-05	1.37E-05	0.0001	2.73E-05
CROP	0.0004	1.50E-06	0.0002	1.52E-06	0.0006	3.02E-06
EXTRAC.WOOD	-5.00E-06	-4.20E-06	-2.08E-06	-4.24E-06	-7.08E-06	-8.44E-06
SUGARCANE	4.88E-05	-1.21E-05	2.03E-05	-1.22E-05	0.0001	-2.43E-05
MAIZE	0.0021	0.0002	0.0009	0.0002	0.0030	0.0003
SOYBEAN	0.0018	-0.0001	0.0007	-0.0001	0.0025	-0.0001
ROADS	0.0351	0.0186	0.0146	0.0188	0.0497	0.0375
SOIL	-0.5184	1.4034	-0.2158	1.4183	-0.7342	2.8217
FEDERAL.RES	6.5641	1.8302	2.7328	1.8495	9.2969	3.6797
STATE.RES	1.2458	-0.4809	0.5186	-0.4860	1.7644	-0.9669
INDIGEN.RES	-1.1909	-0.9864	-0.4958	-0.9969	-1.6867	-1.9833
RAINFALL	0.0019	-0.0005	0.0008	-0.0005	0.0027	-0.0009
FOREST.COVER	0.1016	0.0472	0.0423	0.0477	0.1439	0.0948
W_CATTLE	-5.70E-06	-1.25E-05	-2.37E-06	-1.26E-05	-8.07E-06	-2.51E-05
W_CROP	-0.0002	-8.00E-07	-0.0001	-8.08E-07	-0.0002	-1.61E-06
W_SUGARCANE	0.0001	1.56E-05	0.0001	1.58E-05	0.0002	3.14E-05
W_MAIZE	-0.0022	-0.0002	-0.0009	-0.0002	-0.0031	-0.0003
W_SOYBEAN	0.0004	-1.38E-05	0.0002	-1.39E-05	0.0006	-2.77E-05
W_ROADS	-0.0368	-0.0099	-0.0153	-0.0100	-0.0521	-0.0199

Source: research results.

In summary, the deforestation spatial spillovers imposes a high turning point for both regimes, making more difficult for socioeconomic development act as inhibitor on environmental degradation. To illustrate this effect, the municipalities that are above the new spatial interacted turning point are 69.15% in Cerrado regime and 46.88% in Matopiba, a drop of 3.15% and 13.66% respectively.

The change is greater for Matopiba, indicating that socioeconomic development will boost deforestation in most of its municipalities as agricultural frontier advances in the region. In addition, there are many others variables that affects the environmental degradation in the biome together with socioeconomic development that also have higher impacts due spatial interactions. In this scenario, we can expect, if no inhibitory action is taken, that deforestation will continue to happen in the biome, especially in Matopiba.

3.6 Final considerations

The main purpose of this paper was to investigate the relationship between socioeconomic development and environmental degradation in the Cerrado biome, with a special focus on the current Brazilian agricultural frontier in the region, known as Matopiba, using the Environmental Kuznets Curve approach.

The techniques used indicated a spatial concentration for deforestation, a fact that made it necessary to adopt spatial models that incorporated this effect. As proxy for economic development in the EKC, we created a Socioeconomic Development Index with factorial analysis from multivariate statistics, following methodological advancements in the literature. The ESDA and cluster analyses point two heterogeneous regions on Cerrado with the agricultural frontier in the region, Matopiba, presenting different characteristics than the remaining municipalities in Cerrado. Through the spatial Chow test, we identified the presence of structural instability in the global regression parameters, which confirm the existence of two regimes in Cerrado.

In this context, the present paper estimated the EKC with spatial models, in order to treat the spatial dependence, and with spatial regimes to control the spatial heterogeneity in the region. This procedures attempt to avoid biased and inconsistent estimates, an approach not yet adopted to model deforestation in Cerrado. In addition, the traditional per capita income replacement as a proxy for economic development by a multidimensional index of socioeconomic development was important to represent the EKC, since it helped improve the model’s adjustment and results. This is an important contribution from this paper, since just a fewer studies in the literature used factorial analyses to construct an Index to replace per capita income.

In the EKC model, we get a basic relationship between socioeconomic development and deforestation for both regimes, an inverted "U" curve. However, the curve turning point, where socioeconomic development reaches its maximum impact on environment, are different for both regimes, reinforcing the heterogeneity of Cerrado. The Matopiba presents a lower development than the remaining municipalities and the migratory and agricultural processes is not still consolidated, which induces higher deforestation on the region due socioeconomic advancement. Another important contribution from this paper is the spatial interactions consideration that embodies indirect spatial effects, which amplifies the variables effects on deforestation in the presence of spillovers. After this, we identified that more than 50% of Matopiba and 30% of Cerrado regimes have municipalities with socioeconomic development lower than the maximum turning point, which highlights environmental concerns for the regions, since economic growth could boost degradation on this underdeveloped municipalities.

To worsen this scenario, we identified many variables, especially related to the agricultural frontier expansion in the biome, which affects negatively the Cerrado environment. Among the main influences on both regimes, we have the roads expansion, which attracts migratory waves and agricultural activities due its cost reduction, and the cattle herd that also is an important deforestation inductor in the biome. Crop area affects directly only Matopiba and it has considerable indirect effects on deforestation by displacing cattle to agricultural frontier regions, according to many empirical evidences on the literature.

In this context, agricultural and environmental policies have to consider not only the direct impacts on land use, but also its indirect ones, since some activity may influence the location, advancement and displacement of others. In addition, the heterogeneity in the region may induce different policies outcomes. For example, demographic density, agriculture GDP, crop area, soil suitability, presence of federal reserve, soybean productivity and spillovers from cattle herd, crop area and sugarcane productivity, all presented diverse statistical significance according to the considered regime. Therefore, the spatial regimes estimation is a methodological advancement in the estimation of EKC for the biome, since it revealed a differentiated relationship according to which regime is considered.

Since we have biome heterogeneity, any actions have to take into account possible mixed results, especially for Matopiba because it is at the beginning of its occupation and agricultural expansion process, differently from many Cerrado regions, that initiated it decades ago and are more consolidated. The empirical evidences from this paper can help to identify the deforestation different determinants and possible outcomes for both regimes and to construct focused agricultural and environmental policies that consider heterogeneous characteristics along with spatial and displacement effects.

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APPENDICES

Appendix 3.A – Correlation for the Cerrado variables.

	SOYBEAN	SUGARCANE	MAIZE	CROP	AGRIC.GDP	CATTLE	DEM.DENSITY	CREDIT	WOOD	RAINFALL	ROADS	FOREST.COVER	SDI
SOYBEAN	1												
SUGARCANE	0.2039	1											
MAIZE	0.5435	0.4064	1										
CROP	0.3344	0.0948	0.2690	1									
AGRIC.GDP	0.2263	-0.1452	0.1695	0.0939	1								
CATTLE	0.2003	-0.0765	0.0488	0.1255	0.1280	1							
DEM.DENSITY	-0.0682	-0.0208	-0.0838	-0.0357	-0.2107	-0.0695	1						
RURAL CREDIT	0.1447	0.0608	0.1322	0.3224	-0.0623	0.1287	0.6674	1					
EXTRAC.WOOD	0.0069	-0.1113	-0.1145	0.0538	0.0543	0.0577	-0.0291	-0.0028	1				
RAINFALL	0.2809	-0.0859	0.2077	0.1509	0.1764	0.1088	0.0340	0.0662	-0.1813	1			
ROADS	0.0013	-0.2170	-0.1997	0.1159	0.1592	0.1365	-0.0845	-0.0153	0.2067	-0.0277	1		
FOREST.COVER	-0.2774	-0.5430	-0.5413	-0.0820	0.0477	-0.0402	-0.0945	-0.1229	0.1576	-0.2021	0.2401	1	
SDI	0.3116	0.5296	0.5481	0.1777	-0.2646	0.0992	0.2098	0.2302	-0.1519	0.2382	-0.2971	-0.7336	1

Source: research results.

Appendix 3.B - Correlation for the Matopiba variables.

	SOYBEAN	SUGARCANE	MAIZE	CROP	AGRIC.GDP	CATTLE	DEM.DENSITY	CREDIT	WOOD	RAINFALL	ROADS	FOREST.COVER	SDI
SOYBEAN	1												
SUGARCANE	0.1309	1											
MAIZE	0.5505	0.2607	1										
CROP	0.3298	0.2142	0.6282	1									
AGRIC.GDP	0.2616	-0.0507	0.2991	0.2143	1								
CATTLE	0.0888	0.0328	0.1165	0.0454	0.1267	1							
DEM.DENSITY	-0.2655	0.0272	-0.2585	-0.0871	-0.3127	-0.0809	1						
RURAL CREDIT	0.2822	0.1922	0.5602	**0.9225**	0.1791	0.1878	-0.0935	1					
EXTRAC.WOOD	0.1207	0.0576	0.0118	0.0832	0.0689	0.0457	-0.0536	0.0603	1				
RAINFALL	0.0421	-0.3203	-0.0796	-0.1142	0.1542	0.1826	0.0711	-0.0764	-0.2859	1			
ROADS	0.0347	-0.0897	0.0375	0,0925	0.1377	0,0623	-0.1024	0.0563	0.1792	0.0288	1		
FOREST.COVER	0.0142	0.2176	-0.2029	-0.0522	-0.1635	-0.3938	-0.0057	-0.1030	0.0073	-0.3725	0.0113	1	
SDI	0.2247	0.1008	0.2687	0.0525	-0.1736	0.4262	0.0509	0.0967	-0.0164	0.3588	-0.0673	-0.3612	1

Source: research results.

Appendix 3.C - Correlation for the variables in the Non-Matopiba municipalities in Cerrado.

	SOYBEAN	SUGARCANE	MAIZE	CROP	AGRIC.GDP	CATTLE	DEM.DENSITY	CREDIT	WOOD	RAINFALL	ROADS	FOREST.COVER	SDI
SOYBEAN	1												
SUGARCANE	0.1688	1											
MAIZE	0.5291	0.3119	1										
CROP	0.3306	0.0453	0.1935	1									
AGRIC.GDP	0.2424	-0.1228	0.2111	0.0866	1								
CATTLE	0.2077	-0.1469	-0.0015	0.1233	0.1490	1							
DEM.DENSITY	-0.0865	-0.0585	-0.1298	-0.044	-0.2242	-0.0792	1						
RURAL CREDIT	0.1224	0.0146	0.0622	0.2734	-0.0804	0.1173	0.6820	1					
EXTRAC.WOOD	-0.0275	-0.1286	-0.1257	0.0726	0.0292	0.1014	-0.0281	-0.0012	1				
RAINFALL	0.4007	0.0053	0.3798	0.2388	0.1807	0.1215	0.0472	0.1053	-0.1197	1			
ROADS	0.0435	-0.1411	-0.1672	0.1634	0.1368	0.2042	-0.0808	0.0014	0.1900	-0.0853	1		
FOREST.COVER	-0.3149	-0.5658	-0.5001	-0.0402	0.0271	0.0694	-0.0756	-0.0930	0.1738	-0.2479	0.1651	1	
SDI	0.3011	0.4584	0.4817	0.1784	-0.2693	0.0036	0.2356	0.2470	-0.1467	0.3481	-0.2248	-0.6826	1

Source: research results.

Appendix 3.D **-** Moran's I for the OLS and SLX Models - convention matrix decision.

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
OLS (2)	0.28*	**0.29***	0.27*	0.22*	0.22*	0.19*
OLS (3)	0.27*	**0.28***	0.26*	0.21*	0.22*	0.18*
SLX (2)	0.28*	**0.29***	0.25*	0.20*	0.21*	0.18*
SLX (3)	0.27*	**0.28***	0.25*	0.20*	0.21*	0.17*

Note: * Level of significance of 1%.
Source: research data.

Appendix 3.E – EKC Spatial Models.

Variables	SAR	SEM	SDM	SDEM
Constant	-16.7292***	-20.6939***	-15.7627***	-20.5793***
SDI	0.9474***	0.9500***	0.7802***	1.0096***
SDI²	-0.0279***	-0.0242***	-0.0174***	-0.0243***
SDI³	0.0002***	0.0002***	0.0001**	0.0002***
RURAL CREDIT	0.0000	0.0000	0.0000	0.0000
DEM.DENSITY	-0.0015	-0.0011	0.0002	-0.0008
AGRIC.GDP	0.0324	0.0486*	0.0806***	0.0748***
CATTLE	5.40E-06	1.16E-05*	1.56E-05**	1.40E-05**
CROP	3.11E-05	4.67E-05*	4.99E-05*	4.94E-05*
EXTRAC.WOOD	1.10E-05	8.50E-06	7.70E-06	7.10E-06
SUGARCANE	2.37E-05**	-2.00E-07	-1.64E-05	-8.30E-06
MAIZE	0.0015***	0.0017***	0.0019***	0.0018***
SOYBEAN	0.0002	0.0003	0.0005	0.0005
ROADS	0.0163***	0.0189***	0.0167**	0.0184***
SOIL	2.0471**	2.6235	1.6956**	2.8016**
FEDERAL.RES	4.8031*	5.2511	4.5072**	5.7174**
STATE.RES	-0.9845	-1.1697	-0.7759	-1.0287
INDIGEN.RES	-4.4022	-4.5543	-2.7874	-4.1424
RAINFALL	-0.0001	0.0001	0.0004	0.0003
FOREST.COVER	0.1304***	0.1434***	0.0620**	0.1433***
W_CATTLE	-	-	-1.36E-05**	-1.44E-05*
W_CROP	-	-	-4.13E-05**	-1.82E-05
W_SUGARCANE	-	-	0.0001***	3.35E-05
W_MAIZE	-	-	-0.0017***	-0.0006
W_SOYBEAN	-	-	-0.0002	-4.00E-06
W_ROADS	-	-	-0.0209***	-0.0050
ρ	0.2183**	-	0.6882***	-
λ	-	0,5311***	-	0.5135***

Source: research results. *Note:* Significant at *** 1%; ** 5%; * 10%.

4. Conclusion

The main purpose of this dissertation was to investigate the relationship between economic development and environmental degradation in the Legal Amazon and Cerrado, using the theoretical approach known as the Environmental Kuznets Curve (EKC). It is worth mentioning, that Legal Amazon, an administrative division of the Brazilian territory created in 1953, for regional policies purposes, covers 20% of the Cerrado, in states as Maranhão, Mato Grosso, Pará, Rondônia and Tocantins. Therefore, the geographic cut used in this dissertation have intersections that can reflect on the results.

In addition, the spatial interactions identified in both papers may connect through significant spatial spillovers from deforestation and agricultural activities even municipalities not directly intersect. In other words, land use changes and forest conversion in both papers may be interconnect. In this context, we highlight some possible interconnections between both articles, based on empirical evidence from the papers of this dissertation and related literature. The basic purpose is to bring to the attention possible relationships that deserve to be investigated more closely, serving as suggestions for future research.

In the EKC model, we get an inverted "U" curve relationship between economic development and deforestation for both biomes and the majority of municipalities in Amazon and Cerrado are far below the turning point in the EKC model. This highlights environmental concerns for both biomes since economic development could boost deforestation in the following decades. Therefore, usual hypothesis advocated by various authors, along with economic and political agents, that economic growth is enough to generate environmental sustainability may not be completely true when considering the Brazilians biome. In this context, public policies must address the deforestation problem, otherwise the biomes may present irreparable lost in its biodiversity and capability of generate ecosystem services for society.

The empirical results shows that other variables also affects both biomes and, since economic development are not sufficient to protect the Amazon and Cerrado; we need complementary means to ensure the environmental sustainability of the region. We identified some forces, especially related to the agricultural frontier expansion, which leads to deforestation. Among them, we have crop (soy, maize and sugarcane) displacement of cattle ranching, which reflects from national and international agricultural markets forces that modify relative prices causing significant land use changes, inducing less profitable activities, as cattle raising, to agricultural frontiers where the land is cheaper. The main responsible for this scenario are: Soy Moratorium (SoyM), Brazilian Forest Code (FC) legislation and the increase in the national and international demand for animal feed and biodiesel.

The SoyM and FC focus most of their sustainability objectives in the Amazon, which has been leading to an increased in cultivated area in other regions, especially in the Cerrado. This occurs due to the smaller restrictions applied to savanna biome, phenomenon called as a 'cross-biome leakage' by the literature, which are leading to forest areas reduction, especially in rural properties legally under the FC. For example, 23% of the soybean expansion in the Cerrado between 2007 and 2013 occurred in forest areas, a figure that reaches 40% when the Matopiba is considered, an impact that we confirm in the second article with positive statistical significance for crop are and soybean productivity in the current agricultural frontier regime.

The crop production increase used for biodiesel and animal feed in consolidated agricultural areas, mostly on Cerrado biome[28], shifted livestock towards the agricultural frontiers, together with other non-fuel crops, affecting deforestation indirectly. The increase in the national and international demand for animal feed and biodiesel have been the main responsible for the high profitability that induces the growth of the production of these crops and indirectly displaces the cattle to the regions of agricultural frontiers, where the land is cheaper.

The land use changes in Cerrado resulted in restrictions on the supply of beef, which caused an increase in its price in the national and international markets. Therefore, the agriculture expansion in the biome has been also reallocating the rural organization of the region, with cropland inducing a decrease in cattle ranching. This process induces, due to the inelasticity of the demand for beef, the displacement of cattle rearing to regions where the price of land is relatively lower, in the agricultural frontiers, as the Matopiba and the "Arc of deforestation" regions on Amazon. Those land use changes explains the statistical significance in both paper for cattle herd, indicating that its growth are a deforestation inductor on the biomes.

A possible solution for the problem is to incentive production intensification in existing agricultural areas, which would enable Brazil to reduce significantly its deforestation and greenhouse gas emissions and still maintain agricultural growth. However, according to the empirical evidences from this dissertation, only the soy and maize productivity reduces

[28] To a lesser extent, it also happened in the Legal Amazon, especially in the Cerrado area of this administrative division.

deforestation. Therefore, we cannot define productivity gains incentives uniformly for all agricultural activities, since each has different impacts on deforestation.

These evidences shows the importance of considering land use dynamics and cross-agricultural activities leakages in policies targeting deforestation reduction, since crops like soy, maize and sugarcane may indirectly affect environmental degradation in Amazon and Cerrado. These activities normally replaces livestock in spaces already occupied, shifting production cattle to agricultural frontier regions, where it increase deforestation, even when located far from agricultural frontiers

In this context, agricultural and environmental policies have to consider not only the direct impacts on land use, but also its indirect ones, since some activity may influence the location, advancement and displacement of others. In addition, we have to considerer the heterogeneity problem, which may induce different policies outcomes. Therefore, any possible actions have to take into account possible mixed results, especially considering that within the biomes we have many regions at different stages of agricultural and economic development.