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DEFORESTATION AND HUMAN DEVELOPMENT IN THE BRAZILIAN AGRICULTURAL FRONTIER: AN ENVIRONMENTAL KUZNETS CURVE FOR MATOPIBA*

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ABSTRACT: This paper aims to estimate an Environmental Kuznets Curve (EKC) for the current Brazilian agricultural frontier, located in the region known as MATOPIBA. The question to be answered can be summarized as: how does human development affect the region's environment, captured by deforestation? Specifically, we analyzed the presence of spatial dependence and heterogeneity, as well as the existence of clusters between the 337 municipalities of MATOPIBA in 2010, using exploratory spatial data analysis (ESDA) and spatial econometrics. We identified the presence of spatial dependence for deforestation, which led to the incorporation of this effect into the econometric modeling, which resulted in the SLX as the best spatial model. In addition, we got an inverted-U shape for the EKC; thus, deforestation increases until a certain threshold, as the region develops, from which it begins to fall. The "turning point", where development reaches its maximum impact on the environment, is a Human Development Index of 0.57 and 28.18% of the municipalities are below this value, which highlights environmental concerns, since their development could boost degradation. To worsen this scenario, we identified many variables, especially related to the agricultural frontier expansion, which induces deforestation in MATOPIBA.

Keywords: Environmental Kuznets Curve (EKC); Brazilian agricultural frontier; MATOPIBA; Spatial dependency.

JEL Codes: Q01; Q56.

DESMATAMENTO E DESENVOLVIMENTO HUMANO NA FRONTEIRA AGRÍCOLA BRASILEIRA: UMA CURVA AMBIENTAL DE KUZNETS PARA O MATOPIBA

RESUMO: Este trabalho busca estimar uma Curva Ambiental de Kuznets (CKA) para a atual fronteira agrícola brasileira, localizada na região conhecida como MATOPIBA. A pergunta a ser respondida pode ser resumida em: como o desenvolvimento humano impacta o meio ambiente da região, captada pelo desmatamento? De forma específica, analisou-se a presença de dependência e heterogeneidade espacial, bem como a existência de clusters entre os 337 municípios do MATOPIBA em 2010, utilizando-se da análise exploratória de dados espaciais (AEDE) e econometria espacial. Identificou-se a presença de dependência espacial, fato que levou à incorporação desse efeito na modelagem econométrica, procedimento que resultou no SLX como melhor modelo. O formato encontrado para a CKA foi de "U" invertido, isto é, o desenvolvimento tende a elevar o desmatamento até certo patamar, a partir do qual a relação se inverte, resultando na queda do impacto ambiental. O "ponto de virada", onde o desenvolvimento atinge seu máximo impacto, é um IDH de 0.57, sendo que 28.18% dos municípios estão abaixo desse valor, fato que levanta preocupações ambientais, pois o desenvolvimento pode acelerar o desmatamento nesses locais. Para piorar esse cenário, identificou-se diversas variáveis, principalmente relacionadas ao avanço da fronteira agrícola, que induzem o desmatamento no MATOPIBA.

Palavras-chave: Curva de Kuznets Ambiental (CKA); Fronteira agrícola brasileira; MATOPIBA; Dependência espacial.

Classificação JEL: Q01; Q56.

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1. Introduction

MATOPIBA is the main region of the current Brazilian agricultural frontier. According to Araújo et al. (2019), agricultural frontiers are regions dominated by natural vegetation and which are facing intensive agriculture-related land occupation. The term MATOPIBA refers to the initial syllables of the states that comprise this region: Maranhão, Tocantins, Piauí and Bahia. The agricultural frontier in the area has been expanding due to the implementation of technologies adapted to local conditions, which allows an increase in agricultural productivity. The low price of land and the easy adoption of technologies have attracted investments and intensified their occupation, resulting in a significant growth in the local production, mainly of grains like soybeans and maize (MIRANDA et al., 2014; BRAGANÇA, 2018; ARAÚJO et al., 2019).

Recognizing the region's strategic importance for the Brazilian agribusiness, the country's government created the Decree No. 8447 on May 6, 2015 with the main objective of establishing an Agricultural Development Plan for MATOPIBA seeking to guide federal projects and actions specifically for the region (BRASIL, 2015).

The intensive occupation of MATOPIBA for agricultural production began in the 1980s, and the process is still underway. The existence of underutilized land, where low-productivity techniques are adopted, allows the increase in production with adoption of technology. In addition, there are areas where native forests of the Cerrado biome prevail, and their incorporation into the dynamic areas of MATOPIBA as the agricultural frontier advances is possible (BATISTELLA; VALLADARES, 2009; STUDTE, 2008; BOLFE et al., 2016; ARAÚJO et al., 2019). According to Chagas and Andrade (2017), economic agents located in agricultural frontiers face a considerable opportunity cost by not clearing forest areas for economic use, in light of possible present and future returns.

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 region to present significant increases in its production levels and, consequently, economic growth. Thus, the existence of underutilized and/or not yet occupied land, together with the agricultural frontier expansion and the economic development in MATOPIBA, may result, in the coming years, in a process of deforestation. In fact, according to Borges and Santos (2009), the current deforestation of the Cerrado has been located mainly in these sparsely occupied areas, as MATOPIBA, due to the establishment of new agricultural frontiers.

The factors mentioned have enabled MATOPIBA to present increasing levels of production, especially in the cultivation of soybeans, and local economic growth (BOLFE et al., 2016; ZANIN; BACHA, 2017; BRAGANÇA, 2018; ARAÚJO et al., 2019). To illustrate this, according to Araújo et al. (2019), 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.

In this context, this paper aims to analyze the relationship between economic development and deforestation in MATOPIBA, with a special focus on their connection with the agricultural frontier expansion, in view of its importance for the economic growth of the region. In addition, we investigate the spatial distribution of deforestation, as well as the formation of spatial clusters and the presence of spatial dependence. One of the hypotheses is that there is a spatial effect in deforestation, with centripetal forces acting in the attraction of productive activities, especially agricultural, and consequently generating spatial autocorrelation in this variable. These forces are generated by the existence of different production techniques, climate, topography and soil conditions among the municipalities of MATOPIBA, factors that lead to regional differences.

The basic hypothesis connecting economic development and deforestation comes from the pioneering work of Grossman and Krueger (1991), who state that, at low levels of development, a growth in per capita income leads to an increase in environment degradation. However, from a certain level, this logic would reverse itself, with an increase in per capita income leading to a decrease in environmental degradation. The curve that represents this relationship has an inverted-U shape and is known in the literature as the Environmental Kuznets Curve (EKC).

However, a recurrent problem in the literature, often not considered in the estimations of EKC, is the use of per capita income as a proxy for economic development; it is inadequate for such because it captures only one aspect of development (HILL; MAGNANI, 2002; JHA; MURTHY, 2003; COSTANTINI; MONNIM, 2008; STIGLITZ et al., 2009; COSTANTINI; MARTIGINI, 2010; KUBISZEWSKI et al., 2013; NEVE; HAMAIDE, 2017). Therefore, the present paper proposes to solve this problem by replacing the per capita income with the Human Development Index (HDI) of the MATOPIBA municipalities, following the approach adopted by Hill and Magnani (2002), Jha and Murthy (2003), Costantini and Monni (2008), Costantini and Martini (2010), and Lamb and Rao (2015).

Although there are several papers that have sought to estimate an EKC for Brazil using several indicators of environmental degradation, none has used the HDI as a proxy for economic development. Moreover, deforestation has been used in some studies for the Amazon and the Cerrado biomes, but there are no works specifically developed for the MATOPIBA region. This paper proposes to fill both gaps in the literature.

Finally, the work is structured into four sections, including this introduction. The second section discusses the theoretical framework on the EKC and the relationship between economic development and environmental degradation. In the third section, we detail the methodology and the database used. The results and their analysis are displayed in the fourth section, followed by the final considerations.

2. Theoretical framework

Grossman and Krueger (1991) attempted to decompose the effects that are behind the relationship between economic growth and environmental quality in the EKC, resulting in the identification of three main effects: scale, composition, and technical. The scale effect occurs due to the increase in production, which causes a pressure on the environment due to a greater use of natural resources. The composition effect is the change that occurs in the composition of the goods and services produced. Finally, the technical effect is related to technological advances that increase productivity and/or can make production “cleaner”, generating less waste. The composition and technical effects can be large enough to minimize the scale effect. The descending part of the EKC, therefore, occurs because of this overlay of effects (GROSSMAN; KRUEGER, 1991).

Several authors have attempted to broaden the understanding of why 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), Stern et al. (1996), De Bruyn et al. (1998), and Culas (2007). Shafik and Bandyopadhyay (1992) conducted an empirical study and 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 use of natural resources. 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 shape, according to Selden and Song (1994), mainly stem from positive income elasticity for environmental quality, changes in the composition of production and consumption and technological innovations that increase productivity, induced by market competition and/or adjustments to imposed legislation.

Many researchers, however, argue that the descendant part of the EKC occurs because polluting industries tend to move from developed to underdeveloped countries, in a move encouraged by restrictions imposed by legislation (SURI; CHAPMAN, 1998; STERN et al., 1996). This theory is known in the literature as the Pollution Haven Hypothesis. In the other hand, Institutional changes, according to Culas (2007), are an important element to explain the inverted-U relationship between environmental degradation and per capita income. As income rises, factors such as increased utility from underdeveloped areas, population awareness of the importance of environmental sustainability, and strengthening government capacity for environmental protection help to explain the decline in environmental impact.

Despite the evidence for the existence of an EKC, some authors, such as De Bruyn et al. (1998) argue that this relationship is not sustained in the long run, since there is another turning point in which per capita growth leads once again to environmental degradation. Therefore, an N-shaped curve, rather than an 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 shapes beyond the usual, with a need for verification for each specific case.

According to Neve and Hamaide (2017), per capita income is not the most adequate proxy for economic development to verify the relationship with environmental degradation, given that it only partially captures the development of a region. In this context, Hill and Magnani (2002), Jha and Murthy (2003), Stiglitz et al. (2009), Kubiszewski et al. (2013) and Neve and Hamaide (2017) recommend using a variable that is more related to well-being in general than just economic performance. This occurs because several indicators can lead to increased social welfare, resulting in less environmental damage, without income growth necessarily occurring.

Hill and Magnani (2002) and Jha and Murthy (2003) sought to avoid this problem by using the HDI as a proxy for economic development, replacing the per capita income in the EKC model. The authors also verified that, when using the HDI, there is an improvement in the environmental degradation prediction in relation to the per capita income, suggesting that the HDI is able to capture the relationship with the environment better. From the pioneering works by Hill and Magnani (2002) and Jha and Murthy (2003), many authors have sought to replace per capita income by the HDI, or similar indicators, in their estimates. In general, they have verified an improvement in model adjustment (COSTANTINI; MONNI, 2008; COSTANTINI; MARTINI, 2010; LAMB; RAO, 2015; NEVE; HAMAIDE, 2017).

There is no consensus about the existence of a traditional inverted-U EKC for deforestation in the literature (SHAFIK; BANDYOPADHYAY, 1992; SHAFIK, 1994; CROPPER; GRIFFITHS, 1994; BHATTARAI; HAMMING, 2001; KOYUNCU; YILMAZ, 2009). Chiu (2012) states that the empirical results are controversial and argues that an analysis must be carried out for each locality, since it is not possible to infer causality from studies on other regions.

Shafik e Bandyopadhyay (1992) and Shafik (1994) 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 causes deforestation, but as economic growth occurs, such demand structure tends to change, moving to goods that affect the environment less. In addition, income growth induces an increase in replanting efforts, which ends up reversing the deforestation process in the long run. Koyuncu and Yilmaz (2009) found that the increase in demand for arable land also has a significant impact on deforestation alongside economic growth.

For Brazil, there have been studies seeking to identify the existence of the EKC using deforestation. However, practically all the papers focus on the Legal Amazon, with only one on the Cerrado and no studies specifically for MATOPIBA. For Amazon, we have controversial empirical evidence, which varies according to the year analyzed or method adopted. 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 a U-shaped EKC, and Oliveira et al. (2011) and Oliveira and Almeida (2011) identified an N-shaped relationship. For the Cerrado, the paper by Colusso et al. (2012) is the only one which estimates an EKC for this biome. The authors projected several spatial models, which corroborated significant results for an N-shaped curve for the Cerrado, indicating that, in the long run, economic growth is not sufficient to prevent the deforestation of the biome.

However, among the papers for Brazil, there is none that specifically investigates the existence of an EKC for the MATOPIBA region. Therefore, based on Chiu (2012), it is clear that we need a study focused on the Brazilian agricultural frontier in the Cerrado. The purpose of the next section is to describe the occupation dynamics in this biome, as well as the expansion of its agricultural frontier.

2.1. Occupation of the Cerrado and the expansion of its agricultural frontier

The Cerrado is located 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. The biome is the richest savanna in the world and is of much importance to the balance of the global ecosystem. However, its intensive occupation, especially after the 1970s, 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 Brazilian government has played an active role in the occupation and expansion of the agricultural frontier in the Cerrado. This role began in the 1970s with the military governments, especially after the Second National Development Plan (II PND). In practice, the incentives for the occupation of the Cerrado, especially in the Central-West region, were through the Agricultural Frontier expansion. The basic instrument used was a subsidized rural credit offer, combined with the implementation of an infrastructure that enabled the occupation of the territory. Such incentives and measures resulted in rapid changes in land coverage and use in the region. There is a close relationship between agricultural frontier expansion and the opening of roads, for they allow the creation of access corridors to the region and possibly to deforestation of native vegetation because the road network expansion allows access to previously isolated areas, affecting its environmental degradation rhythm (ASSUNÇÃO; BRAGANÇA, 2015; BRAGANÇA, 2018). Nevertheless, there are no papers in the literature that have sought to analyze this impact of roads on the deforestation of MATOPIBA, or even the Cerrado

According to Chagas and Andrade (2017), human presence in forest areas itself represents a deforestation vector, since the population demands local resources for their subsistence, income growth and material well-being. The agricultural frontier expansion is, in turn, an inductive factor of the occupation of the Cerrado, which increases the pressure to open new areas. This scenario has led to a progressive depletion of the natural resources of the region, making this biome the second that has suffered the most changes due to anthropogenic actions in Brazil, after the Atlantic forest. Despite this, conservation units protect only 7.44% of the territory, which has served to aggravate the intensive use of its natural resources (SANTOS et al., 2009; BORGES; SANTOS, 2009; IBAMA, 2010).

In historical terms, the state that has presented greater deforestation in its Cerrado areas is São Paulo, with 90% of the total, followed by Mato Grosso do Sul (75.87%), the Federal District (70.63%), Paraná (70.00%), Goiás (65.11%), Minas Gerais (56.84%), Mato Grosso (42.83%), Bahia (36.45%), Tocantins (26.40%), Maranhão (22.85%), Piauí (15.10%), and Rondônia (2.88%) (IBAMA, 2010). Although the MATOPIBA states are those with the smallest deforested area, except Rondônia, the current deforestation in the Cerrado has been located mainly in Piauí, Bahia, Tocantins and Maranhão, states that suffered considerable land use changes after the 2000s (BORGES; SANTOS, 2009). Table 1 shows the ten municipalities with the largest deforestation in 2010; we can note that all are located in the states belonging to the MATOPIBA region.

In this context, the Brazilian Government adopted measures to combat and inhibit deforestation in the Cerrado. In 2009, for example, the Brazilian government released the Action Plan for the Prevention and Control of Deforestation and Forest Fires in the Cerrado (PPCerrado) which aimed to reduce continuously and permanently the rate of deforestation, as well as forest fires and wildfires in the Cerrado. In 2014, it launched the second phase of the plan in order to guide the actions, in addition to ratifying the importance of the conservation of the natural resources of the region. An essential element of the plan is the National Policy on Climate Change, Law Nº 12.187/2009, which seeks the reduction of greenhouse gas emissions in the atmosphere. It also established a goal of 40% reduction in the deforestation rate in the biome.

Table 1 – Municipalities of the Cerrado 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).

The intensive occupation of MATOPIBA for agricultural production began in the 1980s, and this process is not yet completed. This is due to the existence of much underutilized land, where low-productivity techniques are adopted. The very conditions of the region facilitate this process of occupation, such as: good climate for agriculture, flat land that enables the adoption of machinery to enhance land productivity, cheap labor and low price of land. In addition, many spaces are not 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; VALLADARES, 2009; STUDTE, 2008; BOLFE et al., 2016; BRAGANÇA, 2018; ARAÚJO et al., 2019).

The low price of land and the easy adoption of mechanized and large-scale agriculture have attracted labor along with investments in capital, which have intensified their occupation, resulting in a significant growth in local production, mainly of grains such as soybeans and maize (MIRANDA et al., 2014; ASSUNÇÃO; BRAGANÇA, 2015; BRAGANÇA, 2018; ARAÚJO et al., 2019). However, according to Garcia and Vieira Filho (2018), approximately 68% of the agricultural expansion in the region between 2002 and 2014 was due to the conversion of native areas.

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; 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 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 inadequate soil management, which causes their progressive degradation, resulted in approximately 9 million hectares of area with moderate degree of desertification and 591,000 hectares with high degree.

The agricultural frontier expansion in MATOPIBA, however, faces some natural challenges, especially in areas transitioning into the Caatinga biome. A transition area normally presents diverse ecosystems and climatic conditions and lower natural fertility. The soybean, for example, is not suitable in regions with annual average rainfall below 1000 mm, 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 soybeans that support rainfall between 800 and 1000 mm. However, this technological innovation could boost deforestation along with the agricultural production in MATOPIBA (ARAÚJO et al., 2019).

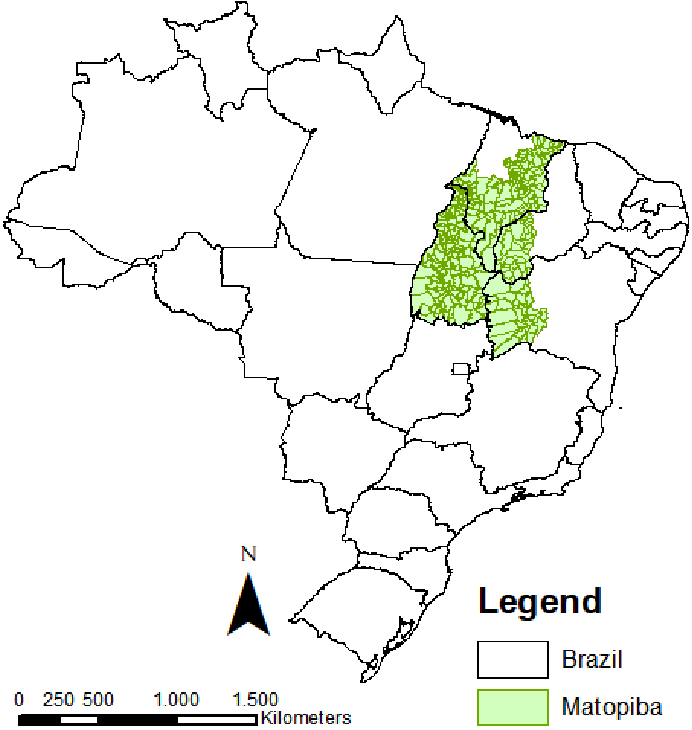
Considering the expansion of the agricultural frontier and the economic development of MATOPIBA, the present paper aims to investigate their relationship with deforestation.

3 Methodology

3.1. Database and region covered

The Brazilian Agricultural Research Corporation (Embrapa) elaborated the MATOPIBA boundary delimitation, having as its main criterion the presence or not of the Cerrado in the four states, as well as other socioeconomic factors, which resulted in 337 municipalities comprising 31 microregions with an area of 73 million hectares. Among the MATOPIBA states, the one with the largest area is Tocantins, with 37.95% of the total (139 municipalities), followed by Maranhão, with 32.77% (135 municipalities), Bahia, with 18.06% (30 municipalities) and Piauí, with 11.21% (33 municipalities) (EMBRAPA, 2017). Figure 1 brings the MATOPIBA location within the Brazilian territory.

Figure 1 – MATOPIBA* Location in Brazil



Source: Research data.
Note: * The shaded area refers to the 337 municipalities of MATOPIBA.

According to the Ministério da Agricultura (2017), The MATOPIBA region reached an 11% share of the total produced by Brazilian agribusiness in 2015. Recognizing the region’s strategic importance for the future of the country's agribusiness, the Brazilian government created the Decree No. 8447 in 2015 with the main objective of establishing an agricultural development plan for MATOPIBA aiming to guide Federal projects specifically for the region (BRASIL, 2015)

According to the population census held by IBGE (2010), MATOPIBA has about 6 million inhabitants, and 35% reside in the rural area, considerably above the Brazilian average of 15.3%. Among the states in the region, the most populous is Maranhão, with 57.6% of the total, followed by Tocantins (25.30%), Bahia (12.72%), and Piauí (4.75%). In relation to the income, the region had a per capita income of only 40% of the Brazilian average in 2010 – R$8,000 in MATOPIBA against R$19,878.00 for Brazil. However, if considering only Tocantins and Bahia, the percentage would go up to approximately 60% of the national average (BOLFE et al., 2016).

The data used concerning the deforestation of the Cerrado in the MATOPIBA region were obtained in the 2010 Technical Report on the Monitoring of Deforestation in the Cerrado Biome from

IBAMA, the Brazilian Institute of the Environment and Renewable Natural Resources. The deforestation variable (DEFOREST) is used as a proxy for environmental degradation, the dependent variable on the EKC model for the 337 municipalities of MATOPIBA. We consider 2010 as a reference year for deforestation, as well as for all the explanatory variables. We used this timeframe due to the limitation of disaggregated data for the municipalities of the region, which made it impossible to have a more extensive temporal analysis. For the economic development proxy, we used the HDI variable, in line with the methodological advances in the estimation of EKC in the literature (HILL; MAGNANI, 2002; JHA; MURTHY, 2003; COSTANTINI; MONNIM, 2008; STIGLITZ et al., 2009; COSTANTINI; MARTIGINI, 2010; KUBISZEWSKI et al., 2013; NEVE; HAMAIDE, 2017).

We included the HDI in a square and cube format in the estimations to investigate the existence of other formats for EKC, i.e., a quadratic or cubic function. The variables described above, as well as the other explanatory variables used in this paper, are displayed in Table 2. The inclusion of the variables aimed to improve the specification of the econometric model, as well as to better structurally represent the region and identify possible relationships that they may have with deforestation. In addition to the variables directly linked to the agricultural frontier expansion, we also consider some geographic and structural features for control purposes. Among them, we used some vector data to construct the variables specifically to this empirical design: ROADS, RAINFALL, SOIL, FEDERAL.RES and INDIGN.RES. We construct the measures using the spatial joint tool in the GIS software (ArcMap 10.3). Some explanations, however, are worth mentioning.

Table 2 – Description of variables, all for 2010

Variables	Description	Unit	Source
DEFOREST	Deforested area	Ha	IBAMA
HDI	Human Development Index (HDI)	cent	IPEA
HDI^2	HDI Squared		-
HDI^3	HDI Cubed		-
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 crop area	Ha	SIDRA/IBGE
SUGARCANE	Sugarcane Productivity	kg/ha	SIDRA/IBGE
MAIZE	Maize Productivity	kg/ha	SIDRA/IBGE
SOYBEAN	Soy Productivity	kg/ha	SIDRA/IBGE
ROADS	Length of roads	Km	MAPBIOMAS
RAINFALL	Average annual precipitation	Mm	CPRM
SOIL	Good or regular suitability of soil 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 constructed using the Map of Brazilian Agricultural Potential compiled by the Brazilian Institute of Geography and Statistics (IBGE) and made available by the Ministry of the Environment. The Brazilian territory was classified according to the agricultural potential of its soils, considering: 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 MATOPIBA map, we identified the predominant type of soil that exists in the municipalities. Finally, we created a binary variable, in which the number 1 was assigned to municipalities with i) good or regular soil and 0 for 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 MATOPIBA, caused by the conversion of forests into arable areas, is occurring in municipalities with greater agricultural potential.

The RAINFALL variable is composed of average annual precipitation data (1977 to 2006), from the national hydrometeorological network, compiled by the *Companhia de Pesquisa de Recursos Minerais* (CPRM, 2018) and made available by the Pluviometric Atlas of Brazil. The ROADS variable refer to the length of state and federal highways in a given municipality in kilometers. The data vector are made available by the Mapbiomas project, using data provided by the Brazilian government. We obtained information on protected areas, which generated the binary variables FEDERAL.RES, STATE.RES and INDIGN.RES, from the Center for Remote Sensing of the Federal University of Minas Gerais (CSR-UFMG). Joining the MATOPIBA 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.

3.2. Descriptive statistics

In order to investigate the characteristics of MATOPIBA municipalities and the changes in the period, Table 3 reports the descriptive statistics for the variables used in the EKC model. In terms of deforestation, there was an average of 15,91 ha of cleared area in 2010 and 5,360 ha in all the MATOPIBA region. Regarding forest cover, in turn, 60% of the total area was comprised of forest remnants, with some municipalities having 98% of their area composed of native forests. The variables related with economic development, as HDI and per capita GDP, the averages were 0.61 and R$7,359.64. In addition, there was a considerable difference in the characteristics of the municipalities when considering the maximum and minimum values, which may reflect variances in the occupation stage.

Table 3 - Descriptive statistics

Variable	Mean	Std. Dev.	Min	Max	Total
DEFOREST	15.91	26.25	0.00	227.34	5,360.80
HDI	0.61	0.05	0.44	0.79	-
GDP	7,359.64	5,817.02	2,292.04	52,736.02	2,480,199.95
RURAL CREDIT	11,500,000.00	37,700,000.00	5,045.52	485,000,000.00	3,872,740,512.53
DEM.DENSITY	13.43	18.56	0.23	180.79	-
AGRIC.GDP	30.07	14.78	0.62	74.86	-
CATTLE	44,540.95	46,843.11	1,300.00	423,650.00	15,010,299.00
CROP	12,573.65	37,616.84	68.00	441,164.00	4,237,320.00
SUGARCANE	22,048.66	21,816.03	0.00	100,000.00	-
MAIZE	2,048.35	1,716.39	85.00	8,617.00	-
SOYBEAN	1,020.65	1,317.37	0.00	3,449.67	-
ROADS	149.77	101.40	7.50	623.70	50,472.79
RAINFALL	1,456.08	277.71	800.00	2,100.00	-
FOREST.COVER	0.60	0.20	0.04	0.98	-

Source: Research data.

We can also highlight some total values for MATOPIBA, which are related with the region of agricultural frontier expansion. The offer of rural credit reached a value of approximately R$3.8

billion. The size of the cattle herd and crop area, in turn, reached 15 million heads and 4.2 ha, respectively. Finally, the length of roads totaled 50,472 km². A recurrent problem in the EKC model is multicollinearity, which can invalidate statistical inferences. The Appendix A shows the correlation between the variables used. From them, we can notice no extremely high correlations that could compromise the estimation of the EKC model, with the exception of the CROP and RURAL.CREDIT variables.[1] Therefore, we included only crop area in the econometric model.

3.3. Exploratory Spatial Data Analysis (ESDA) and spatial econometrics

The Exploratory Spatial Data Analysis (ESDA) is a technique used to identify spatial effects, specifically those of spatial dependence and heterogeneity. Both, if identified, should be treated to avoid problems in econometric models, such as bias and inconsistency (ALMEIDA, 2012). Moran's I statistic seeks to capture the spatial autocorrelation between a variable across the regions. The expected value of this statistic is $E(I) = -1/(n-1)$ and statistically larger (minor) values, relative to expected, indicate positive spatial autocorrelation (negative). Mathematically, we have

$$I_t = \left(\frac{n}{S_0}\right)\left(\frac{z_t' W z_t}{z_t' \, z_t}\right) \quad t = 1, \dots n \tag{1}$$

where n is the number of regions, S_0 is a value equal to the sum of all elements of W, z is the value of the standardized variable analyzed, and Wz is the average value of the standardized variable in the neighbors according to a weighting matrix W. The local Moran's I (LISA), in turn, is

$$I_i = z_i \sum_{j-1}^{J} w_{ij} \, z_j \tag{2}$$

where z_i represents the region's i standardized variable, w_{ij} is the element of the spatial weighting matrix (W) and z_j is the standardized variable of region j.

The spatial component is incorporated into the econometric model with spatially lagged variables. It is possible to propose a general spatial model that, by imposing restrictions on parameters, allows to obtain the desired specifications. Such model is

$$\begin{gathered} y = \rho W y + X\beta + WX\tau + \xi \\ \xi = \lambda W \xi + \varepsilon \end{gathered} \tag{3}$$

where X is the matrix of explanatory variables; β is the vector $k \times 1$ of regression coefficients; ε is the error term with average zero and constant variance.

The Spatial Autoregressive Model (SAR) is obtained by imposing the following restrictions on the model (3): $\rho \neq 0,\ \tau = 0$ and $\lambda = 0$. The SAR model seeks to capture the spatial autocorrelation effects of the dependent variable between neighboring units. Therefore, it is included as an explanatory variable in the econometric model the spatially lagged dependent variable ($\rho W y$), which can be interpreted as the average value of that variable in neighboring units. In this paper, the SAR model seeks to identify if the deforestation rate of a given municipality is influenced by the value of that variable of its neighbors, determined according to a spatial weight matrix. If we get a significant $\rho > 0$, we have a positive spatial autocorrelation, while $\rho < 0$ is a negative spatial dependence. The model will suffer from the endogeneity problem of the lagged variable; therefore, it should be estimated with instrumental variables, which are the lagged explanatory variables (WX).

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

The Spatial Error Model (SEM) emerges if $\rho = 0,\ \tau = 0$ and $\lambda \neq 0$ when spatial dependence manifests itself in the error term. The closer to one the parameter λ is, greater is the effect of this shock on the neighborhood. The estimation by OLS is not adequate, because the error bias makes the model parameters inefficient. According to Kelejian and Prucha (1999), we should estimate the model with maximum likelihood estimation (MLE) or by the generalized method of moments (GMM). The Spatial Lag of X Model (SLX) occurs when $\rho = 0,\ \tau \neq 0$ and $\lambda = 0$. The model seeks to capture the spatial spillovers from the independent variables, using a matrix of spatial weights W as a spatial lag operator. This lag is exogenous because the variables are determined outside the model. For this reason, the model does not present an endogeneity problem, thus it is possible to estimate by OLS.

The Spatial Durbin Model (SDM) and the Spatial Durbin Error Model (SDEM) are a combination of the previous ones. The SDM occurs when $\rho \neq 0,\ \tau \neq 0$ and $\lambda = 0$, with the spatial autocorrelation in the dependent and the explanatory variables. The SDEM, in turn, means $\rho = 0,\ \tau \neq 0$ and $\lambda \neq 0$, when spatial dependence manifests itself in the explanatory variables and the error term. The model choice, however, is not arbitrary, because the spatial effects can manifest in just one of the forms, in some combination of them or even in all. The chosen model that is able to minimize the spatial autocorrelation in the residuals of the models, following Almeida (2012), will be identified ahead.

3.4. Empirical strategy

In this paper, the deforested MATOPIBA area is included as a dependent variable in the EKC model. The municipalities' HDI levels are used as a proxy for the level of economic development. In addition, to better verify the relationship between environmental degradation and economic development, we estimate EKC with quadratic and cubic forms. Therefore, the general equation is

$$DEFOREST_i = \beta_0 + \beta_1 HDI_i + \beta_2 HDI^2{}_i + \beta_3 HDI^3{}_i + \varepsilon_i \tag{4}$$

where $DEFOREST$ is the percentage of deforested area of the Cerrado in municipality i; HDI is the Human Development Index. The incorporation of additional explanatory variables is important to avoid the problem of omission of relevant variable. Therefore, geographical, structural and agricultural variables are included, as in Table 2. Hence, in a general form, the model is

$$DEFOREST_i = \beta_0 + \beta_1 HDI_i + \beta_2 HDI^2{}_i + \beta_3 HDI^3{}_i + \beta_k Z_i + \varepsilon_i \tag{5}$$

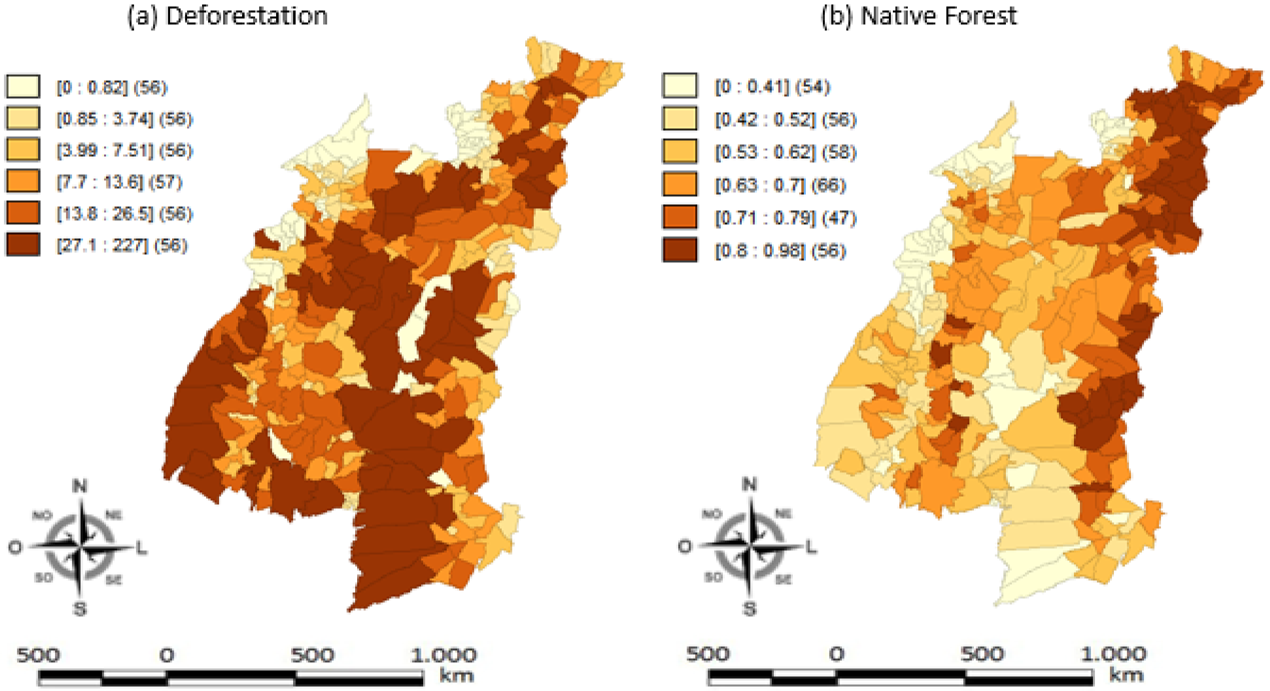
where Z is a matrix with the k of additional explanatory variables included in the model.

The EKC format is related to the signs and significance presented by the coefficients $\beta_1, \beta_2\ and\ \beta_3$ in the model (6). It is a sufficient condition for the curve to present a linear shape when we get a significant $\beta_1 > 0$ or $\beta_1 < 0$, while $\beta_2\ and\ \beta_3$ are not. In this configuration, an increase in the HDI is linearly related to deforestation. For the inverted-U shape, it is sufficient that $\beta_1 > 0, \beta_2 < 0$, while for the U shape, $\beta_1 < 0, \beta_2 > 0$; both significant while β_3 is not. Finally, the cases in which $\beta_1 > 0$, $\beta_2 < 0$ and $\beta_3 > 0$ or $\beta_1 < 0$, $\beta_2 > 0$ and $\beta_3 < 0$, being all statistically significant, display necessary and sufficient conditions for a N shape or inverted-N shape, respectively.

4. Results and discussion

To verify the relationship between deforestation and forest cover, Figure 2 shows the spatial distribution of deforestation (Figure 2a) and native forest remnants (Figure 2b). The municipalities with high cleared area (Figure 2a) are concentrated especially in western Bahia, the central area of MATOPIBA, southwest of Tocantins 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 of soybeans, resulting in significant increases in their production and yield after the 2000s. According to the authors, this phenomenon may be one of the explanations for the recent deforestation in the region.

Figure 2 - Distribution of deforestation (a) and native forest (b) in MATOPIBA.



Source: Research data.

Regarding the native forests (Figure 2b), we can see that most of the municipalities with more than 80% of their territory covered by forests are located east, in transition areas with the Caatinga biome. According to Araújo et al. (2019), a transition area normally presents diverse ecosystems and climatic conditions and lower natural fertility. In addition, the authors argue that soybean cultivation, the main driver of occupation in MATOPIBA, is suitable only in areas with annual average rainfall above 1000 mm, which does not occur in Cerrado areas near the semi-arid region. Therefore, the future agricultural expansion in this region depends on the development of new varieties of soybeans that support rainfall between 800 and 1000 mm and, if this occurs, we can expect profound land use changes with reductions in forest cover.

The spatial concentration of deforestation is visible in Figure 2, indicating the existence of patterns, which may result in spatial dependence and heterogeneity. To verify this hypothesis, Table 4 presents Moran's I statistic, according to several spatial matrix conventions. We confirm the existence of spatial dependence for deforestation, regardless of the convention adopted, indicating that deforestation tends to be spatially concentrated. Theoretically, this may result from spatial spillovers, which stem from productive links and concentration of human and physical capital.

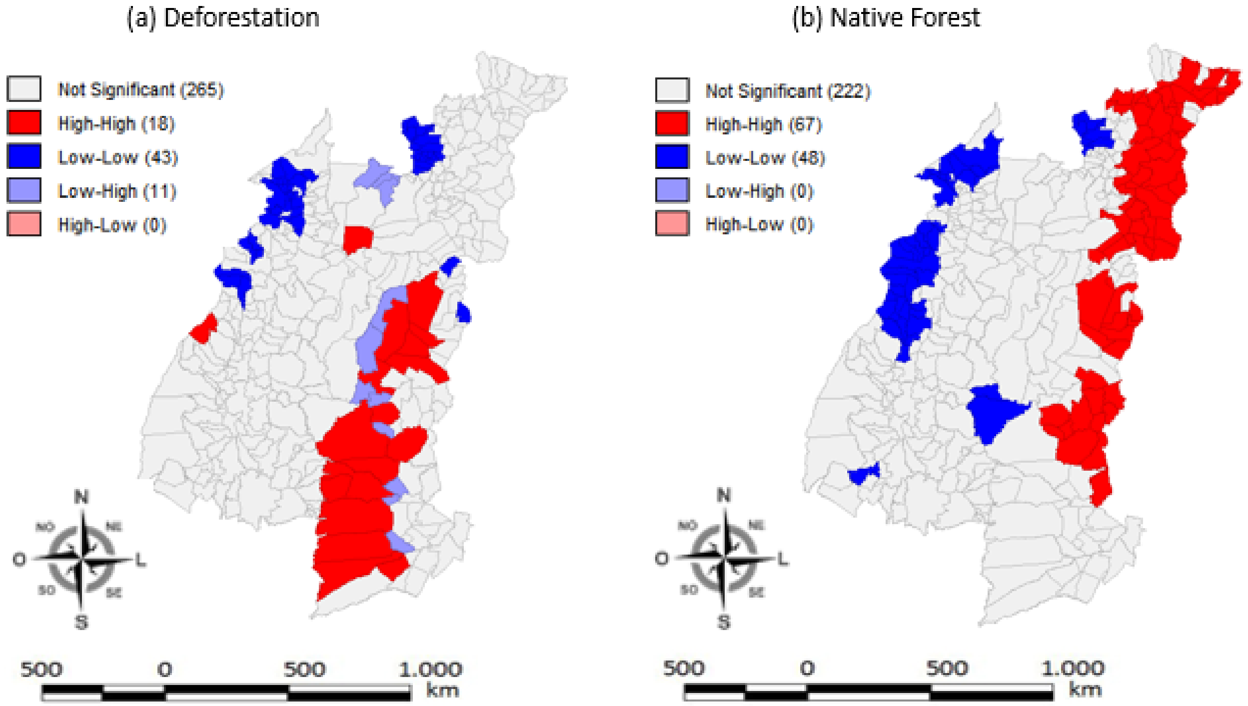
Table 4 - Moran's I for deforestation in MATOPIBA

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
Deforestation	0.29*	0.30*	**0.31***	0.22*	0.22*	0.15*

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

Figure 3 shows the LISA maps of spatial clusters for deforestation. It presented two significant High-High clusters for deforestation (Figure 3a): one in western Bahia and the other in the Southwest of Piauí. For the native forest (Figure 3b), we have spatial clusters located especially in the east transitional areas with the semi-arid biome. Therefore, the clusters presented a similar spatial pattern to Figure 2, corroborating the arguments of Araújo et al. (2019).

Figure 3 – LISA maps for deforestation (a) and native forest (b) in the MATOPIBA



Source: Research data.

Regarding the Environmental Kuznets Curve, we estimated the model in its quadratic and cubic versions using the classical linear regression model estimated by the OLS method. Table 5 presents the estimations.[2] This procedure is necessary to verify the existence of spatial dependence, captured by the Moran's I of the residuals, which are significant for all estimated models in Table 5.

The best model estimated, according to the Akaike information criterion, is one that incorporates a quadratic relationship between the HDI and deforestation, i.e., the HDI (2). Therefore, this model will be the base for the following analyses and we confirm that the HDI is a better proxy for economic development in line with Hill and Magnani (2002), Jha and Murthy (2003), Costantini and Monni (2008), Costantini and Martini (2010), and Lamb and Rao (2015). Since deforestation, agricultural and geographic variables usually suffer from spatial interactions, 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 (ALMEIDA, 2012). Therefore, the next step is to estimate HDI (2) by incorporating spatially lagged variables, aiming to control spatial dependence in the residuals.

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 rejected the homoscedasticity hypothesis, indicating the presence of a non-constant variance in the residuals. The spatial models in Table 6, due to the non-normality in the residuals, are estimated with the Generalized Method of Moments of Kelejian and Prucha (1999). In addition, White's robust error (WHITE, 1980) is employed in the SAR, SLX and SDM models, and the robust error of Kelejian and Prucha (1999) for models SEM and SDEM, both aiming to control the presence of heteroscedasticity.

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[2] The software used to estimate the models was GeoDaSpace, made available by the Center for Spatial Data Science – University of Chicago.

In addition, we chose the spatial lag matrix that generated the largest Moran's I coefficient for the HDI (2) residues (Appendix B) to estimate the spatial models, opting for the rock matrix.

Table 5 – Econometric results for the EKC estimated with OLS

	HDI (2)	HDI (3)	PIB(2)	PIB (3)
CONSTANT	-180.1141***	-180.5291***	-11.6019**	-9.7553*
HDI	587.5692***	601.7303**	-0.0001	-0.0008
HDI²	-511.8558***	-558.5114**	0.0000	0.0000
HDI³		39.5611		0.0000
DEM.DENSITY	-0.0815	-0.0840	-0.1180**	-0.1153**
AGRIC.GDP	-0.0562	-0.0548	-0.0061	0.0001
CATTLE	0.0001***	0.0001***	0.0001***	0.0001***
CROP	0.0004***	0.0004***	0.0004***	0.0004***
SUGARCANE	0.0001**	0.0001**	0.0001*	0.0001*
MAIZE	0.0014*	0.0014*	0.0013	0.0015*
SOYBEAN	0.0006**	0.0006**	0.0006**	0.0006**
ROADS	0.0273***	0.0273***	0.0223**	0.0232**
RAINFALL	0.0020	0.0020	0.0016	0.0016
SOIL	-1.1945	-1.1981	-1.5379	-1.4392
FEDERAL.RES	6.5379**	6.5600**	7.1074***	7.0777***
ESTATE.RES	-0.4191	-0.5988	-1.2974	-1.4553
INDIGEN.RES	-1.0752	-1.1256	-1.5783	-1.7170
FOREST.COVER	14.3776***	14.4532***	15.9287***	15.8401***
Akaike	2818.953	2820.911	2826.123	2827.512
Jarque-Bera	4267.002***	4248.649***	4442.388***	4552.182***
Koenker-Bassett	60.185***	60.765***	56.194***	56.521***
Moran's I	0.135***	0.134***	0.124***	0.122***

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

According to Almeida (2012) and Raiher and Candido (2018), the best spatial model is the one that minimizes the spatial autocorrelation in the residuals. Therefore, considering Moran's I in the EKC spatial model residuals (Appendix B), the SLX and SDEM models presented the lowest coefficients for this statistic, indicating that they are the models that best controlled the spatial dependence problem. In other words, the approach, by incorporation relevant spatial spillovers related to deforestation and the agricultural frontier expansion, was able to minimize spatial dependence.

However, in the SDEM model in Table 6, the spatial lag of the error term ($W\xi$) did not presented statistical significance, indicating that only the spatial spillovers from the explanatory variables are important to explain deforestation in MATOPIBA. In any case, all the statistical significant variables in the SLX and SDEM models are the same and the coefficients are similar, indicating the robustness of the results. In addition, according to Almeida (2012), structural stability in the model parameters is a sign that the spatial heterogeneity is not present in an extent that invalidates the results. In this context, we considered the SLX model in the following analyses.

Since the quadratic models have statistically significant economic development proxies with coefficients, $\beta_1 > 0, \beta_2 < 0$, we have an inverted-U relationship between deforestation and development in MATOPIBA. This fact demonstrates that deforestation will increase until a certain threshold as the region develops, from which it shall begin to fall, in line with Grossman and Krueger (1991; 1995). In addition, we can cite the robustness of the results, because all the models that included the HDI in their linear and quadratic forms had significant coefficients. This empirical evidence differs from Colusso et al. (2012), who identified an N-shaped relationship when analyzing the whole biome, which highlights that MATOPIBA may present different characteristics regarding the impact of economic development on the environment.

Table 6 – EKC spatial models for MATOPIBA

Variables	SAR	SEM	SLX	SDM	SDEM
CONSTANT	-121.2634**	-151.3787***	-145.5197***	-164.9267***	-150.2584***
HDI	388.1051**	472.5044***	489.7202***	544.7760***	501.1248***
HDI^2	-337.4297**	-396.9236***	-427.8252***	-458.1134***	-434.3899***
DEM.DENSITY	-0.1046***	-0.0647***	-0.0574*	-0.0609**	-0.0554*
AGRIC.GDP	-0.0213	0.0032	-0.0758	-0.0572	-0.0652
CATTLE	0.0001**	0.0001**	0.0001**	0.0001**	0.0001**
CROP	0.0003***	0.0003***	0.0003***	0.0003***	0.0003***
SUGARCANE	0.0001**	0.0000	4.16E-05	2.79E-05	3.71E-05
MAIZE	0.0013	0.0012	0.0022**	0.0021**	0.0021**
SOYBEAN	0.0004**	0.0003	0.0003	0.0002	0.0003
ROADS	0.0210**	0.0234***	0.0236***	0.0265***	0.0246***
RAINFALL	0.0015*	0.0009	0.0005	0.0003	0.0005
SOIL	-1.0668	-0.8967	-1.0048	-1.0166	-0.9441
FEDERAL.RES	7.4203**	6.9657**	8.1435***	7.5392***	8.1312***
ESTATE.RES	5.3336	4.5345	5.6590	5.9516	5.7087
INDIGEN.RES	-4.6199	-4.3685	-5.7509	-6.0728*	-5.7100
FOREST.COVER	18.5311***	16.4407***	17.2549***	17.1812***	16.8820***
D_OUTLIER	54.9167***	50.9545***	54.6023***	52.9212***	53.3676***
ρ	-0.1581	-	-	0.2890**	
λ	-	0.2748**	-		0.1838
W_DEM.DENSITY			-0.1242**	-0.0651	-0.1150**
W_AGRIC.GDP			0.0583	0.0456	0.0483
W_CATTLE			3.90E-06	-8.90E-06	5.60E-06
W_CROP			-0.0001**	-0.0002***	-0.0001**
W_SUGARCANE			0.0001**	0.0001	0.0001**
W_MAIZE			-0.0018	-0.0018	-0.0016
W_SOYBEAN			0.0003	0.0001	0.0003
W_ROADS			-0.0167	-0.0240*	-0.0184
W_RAINFALL			0.0022	0.0013	0.0020
W_FORES.COVER			-4.4538	-8.4427	-4.3892

Source: Research results. *Note:* *** Significant at 1%; ** Significant at 5%. * Significant at 10%.
D.OUTLIER is a dichotomous variable for the municipalities comprised of leverage points detected in the ESDA, that is, they reinforce the deforestation pattern observed.[3]

According to Grossman and Krueger (1991; 1995), at low development levels, growth initially causes a scale effect by increasing the use of natural resources, which leads to deforestation. However, after a "turning point"[4], the composition and technical effects become large enough to mitigate the scale effect, reducing environmental degradation. Considering the results for the SLX model in Table 6, the turning point for MATOPIBA is an HDI level of 0.57, slightly below the region's average of

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[3] Oliveira et al. (2011) proposed the procedure for deforestation in the EKC model for Legal Amazon, which improved econometric estimates.

[4] A region where the curve reaches its maximum value. We can obtain the "turning point" with: $\tau = -\beta_1/2\beta_2$.

0.61. Therefore, 71.82% of the municipalities in the current Brazilian agriculture frontier have an HDI above the turning point, which indicates that deforestation will decrease its pace as development increases. On the other hand, we still have a trade-off between development and forest conservation for the remaining 28.18% that are below the turning point, since their development will boost deforestation.

In addition, we highlight the statistical significance in the SLX model for the following additional variables: demographic density, cattle herd, crop area, maize productivity, length of roads, Federal Reserve and forest area. Regarding the spatial spillovers from the agricultural frontier expansion, we have demographic density, crop area and sugarcane productivity with statistical significance. With the exception of demographic density and spillovers from crop area, all the variables presented a positive relationship with deforestation, with its increase leading to deforestation in MATOPIBA.

The length of roads has a positive impact on deforestation in MATOPIBA. One possible explanation is that the expansion of the road network allows access to previously isolated areas by creating corridors to the region, reducing transportation costs and pushing the agricultural frontier further by intensifying the migration and occupation of the territory, which causes deforestation (ASSUNÇÃO; BRAGANÇA, 2015; BRAGANÇA, 2018; ARAÚJO et al., 2019). This empirical evidence is an important contribution to the literature on deforestation in Brazil, since there are no papers that have address this issue for this region directly.

Cattle herd is also an important deforestation inductor in MATOPIBA. According to Bragança (2018), this phenomenon is explained mainly by changes in land use due to the advancement in the cultivation of soybeans and sugarcane in recent periods in Brazil, which has adopted more technologically advanced inputs, with greater potential to generate profits. This has led to a displacement of cattle ranching to agricultural frontier regions with lower land prices, causing deforestation.

Crop area presented a positive statistical significance and a negative spillover for Matopiba. Garcia and Vieira Filho (2018) argue that its expansion – for soybeans in particular – is occurring in a considerable part due to forest area reduction, especially at the agricultural frontier. According to the authors, 68% of the agricultural expansion in Matopiba between 2002 and 2014 was due to the conversion of native areas. On the other hand, empirical evidence suggests that crop area expansion in a municipality diminishes its neighbor's deforestation in a negative spatial spillover effect. Productivity spillovers from maize and sugarcane presented significant positive impact on deforestation in MATOPIBA. One possible reason is that both crops recently gained market value due to the increase of national and international demand for animal feed and biodiesel, which resulted in high profitability and environmental degradation.

Demographic density and its spatial spillovers, in turn, presented a statistically significant negative sign, indicating that less densely populated municipalities tend to be deforested more than those with large demographic density. This result contradicts those found by Grossman and Krueger (1995) and especially those by Cropper and Griffiths (1994), who used deforestation as an indicator of environmental degradation. On the other hand, in the Brazilian context, in Oliveira et al. (2011) and Colusso et al. (2012), the demographic density variable did not present statistical significance, indicating that it may not be relevant to explain deforestation in the country. Despite this, the results found in this paper highlight a different characteristic for the MATOPIBA region.

The remaining forest cover in the municipalities is statistically significant, indicating that higher deforestation is associated with greater proportion of native forests. This fact makes logical sense, since some municipalities may deforest less because they do not have much remaining forest area to do it. In addition, a higher proportion of forests is related to regions where agricultural activities, basic infrastructure and migratory attraction have not reach their full potential yet (BOLFE et al., 2016; ZANIN; BACHA, 2017; ARAÚJO et al, 2019). In other words, the growth of these factors translates into the agricultural frontier expansion, which is the main environmental degrader in the Cerrado (GARCIA and VIEIRA, 2018). In addition, according to IBAMA (2010), only 7.44% of the Cerrado biome territory is comprised of conservation units, which has served to aggravate deforestation. However, in the MATOPIBA regime, the Federal Reserve variable presented a significant positive impact, contradicting the idea that conservation units act as inhibitors of deforestation. This demonstrates a need for an expansion of government supervision over conservation areas in MATOPIBA, since the status granted to these localities does not serve to hold back deforestation.

It is worth mentioning that the characteristics of the soil in the MATOPIBA region do not affect land use changes. In other words, deforestation occur regardless of the soil being suitable or not for agricultural production, corroborating Bolfe et al. (2016), who point out that a considerable part of the forest conversion in MATOPIBA did not occur on soil with agricultural suitability.

5. Final considerations

This paper aimed to investigate the relationship between human development and environmental degradation at the current Brazilian agricultural frontier, a region known as MATOPIBA. The hypothesis used is the Environmental Kuznets Curve, which states that the level of environment degradation increases with economic development initially, but, after a certain level, the relationship reverses, with an increase in development leading to a reduction of degradation.

The municipalities with high cleared area in MATOPIBA are concentrated especially in western Bahia, the central area of the region, southwest of Tocantins and the northern part of Maranhão. These regions have undergone an intense modernization of their agricultural activity, especially related to soybeans, resulting in significant increases in their production and yield after the 2000s. In addition, we confirm the presence of spatial dependence for deforestation, indicating that it tends to be spatially concentrated, which leads to the adoption of spatial econometrics.

The dependent variable used as a proxy for environmental degradation is the deforestation of the Cerrado in the MATOPIBA region for the year 2010. In addition, we used the Human Development index (HDI) as a proxy for economic development, which is considered more appropriate to represent development when compared to per capita income, usually adopted by the literature, according to methodological advances in the estimation of EKC. The explanatory variables included in the EKC model, in addition to the HDI in its linear, quadratic and cubed form, are: cattle herd, demographic density, productivity of maize, sugarcane and soybeans, crop area, agricultural participation in the GDP, length of roads, average annual precipitation, soil suitability, and presence of federal, state and indigenous reserve, all set at the municipal level.

Initially, we estimated the models using conventional econometric techniques to identify the presence of spatial effects in the residuals. We also estimated several spatial models in order to verify the robustness of the results: SAR, SEM, SLX, SDM and SDEM. The model that best captured the EKC relationship, according to Moran's I in the spatial model residuals, are the Spatial Lag of *X* Model (SLX), since it is the one that minimizes spatial dependence. In the estimations, we found an inverted-U shape for the EKC, corroborating the initial hypothesis on economic development and environmental degradation for the current Brazilian agricultural frontier. Therefore, human development, although leading to deforestation initially, induces a sustainable development after a certain level. The turning point of the EKC curve, where economic development reaches its maximum impact on the environment, is an HDI level of 0.57, which is slightly below the region's average of 0.61. Therefore, 71.82% of the municipalities in the current Brazilian agriculture frontier have an HDI level above the turning point, which indicates that deforestation will decrease its pace as these municipalities develop. On the other hand, there is still a trade-off between development and forest conservation for the remaining 28.18% of municipalities that are below the turning point. These highlights environmental concerns for the region, since its development could boost degradation in these underdeveloped municipalities

To worsen this scenario, we identified many variables, especially related to the expansion of the agricultural frontier in MATOPIBA, which affect the environment negatively. Among the main influences, we have the expansion of roads, which attracts migratory waves and agricultural activities due to its cost reduction, cattle herd, crop area, maize productivity, Federal Reserve and forest area. Regarding the spatial spillovers from the agricultural frontier expansion, demographic density, crop area and sugarcane productivity are statistically significant. With the exception of demographic density and spillovers from crop area, all these variables presented a positive relationship with deforestation, with their increase leading to deforestation in MATOPIBA.

The empirical evidence from this paper can help to identify the determinants and possible outcomes of deforestation in MATOPIBA and to construct specific agricultural and environmental policies that consider idiosyncratic characteristics of the region along with spatial effects. However, some possible limitations of the present paper are worth mentioning. For example, the IBAMA database adopted here has a limited timeframe, which makes the deforestation phenomenon in MATOPIBA difficult to analyze more broadly. In addition, we recommend the adoption of alternative methodologies, such as the Geographically Weighted Regression (GWR), in order to map the local effects of the agricultural frontier expansion in the region.

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Appendices

Appendix A – Correlation for the variables

	HDI	GDP	MAIZE	R.CREDIT	SOY	CANE	CROP	AG.GDP	CATTLE	RAINF	ROADS	F.COVER	D.DENS
HDI	1												
GDP	0.4477	1											
MAIZE	0.2722	0.6058	1										
RURAL CREDIT	0.0877	0.4884	0.5465	1									
SOYBEAN	0.1892	0.4443	0.5305	0.2838	1								
SUGARCANE	0.1038	0.1041	0.2467	0.1945	0.1411	1							
CROP	0.0446	0.5382	0.6052	0.922	0.3312	0.2123	1						
AGRIC.GDP	-0.1764	0.1274	0.3115	0.1792	0.2613	-0.0492	0.2155	1					
CATTLE	0.4196	0.2309	0.1474	0.188	0.0895	0.034	0.0458	0.1268	1				
RAINFALL	0.34	0.1321	-0.0166	-0.0732	0.046	-0.2678	-0.1092	0.1401	0.2084	1			
ROADS	0.2639	0.2789	0.3705	0.3543	0.3013	0.2051	0.3495	-0.0494	0.3107	-0.0535	1		
FOREST.COVER	-0.3541	-0.2657	-0.2297	-0.1029	0.0143	0.2162	-0.0529	-0.1635	-0.3938	-0.3668	0.0223	1	
DEM.DENSITY	0.1105	-0.1385	-0.2566	-0.0955	-0.2702	0.0174	-0.0879	-0.3119	-0.0814	0.0805	-0.1257	-0.0058	1

Source: research results.

Appendix B - Moran's I for the EKC Models - convention matrix decision

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
HDI (2)	0.126*	**0.135***	0.126*	0.046	0.069*	0.035
HDI (3)	0.126*	**0.134***	0.126*	0.046	0.069*	0.035
PIB (2)	0.116*	**0.124***	0.111*	0.050	0.069*	0.038
PIB (3)	0.113*	**0.122***	0.107*	0.051	0.069*	0.037

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

Appendix C - Moran's I for the ECK Spatial Models residuals

	Weights Matrix					
	Queen	Rook	Three neigh.	Five neigh.	Seven neigh.	Ten neigh.
SAR	0.08	0.08	0.04	0.01	0.07*	0.04
SEM	0.12*	0.13*	0.07*	0.03	0.08*	0.05
SLX	0.06	0.06	0.03	0.06*	0.06	0.04
SDM	0.07	0.08	0.04	0.01	0.07*	0.04
SDEM	0.07	0.08	0.03	0.00	0.06*	0.04

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