The Environmental Impacts of the Agricultural Frontier Expansion in the Cerrado, Brazil

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Abstract: This paper 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 in the specialized literature. i) The Socioeconomic Development Index creation to replace per capita income as proxy for economic development; ii) the omitted-variable bias problem consideration, especially from spatial spillovers; iii) and spatial regimes adoption for heterogeneity control. From the spatial EKC model, we get an inverted U-shaped relationship between development and deforestation for both regimes. After considering indirect spatial effects, more than 50% of Matopiba and 30% of Non-Matopiba municipalities are lower development than the maximum turning point, which highlights environmental concerns, since economic growth could boost deforestation. The roads network 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. Finally, heterogeneity, spatial interactions and displacements effects present in Cerrado are important to understand land use changes in Cerrado and can help policymaking design by considering possible different outcomes.

Keywords: Land Use Changes. Agricultural Frontier Expansion. Cerrado. Matopiba.

Resumo: Este artigo 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 para controlar heterogeneidade espacial. 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 malha rodoviária e o 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. A 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: Mudança no Uso da Terra. Expansão da Fronteira Agrícola. Cerrado. Matopiba.

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

In 2010, the annual rate of deforestation were 0.3%, the highest for all biomes present in the Brazilian territory, reaching 47.8% of total deforested area. In terms of territorial extension, the clearing in Cerrado also exceeds the cleared area of the Amazon forest. Nevertheless, the 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).

The current Cerrado deforestation occurs due to the establishment of new frontiers for agricultural production, such as Matopiba[4], which is the main region of the current Brazilian agricultural frontier and has presented a rapid economic growth (DIAS et al., 2016; BRAGANÇA, 2018). The opening of roads that creates access corridors to the regions often precedes the expansion, which often induce deforestation of native areas since it allows access to previously isolated areas, affecting its environmental degradation rhythm. Nevertheless, papers analyzing the road network impact 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).

In addition, there are several underutilized lands in the region that can be incorporated into the dynamic areas of the Cerrado, with the adoption of higher productivity techniques that are available in other regions. Moreover, the Matopiba have many areas with considerable amount of native forests, which can be incorporated, as the agricultural frontier expands, resulting in rapid deforestation (BOLFE et al, 2016; NOOJIPADY et al., 2017; ARAÚJO et al. 2019). In 2010, for example, the municipalities with higher deforestation rate in Cerrado were located in Matopiba (IBAMA, 2010).

These factors enabled 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), 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 Assunção and Bragança (2015) and Bragança (2018) argues that 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; 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 the Cerrado occupation, resulting in an expressive growth in local production, mainly of grains like soybeans and maize (SPEHAR, 1994; ASSUNÇÃO and BRAGANÇA, 2015; BRAGANÇA, 2018; ARAÚJO et al. 2019). 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 (ASSUNÇÃO and BRAGANÇA, 2015).

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

[4] 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).

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[5] (BRAGANÇA, 2014; ASSUNÇÃO and BRAGANÇA, 2015) . This is an important indirect impact due to land use changes, and may lead to deforestation in Brazil (BARONA et al., 2010, ARIMA et al., 2011; MACEDO et al., 2012, ANDRADE DE SÁ et al., 2013, 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 comes from Grossman and Krueger (1991; 1995), who states that at low levels of development, economic growth leads to an increase in environmental degradation. However, from a certain level this logic would reversed, leading to a decrease of environmental degradation. 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, 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 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.

2. The Environmental Kuznets Curve (EKC): Evidences and Methodological Considerations

For Brazil, some papers sought to identify the Environmental Kuznets Curve (EKC) using deforestation. However, practically all are for Legal Amazon, with only one paper in the literature for Cerrado. Therefore, the present paper, because it seeks to understand the relationship between economic development and deforestation in the 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 year or method adopted. For example, Gomes and Braga (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"; while Oliveira et al. (2011) and Oliveira and Almeida (2011) identified a relationship in the "N" format. For Cerrado, Colusso et al. (2012) are the only paper that estimate an EKC for the biome. The authors used several spatial models, which corroborated significant results for an "N" shaped curve, indicating that, in the long run, the economic growth is not sufficient to prevent the biome deforestation. Considering these papers, the results are not conclusive in relation to an EKC existence for the country, which highlight the need for additional studies. In any case, the empirical evidences point to the existence of an "N" relationship with economic growth, a fact that we seek to search in this paper.

The EKC model, according to Stern (2017), has been the main method used to model the relationship between economic development and environmental degradation. However, the relationship proposed by

[5] Legal Amazon covers 20% of Cerrado.

EKC, according to Stern (2004), is an essentially empirical phenomenon, despite having some econometric problems. Among them, the author refers to the omission of relevant variables, since many studies include only the linear, quadratic and cubic form of per capita income, 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 avoid such problem.

There are papers 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 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 due to their poor specifications, invalidating most of the work done with EKC (LIEB, 2003; STERN, 2004; CARSON, 2010; STERN, 2017). A recurrent problem of omission of relevant variable is the non-consideration of the spatial location influence. 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 cause significant regional differences; attract productive activities, especially agricultural and livestock (MADDISON, 2006; WEINHOLD and REIS, 2008; ROBALINO and PFAFF, 2012). For Brazil, 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) for Legal Amazon and Colusso et al. (2012) for Cerrado captured spatial spillovers from deforestation. In general, the results indicate that spatial dependence control improves the EKC estimation results.

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), the variable is not 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 more related to general well-being than just economic performance. The authors argues, 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, replacing the per capita income variable. The authors 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), Neve and Hamaide (2017), 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. Araújo et al. (2009) and Zaman et al. (2016) used this approach to synthesize highly correlated variables in an index that are later included 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 approach in the EKC context, 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 synthesized several social variables in an index that could serve as a proxy more suitable for the EKC estimation. The index were included in the model in its linear, quadratic and cubic form, seeking to capture the various possible formats for EKC.

Finally, we can mention the heterogeneity problem that is recurrent in the literature. In general, the empirical papers assume that all spatial units are homogeneous, estimating a coefficient representing the entire sample. According to Lieb (2003), the estimates can be biased and inconsistent, invalidating possible conclusions, since even in 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) supports that most of the papers, each subsample tends to present a different coefficient and turning point.

In summary, the factors mentioned make fragile many of the inferences using the EKC (LIEB, 2003; STERN, 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. This paper seeks to fill this gap in the literature, estimating an EKC model with spatial regimes, a way of controlling sample heterogeneity, along with spatial dependence and additional explanatory variables. In addition, we replace the per capita income as proxy for economic development by a socioeconomic development indicator, created with factorial analysis, improving the deforestation explanation while avoiding the multicollinearity problem.

3. Methodology
3.1 Factor analysis

The approach used to create the Socioeconomic Development Index (SDI) is factor analysis due to the multidimensional nature of economic development. This technique make it possible to include a large number of variables that explain development, avoiding the bias of poor model specification , while allows to control the multicollinearity problem. The procedure are based on Jha and Bhanu Murth (2003), Paudel and Shafer (2009), Araújo et al. (2009) and Zaman et al. (2016).

The factorial analysis is characterized as a method that aims to summarize p variables that are correlated with each other, in a number of k variables (with $k < p$, both finite and $k, n \in \mathbb{N}$). These new variables are called factors, which are obtained with the minimum loss of information possible. The Socioeconomic Development Index (SDI) are calculated from the factorials loads because they reflect the influence at the development. The SDI the municipality m are

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

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. Finally, the choice of the variables that compose the index (Chart 1) are based on several dimensions of economic development.

Chart 1 – Variables used in the factorial analysis model and their respective sources.

Variables		Source
Income_pc	Per capita income	ATLAS[6]
Higher_education	Population with higher education (%)	IBGE[7]
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 specifically follow Paul and Shafer

[6] Atlas of Human Development (2013).
[7] Demographic Census (2010).

(2009), which adopted factorial analysis for EKC to develop a better proxy for the economic development, replacing the per capita income. All variables refer to the year 2010.

3.2 Exploratory Spatial Data Analysis (ESDA) and Spatial Econometrics

The ESDA capture effects of spatial dependence and heterogeneity, association patterns (spatial clusters) and indicate how the data are distributed. The Moran's I statistics seeks to capture the degree of spatial correlation between a variable across regions. Mathematically,

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

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. However, the Moran's I statistic only capture global autocorrelation, not identifying association at a local level. In this context, we use the LISA (statistic, which are capable to capture local spatial autocorrelation and clusters,

$$I_i = z_i \sum_{j-1}^{J} w_{ij} z_j \qquad (3)$$

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

$$\begin{aligned} y &= \rho W y + X\beta + WX\tau + \xi \\ \xi &= \lambda W \xi + \varepsilon \end{aligned} \qquad (4)$$

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 Spatial Autoregressive Model (SAR) is obtained by imposing the following constraints on the model (16): $\rho \neq 0$, $\tau = 0$ and $\lambda = 0$. The SAR model 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) emerges if $\rho = 0$, $\tau = 0$ and $\lambda \neq 0$, which must be estimated, according to Kelejian and Prucha (1999), by maximum likelihood (MV) or generalized method of moments (MGM). The Spatial Lag of X model (SLX) occurs when $\rho = 0$, $\tau \neq 0$ and $\lambda = 0$. The model does not present the problem of endogeneity, and it is therefore possible to estimate by OLS. The Spatial Durbin Model (SDM) and the Spatial Durbin Error Model (SDEM) combine the previous models. SDM is obtained if $\rho \neq 0$, $\tau \neq 0$ and $\lambda = 0$ while 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. According to Florax et al. (2003), the best way to proceed is by following the steps: (i) estimate by OLS using conventional econometrics. (ii) Perform the lagrange multiplier tests[8], one for the SAR (MLp) and another for SEM (MLe). (iii) If the tests are non-significant, there is no spatial dependence, then the OLS model is adequate. (iv) If the two focused tests are significant, the appropriate model are the one for which the test had a higher statistical significance.

The spatial models are not capable of incorporating heterogeneity, a recurrent problem in the EKC, which makes global estimations inadequate. The EKC, according to Lieb (2003), List and Gallet (1999) and De Bruyn (2000), often suffers from heterogeneity, which makes spatial regime estimation

[8] The lagrange multiplier test seek to verify if there is spatial autocorrelation in OLS residues (FLORAX et al., 2003).

methodology adequate[9]. Almeida (2012) argues that spatial models, with spatial regimes is capable of simultaneously controlling spatial dependence and heterogeneity. Each regime is estimated by using a data subset, controlling heterogeneity through different intercepts and inclinations for each group. In general, it is possible to represent a model with g spatial regimes as

$$\begin{bmatrix} y_1 \\ \vdots \\ \vdots \\ y_g \end{bmatrix} = \begin{bmatrix} X_1 & 0 & \dots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & X_g \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \vdots \\ \beta_g \end{bmatrix} + \begin{bmatrix} \xi_1 \\ \vdots \\ \vdots \\ \xi_1 \end{bmatrix} \qquad \xi \sim Normal\ (0, \Omega) \tag{5}$$

The Spatial Chow test, in turn, verify if the regimes is better than the global estimation, as in

$$C = \left\{ \frac{(e_r' e_r - e_{IR}' e_{IR})/k}{(n-2k)} \right\} \tag{6}$$

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

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

$$H_1 \colon y = \begin{bmatrix} X_1 & 0 & \dots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & X_m \end{bmatrix} \begin{bmatrix} \beta_1 \\ \vdots \\ \vdots \\ \beta_m \end{bmatrix} + \varepsilon \tag{7}$$

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

3.3 Data, Descriptive Statistics and Empirical Design

Deforestation is the environmental degradation proxy 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 *Instituto Nacional de Pesquisas Espaciais (INPE).* We consider the year 2010 for deforestation and for all the explanatory variables. We choose this year due to the wide availability of variables related to the socioeconomic development of the municipalities, coming from the Demographic Census and the Altas of Human Development, important to make the Socioeconomic Development Index (SDI) and there are no available data for deforestation after 2011[10]. In line with the literature, we used the SDI as an economic development proxy, considering that per capita income does not capture all development dimensions, limiting its ability to explain environmental degradation (HILL and MAGNANI, 2002; JHA and BHANU MURTH, 2003; STIGLITZ et. al., 2009; KUBISZEWSKI et. al., 2013; NEVE and HAMAIDE, 2017). The Chart 2 brings the description of all variables used in the econometric model.

The inclusion aimed to improve the EKC specification, as well as better represent structurally the Cerrado and explain deforestation. This procedure follows Stern (2004; 2017) recommendation, which states that 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

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[9] The GWR methodology can also address this issue and it's widely adopted by the EKC deforestation literature (OLIVEIRA and ALMEIDA, 2011; 2012; JUSYS, 2016). We estimate the EKC model using the GWR methodology, however, the majority 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 in Matopiba, current agricultural frontier in the biome, and another for the remaining municipalities.

[10] 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.

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.

Chart 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.

We construct the SOIL variable by 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. 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 is 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 by the average annual precipitation data (1977 to 2006), from the national hydrometeorological network. The *Serviço Geológico do Brasil (CPRM)* it and made available in the Pluviometric Atlas of Brazil. The ROADS refers to the extension in kilometers of 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.

Gallet (1999), Lieb (2003) and Stern (2017) argues that the heterogeneity can invalidated the estimations. In general, the literature assume that all spatial units are homogeneous, estimating coefficients that represents the entire sample. In order to investigate this problem, Table 1 reports the descriptive statistics for Matopiba and for the Non-Matopiba municipalities of Cerrado, considering the variables used in the EKC model. We can notice 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 reflects the fact that Matopiba have approximately 60% of remaining forest cover, twice compared to the rest of the Cerrado. On the other hand, Matopiba has half of the socioeconomic development, which could induce the regions to be in different parts of the Environmental Kuznets Curve or even have different turning points. In addition, all the variables showed some degree of difference between the two regions, except for the annual average precipitation. Therefore, the heterogeneity in the Cerrado biome can invalidated the results due to biased and inconsistent estimation. (LIEB, 2003; STERN, 2017). The Spatial regimes, adopted in this paper, precisely seek to circumvent this problem, by estimating different coefficients for each region.

Another problem in EKC is multicollinearity that affects the coefficients variance, invalidating 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, we estimate the variable's correlation. From them, we notice no extremely high correlations that could compromise the EKC estimation, with the exception of the variable CROP and RURAL.CREDIT for Matopiba[11]. Therefore, the socioeconomic development index creation was able to mitigate the multicollinearity problem.

Table 1 – Descriptive statistics of variables for Matopiba and Non-Matopiba municipalities.

Variable	Mean		Standard Deviation		Minimum		Maximum	
	Non-Matop	Matopiba	Non-Matop	Matopiba	Non-Matop	Matopiba	Non-Matop	Matopiba
DEFOREST	4.1670	16.1469	8.5068	26.3755	0	0	103.53	227.34
SDI	50.3300	26.8719	13.4998	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	67.5431	13.2597	366.3196	18.6084	0.33	0.23	7387.69	180.79
AGRIC.GDP	25.8388	30.0870	16.6356	14.8885	0	0.62	78.46	74.86
CATTLE	74634.6100	44609.33	130844.600	47192.230	0	1300	1930475	423650
CROP	24104.8900	12510.00	60644.100	37912.340	0	0	875851	441164
EXTRAC.WOOD	6843.9480	21849.96	36877.500	73749.180	0	0	871166	749060
SUGARCANE	52677.160	22380.720	31524.310	21809.960	0	0	136666.7	100000
MAIZE	3897.0040	2126.080	1925.9940	1713.8580	0	276.67	9433.33	8770.33
SOYBEAN	1501.5520	1036.020	1370.8470	1321.2490	0	0	4266.67	3449.67
ROADS	24.7130	36.9751	18.1788	22.3745	0	0	135	119.3
RAINFALL	1428.891	1465.512	219.0353	295.7933	700	800	2250	2100
FOREST.COVER	0.3018	0.6026	0.2014	0.1997	0.01	0.04	0.97	0.98

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

In the empirical design, we follow the De Bruyn et al. (1998) recommendation that is necessary to include the development proxy in its squared and cube version. In addition, forest conversion and land use changes may present spatial interactions that result in significant spillovers, influencing the economic agent decision. Therefore, the model is

$$DEFOREST_i = \beta_0 + \beta_1 SDI_i + \beta_2 SDI^2{}_i + \beta_3 SDI^3{}_i + \beta_k Z_i + \tau WS + \varepsilon_i \quad (8)$$

$DEFOREST$ is the municipality cleared area; SDI is the Socioeconomic Development Index; i refers to the municipality; Z is the matrix of k additional explanatory variables; S is a vector containing elements that represents the agricultural frontier expansion: sugarcane, maize and soy productivity; roads, cattle herd and crop area. The spatial matrix W represents the structural configuration between the regions and capture spatial spillovers from the agricultural frontier expansion.

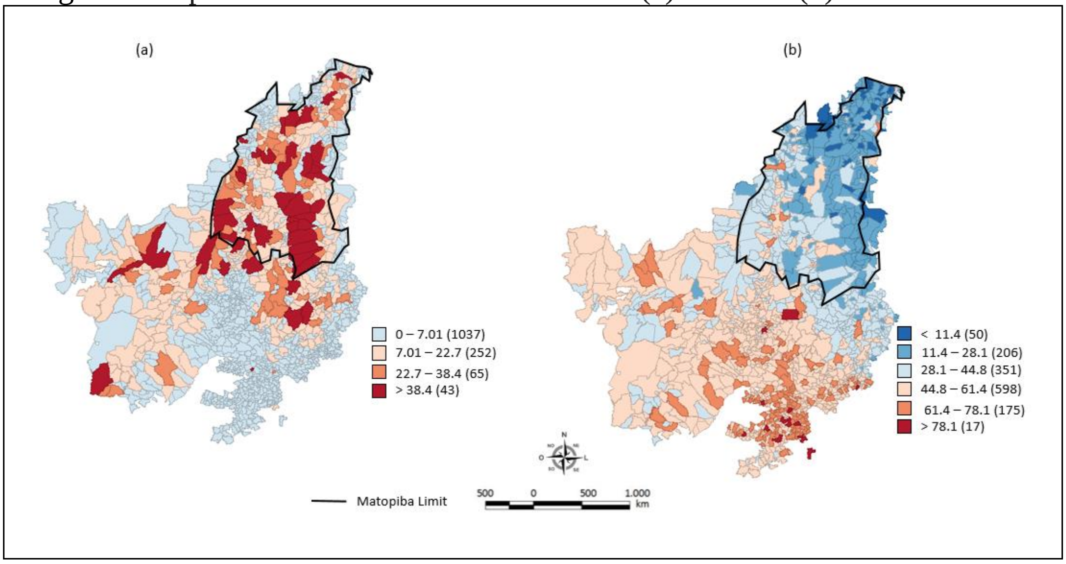
[11] In other words, there are a strong relation between the amount of rural credit destined and the cultivated area.

4. Results and Discussion

After the factorial score estimation, we built the Socioeconomic Development Index (SDI) and the Figure 1 shows the spatial distribution of deforestation (Figure a) and 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 the northern 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. This phenomenon may explain the recent deforestation in the region. We can also identify, although with less intensity, regions in Mato Grosso and Mato Grosso do Sul states that have deforested significant parts of their natural area. The soybean cultivation and cattle raising are advancing on both states, a fact that may have resulted in deforestation (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, which are among those that deforested their forests the most (IBAMA, 2010; MAPBIOMAS, 2019). Therefore, their low rates may be a result of them having fewer forest areas.

Considering SDI (Figure b), we have a division of 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 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. This fact corroborate Bolfe et al. (2016) and Bragança (2018), which identified in Matopiba, a region with lower socio-economic development compared to other parts of the Cerrado. Despite this, the authors emphasize that, due to the agricultural frontier expansion, the region has presented higher economic growth rates, which has diminished the disparities in recent years.

Figure 1 – Spatial Distribution of deforestation (a) and SDI (b) in the Cerrado.

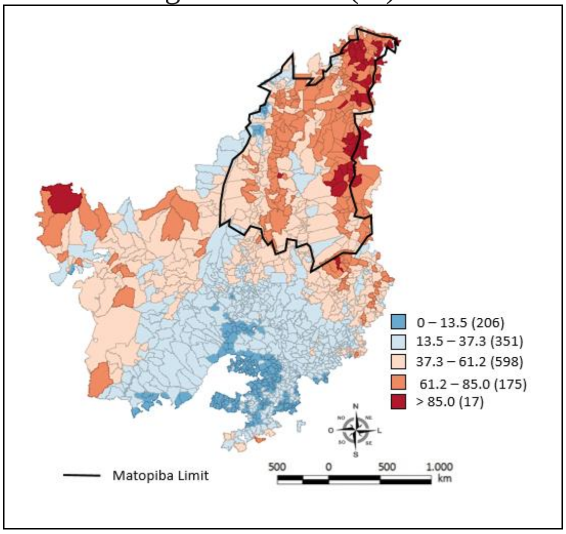


Source: research data.

A possible explanation for the spatial configuration for deforestation and development may be the Cerrado occupation and colonization process. 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.Figure 2 shows, in percentage terms, the Cerrado forest remnants. 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 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 supports 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 occurs, we can expect profound land use changes with reductions in forest cover.

Figure 2 –The remaining forest cover (%) distribution in Cerrado.



Source: research data.

The deforestation and development spatial concentration is visible in Figure 1, indicating the existence of patterns, which can result in spatial dependence and heterogeneity. To verify this hypothesis, Table 2 presents the Moran's I statistic, according to several spatial matrices conventions. We confirm the existence of statistically significant positive spatial autocorrelation for both variables, regardless of the convention adopted, indicating that deforestation and SDI tend to be surrounded by municipalities with similar values.

Table 2- 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*

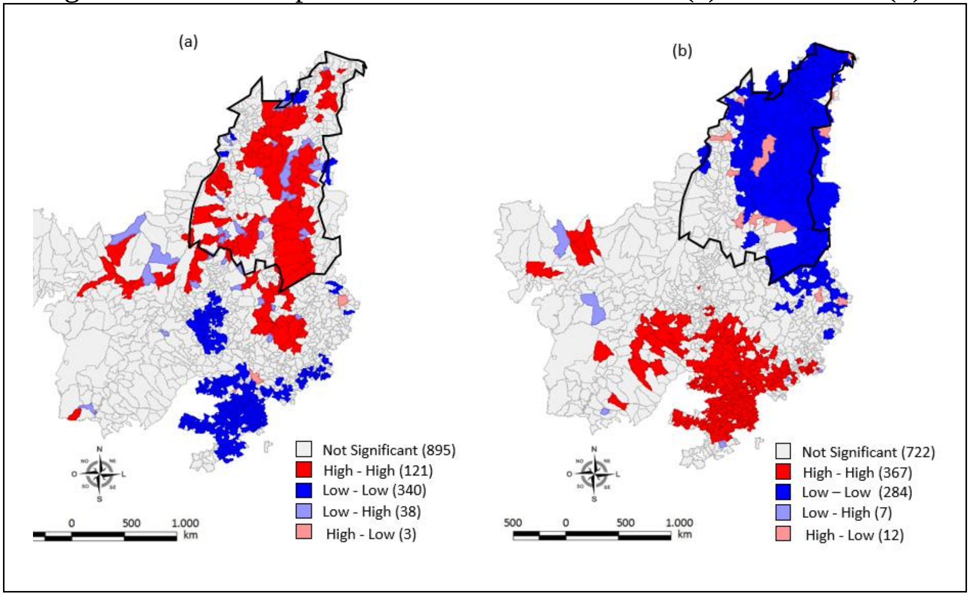
Source: research data. *Note*: * Level of significance of 1%.

Theoretically, the deforestation spatial concentration result from spatial spillovers, resulting from productive links and from human and physical capital concentration. For deforestation, this is in line with several empirical studies for 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) for Legal Amazon; and Colusso et al. (2012) for Cerrado. Figure 3 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 from 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 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 1.

One relevant aspect is that the deforestation spatial clusters are not located in the same regions as the socioeconomic development clusters. The Matopiba presents a spatial concentration for high deforestation at the same time that is a region with low SDI, while the opposite phenomena 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 2, the forests availability in the municipality may also be one important reason for this scenario, a fact that we will investigated in the EKC model.

Figure 3 – LISA map for deforestation in Cerrado (a) and for SDI (b).



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

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 presents the estimations results. The OLS (2) and SLX (2) had no statistical 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 significance for its linear, quadratic and cube format at 1%. Therefore, this empirical evidence implies an "N" format for EKC in Cerrado as supported by De Bruyn et al. (1998). This means that in the long-run, the increase in socioeconomic development may induce the return of environmental degradation, an evidence in line with Colusso et al. (2012) who identified an "N" curve for the biome.

However, we can notice in Table 3 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 reflects the presence of spatial heterogeneity, which leads to the parameters structural instability. Therefore, the model with spatial regimes are suitable since 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 specific econometric methods to address the spatial effects (IGLIORI, 2006; MADDISON, 2006; ALMEIDA, 2012). In addition, the ML test for both the dependent variable and the error variable are significant. On the other hand, by using the MLR, only the lag term is significant.

By following Florax et al. (2003), we consider the spillovers from deforestation as the pattern that represents the spatial autocorrelation in the residuals. Therefore, we estimate the Spatial Durbin Model (SDM), which incorporates spatial spillovers from deforestation and from the agricultural frontier expansion. Although the models in Table 3 indicates spatial heterogeneity, we estimate all the spatial models to better verify the robustness of the results. 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 the spatial models with regimes per se, it is necessary to perform the Spatial Chow test, which was significant at 1% for all models. In other words, the previous models are inadequate due to spatial heterogeneity.

Table 3 –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***
SDI²	-0.0020*	-0.0316***	-0.0032***	-0.0312***
SDI³		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%.

To estimate the spatial models with regime, we chose the spatial lag matrix that generated the largest Moran's I coefficient for the SLX (3) residues, opting for the rock matrix. Moreover, due to the residuals non-normality and the heteroscedasticity, we used the Generalized Method of the Moments by Kelejian and Prucha (1999), together with the robust error of White (1980) for the SDM model. It is worth mentioning that we excluded the rural credit from the spatial models for Matopiba regime since we identified high correlation between rural credit and crop area for Matopiba. Finally, we have in Table 4 the estimated models. 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.

According to Grossman and Krueger (1991; 1995) and De Bruyn et al. (1998), the model choice 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 coefficients, with $\beta_1 > 0, \beta_2 < 0$, we have an inverted-"U" relationship between deforestation and socioeconomic development for both regimes. The results differs from Colusso et al. (2012) and from the Global EKC models (Table 3) that presented an "N" relationship for the biome. However, both have not considered the spatial heterogeneity existence in Cerrado, which can led to structural instability in the parameters, resulting in bias and inconsistent estimations (LIST and GALLET, 1999; LIEB, 2003; STERN, 2017). Therefore, spatial regimes is a methodological advance in the EKC estimation for Cerrado, since make it possible to obtain better results, what may explain the shift to an inverted-"U" relationship. The empirical evidence supports the Grossman and Krueger's (1991; 1995) EKC hypothesis that at low socioeconomic standards, development growth initially increases natural resources use, which leads to deforestation. However, after a "turning point"[12] threshold, environmental degradation starts to fall.

Table 4 –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
SDI²	**-0.0113*****	-0.0191	**-0.0016****	-0.0001
SDI³	**-**	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***
W_DEFOREST (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%.

In Table 5, we have the turning point, the SDI mean, standard deviation and the percentages of municipalities above the threshold for both regimes. We can notice different turning points between the regimes, indicating that development do not affect both in the same magnitude. We have approximately 40% and 28% of municipalities that did not reach its maximum environmental degradation in Matopiba and Cerrado*, respectively. 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 economic growth will continue to boost Cerrado deforestation. However, even in the long run, development may not be a sufficient factor to generate biome protection, since there are also other variables that impacts deforestation.

[12] Where the curve reaches its maximum. We can calculated the "turning point" with: $\tau = -\beta_1/2\beta_2$

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-Matopiba*	44.5	50.33	13.49	72.30%
Matopiba	21.80	26.87	12.84	60.54%

Source: research data.

The coefficients ρ (Rho) are significant for both regimes, indicating the presence of spatial spillover of deforestation among the municipalities, a similar result to that found by Colusso et al. (2012). However, we can notice that the spillovers from deforestation is smaller in Matopiba 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). We also have significant variables that captures spillovers from the agricultural frontier expansion, reinforcing the importance of spatial interactions in explaining deforestation in Cerrado.

The SDM approach, by incorporation relevant spatial spillovers related to deforestation and the agricultural frontier expansion, controlled the spatial dependence problem. The Anselin-Kelejian test is not significant, not rejecting the hypothesis of spatial autocorrelation absence in the residuals. Therefore, the methodology adopted permitted to control the spatial dependence and heterogeneity, diminishing the bias and inconsistency often present in the EKC (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 it spillover negatively to its neighbors, decreasing environmental degradation. The road network expansion allows access to previously isolated areas by creating corridors to the region, reducing 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. (WEINHOLD and REIS, 2008). The spatial attracting elements helps to explain the greater value (in absolute terms) for Matopiba regime, since those forces are stronger due the stage of agricultural development and colonization in the region. This empirical evidence are an important contribution to the literature on deforestation, since there are no papers that address directly this issue for the biome.

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. (BARONA et al., 2010, ARIMA et al., 2011; MACEDO et al., 2012, ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013, 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, the Soy Moratorium, an industry effort, 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. 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. In fact, crop area presented positive statistical significance and significant negative spillover for Matopiba. Considering Gibbs et al. (2015), Noojipady et al. (2017) and Zanin and Bacha (2017) evidences, municipalities with greater rural proprieties area, infrastructure and agricultural activities attracts crop expansion, diminishing its neighbor's deforestation, helping to explain the direct impact and the negative spatial spillovers.

The sugarcane productivity 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). 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. 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 are significant for both regimes, indicating that higher deforestation is associated with greater proportion of native forests. This scenario reflects the fact that some municipalities may deforest less simply because they do not have much remaining forest area to do it. In addition, higher proportion of forests are related to regions where 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). Regarding soil suitability, we have statistical significance for the Non-Matopiba regime, which corroborates Bragança (2014) and Assunção and Bragança (2015) arguments that soil conditions are essential for agricultural production in Cerrado. Better suitability translates into higher productivity and profitability, when compare to unfit soils, which induces deforestation. However, soil characteristics in Matopiba do not affect land use changes. In other words, deforestation in the region occurs independently if the soil is suited for agricultural production, corroborating Bolfe et al (2016) evidences, who supports that considerable proportions of 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. 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 as a natural barrier. Araújo et al. (2019) emphasizes that the development of drought resistant crops or pasture could outline this problem, but the authors also highlight that this innovation could boost deforestation. In Matopiba regime, we also have the Federal Reserve with a significant positive impact, contradicting the idea that conservation units acts as an inhibitor of deforestation. This highlight the 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 it induce the natural resources use for its production, causing a scale effect. The authors emphasizes that this 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 this theoretical proposition. In other words, municipalities that depends more from the agricultural sector presents higher deforestation. 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, differently from the Non-Matopiba regime. 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 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, increasing demographic density.

According to Lesage and Pace (2009), spatial interactions between the municipalities 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: $(1-\rho)^{-1}\beta_k$. In this spatial context, socioeconomic development causes environmental degradation with different magnitude, implying a new turning point. The Non-Matopiba regime turning point goes from 44.50 to 46.19 while the Matopiba regime changes from 21.80 to 25.66. 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, we have 69.15% in Non-Matopiba and 46.88% in Matopiba municipalities that are above the new spatial interacted turning point, a drop of 3.15% and 13.66% respectively. The change is greater for Matopiba, indicating that socioeconomic development can boost deforestation in most of its municipalities as agricultural frontier advances in the region. In addition, we have others variables that also causes environmental degradation in the biome that also have higher impacts due to spatial interactions. In this scenario, we can expect, if no inhibitory action is taken, the deforestation permanence, especially in Matopiba.

5. Final considerations

This paper investigated 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 EKC approach. As proxy for economic development in the EKC, we created a Socioeconomic Development Index with factorial analysis, following methodological advancements in the literature. The ESDA pointed to spatial autocorrelation and to the existence of two heterogeneous regions on Cerrado with Matopiba presenting different characteristics than the remaining municipalities. 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 with regimes, in order to treat spatial dependence and heterogeneity. This procedures attempt to avoid biased and inconsistent estimates, an approach not yet adopted to model deforestation in Cerrado. The multidimensional index of socioeconomic development was important to represent to model the EKC, since it helped to improve the model's 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 the traditional per capita income.

In the EKC model, we get an inverted "U" relationship between socioeconomic development and deforestation for both regimes. However, the curve turning point, where socioeconomic development reaches its maximum impact on environment, are different for each regime, reinforcing the Cerrado heterogeneity. The Matopiba have lower development than the remaining municipalities and the migratory and agricultural processes is not consolidated yet, which induces higher deforestation due to 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 Non-Matopiba have municipalities with socioeconomic development lower than the maximum turning point, which highlights environmental concerns, since economic growth could boost degradation on this underdeveloped municipalities.

To worsen the scenario, we identified many variables, especially related to the agricultural frontier expansion, which affects negatively the Cerrado. 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. Concomitantly, the region's heterogeneity 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 regime. Therefore, the spatial regimes estimation is a methodological advancement in the EKC estimation for the biome, since it revealed a spatially differentiated relationship.

Since we have biome heterogeneity, any actions need to take into account possible mixed results, especially for Matopiba, since the region is at the beginning of its occupation and agricultural expansion process, differently from many consolidated Cerrado regions, that initiated it decades ago. 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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