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

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Abstract: This paper aims to understand how economic development affected deforestation in the Brazilian Amazon from 2000 to 2015, using an Environmental Kuznets Curve (EKC). We analyzed and controlled the presence of spatial and temporal dependence with ESDA and Dynamic Spatial Panel methodologies. For the EKC model, despite obtaining an inverted "U" format, the majority of municipalities in Amazon are far below the turning point. Therefore, economic development may act as a deforestation inductor in the following decades. We confirmed the importance of the spatial-temporal components, which explains the spatial spillovers and agglomeration along with temporal inertia for deforestation. In addition, cattle herd growth along with rural credit, sugarcane productivity, extraction of wood and scale effects from agricultural sector are statistical significant, acting as environmental degraders. On the other hand, we have the productivity gains on soy and maize that inhibit deforestation. We also highlight the importance of considering land use dynamics and cross-agricultural activities leakages in policies targeting deforestation, since crops indirectly affect environmental degradation in Amazon by shifting cattle production to agricultural frontier regions, where it increase deforestation.

Keywords: Environmental Kuznets Curve (EKC). Brazilian Amazon. Agricultural Frontier Expansion. Dynamic Spatial Panel.

Resumo: O artigo buscou entender como o desenvolvimento econômico afetou o desmatamento na Amazônia Brasileira no período de 2000 a 2015, utilizando-se da Curva Ambiental de Kuznets (CAK). Buscou-se analisar a presença de dependência espacial e temporal com as metodologias AEDE e Painel Dinâmico Espacial. Para a CAK, apesar da obtenção de uma curva em “U” invertido, a maioria dos municípios da Amazônia se encontram consideravelmente abaixo do “ponto de virada”. Dessa forma, o desenvolvimento econômico possivelmente será um indutor de desmatamento nas próximas décadas na região. Confirmou-se a importância dos componentes espaciais e temporais, os quais induzem *spillovers* e aglomerações espaciais conjuntamente a inércia temporal. Além disso, o aumento do rebanho bovino, crédito rural, produtividade da cana-de-açúcar, extração de madeira e efeito escala do setor agrícola foram estatisticamente significativo, atuando como degradadores do meio ambiente. Por outro lado, ganhos de produtividade da soja e milho atuam como conservadores da floresta, inibindo o desmatamento. Destaca-se também a importância de se considerar a dinâmica de uso da terra e as ligações existentes entre as atividades agrícolas em políticas visando a redução do desmatamento, pois o cultivo de grãos podem afetar indiretamente a degradação ambiental na Amazônia ao deslocar a produção bovina para regiões de fronteira agrícola, aumentando o desmatamento.

Palavras-chave: Curva Ambiental de Kuznets (CAK). Amazônia Brasileira. Expansão da Fronteira Agrícola. Painel Dinâmico Espacial.

JEL: Q01, Q56

Área 11 - Economia Agrícola e do Meio Ambiente

1. Introduction

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

Nevertheless, the occupation and deforestation of this region has caused concern not only because of the irreparable loss of its natural wealth, but also due the perception that economic and social gains are inferior in relation to environmental degradation (MARGUILIS, 2004; MALHI et al., 2008; RODRIGUES et al., 2009; ASSAD, 2016). According to Nascimento (2017), deforestation between 2007 and 2016 (an average of 7,502 km² / year) had the potential to add only 0.013% annually to the Brazilian GDP, a negligible value when compared to potential environmental damages. In addition, deforestation, besides causing direct effects on the environment, is also the main responsible for the emissions of greenhouse gases in Brazil. Therefore, combating deforestation has the potential to minimize the threats posed by biodiversity loss and climate change.

Deforestation in the Brazilian Amazon reached its peak in 2004, when it suffered a reduction in its forest area of about 28,000 square kilometers (km²). Since then, the degradation has shown a considerable decrease in its rate, which reduced to approximately 7,000 km² in 2017, a significant drop of 75% (INPE, 2018). According to Assunção et al. (2015), the main factors that led to this reduction are: i) the fall in the price of agricultural commodities after the mid-2000s. ii) implementation of the *Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm)* in 2004; and iii) the conditionality of environmental preservation in the concession of agricultural credit to establishments located in the Amazonian biome.

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

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

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

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

the country to reduce significantly the deforestation and greenhouse gas emissions, maintaining agricultural growth.

The production of soybeans and maize, often adopted jointly due to crop rotation[2], are the agricultural crops that contribute the most in the occupation of the Amazon rainforest (BARONA et al., 2010; MARTINELLI et al., 2010; ARVOR et al., 2011; ARVOR et al., 2012; FARIA and ALMEIDA, 2016). However, according to Macedo et al. (2012), many municipalities that produce soybean, especially in the Mato Grosso state, have been able to increase their harvests without significant impacts on deforestation. The author points out that this result reflects a combination of factors, especially the adoption of modern production technologies and due to government policies.

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

Several studies point to the fact that the indirect impacts of soybean are possibly more important to explain deforestation in the Legal Amazon than the direct ones (BARONA et al., 2010; GOLLNOW and LAKES, 2014). This is mainly due to changes in land use in both the Amazon region and elsewhere in the country, as increased production has occurred on land already occupied, especially those used by extensive livestock (BARONA et al., 2010; ARIMA et al., 2011; MACEDO et al., 2012; RICHARDS et al., 2012). This process induces, due to the demand inelasticity for beef, the displacement of cattle rearing to regions where the price of land is relatively lower, usually in localities belonging to the agricultural frontier (ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013; GOLLNOW e LAKES, 2014).

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

In addition, we can mention the work of Barona et al. (2010), Andrade de Sá et al. (2012) and Jusys (2017), who found evidence that an increase in sugarcane production for biodiesel production in the São Paulo state, and to a lesser extent in other regions, shifted livestock towards the agricultural frontier in Amazonia, together with other non-fuel crops. According to Jusys (2017), between 2002 and 2012, we had approximately 16,000 km² of forests cleared by economic agents displaced by the advance of sugarcane in Brazil, which corresponds to 12.2% of the total value deforested in the period. Although sugarcane is not a predominant crop in the region, as soy and maize, the recent expansion of Brazilian ethanol production is also leading to direct deforestation (ASSUNÇÃO and ROCHA, 2019).

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

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

According to Assunção et al. (2013), the conditionality established by Resolution 3,545 has proved to be an effective policy instrument to combat deforestation in the Amazon by restricting rural credit to environmental offenders. The author states that conditionality causes a reduction of approximate R$ 2.9 billion in the credit granted, which affected mainly cattle farmers, which was responsible for 90% of this

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

decrease. In addition, this reduction avoided 2,700 km² of deforestation per year; especially in municipalities that is specialize in livestock production, with less impact on those who have agriculture as their main activity.

In view of the importance of the agricultural sector for the economy in the Legal Amazon, it would be natural to infer that a slowdown in the pace of expansion of the agricultural frontier in the region can negatively affect its economic development. However, according to Assunção et al. (2015) and Assunção and Rocha (2019), there is no trade-off between economic development and environmental conservation on the region. On the contrary, the agricultural sector continued to perform well despite policies to inhibit deforestation. This fact is in accordance with the Grossman and Krueger (1991, 1995) theoretical preposition, known as the Environmental Kuznets Curve (EKC), which proposes an inverted U-relationship between economic development and environmental degradation. In other words, several municipalities in the Amazon region, according to evidences from Assunção et al. (2015) and Assunção and Rocha (2019), may be located in the downstream part of the EKC, with environmental protection not hindering economic advancement.

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

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

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

For deforestation in the Legal Amazon in particular, we have several empirical studies that sought to identify the existence of an EKC. Authors such as Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) found evidence of an inverted "U" relationship, with development inducing the reduction of deforestation in the long run. On the other hand, Araújo et al. (2009) and Jusys (2016) captured a EKC in "U", with development initially decreasing degradation, but again increasing it after a certain income level. Finally, Oliveira et al. (2011) and Oliveira and Almeida (2011) identified the possibility of deforestation presenting a relationship in the "N" format (as well as its inverted form), that is, with environmental degradation returning to increase after high levels of development. This possibility are proposed by De Bruyn et al. (1998), who defended this hypothesis, specifically stressing the importance of also including per capita income in a cubic format in econometric modeling, in addition to its linear and quadratic format to capture this effect.

Therefore, based on the results for the Legal Amazon, we have contradictory evidences, a fact that prompts the need for further studies. On other words, there is still no consensus on the relationship between economic development and deforestation, from the EKC perspective, for deforestation in the Legal Amazon. Therefore, it is necessary to identify possible misconceptions and adopt complementary methodologies not yet tested to push the literature. In fact, the main goal of this paper is to contribute to this debate, with a new approach to understand the economic development impact on deforestation in the Legal Amazon. The Environmental Kuznets Curve, according to Stern (2017), is the main method used to verify the relationship between economic development and environmental degradation. Despite this, the author emphasizes the importance of considering econometric problems, often neglected by literature. Among them, the main ones are the relevant variables omission and sample heterogeneity (LIST e GALLET, 1999; DE BRUYN, 2000; LIEB, 2003; STERN, 2004; STERN, 2017). Therefore, the additional variables inclusion and appropriate methods is important to avoid spurious results.

An important aspect confirmed by the literature, and often not considered, is the spatial interactions existence in forest conversion and land use changes (MADDISON, 2006; ROBALINO and PFAFF, 2012). In addition, several studies point out these factors as relevant to the Legal Amazon, with a strong positive spatial interaction impacting deforestation in the region (IGLIORI, 2006; AGUIAR et al., 2007; PFAFF et al., 2007; OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; ANDRADE DE SÁ et al., 2015; JUSYS, 2016; AMIN et al., 2019). One of the possible explanations is that centripetal forces, generated by productivity differences, transport costs, climate, topography and soil conditions that can cause significant regional differences; attract productive activities, especially agricultural and livestock (WEINHOLD and REIS, 2008). In addition, according to Andrade de Sá et al. (2015) and Amin et al. (2019), several deforestation determinants present dynamic aspects, with factors changed in previous periods affecting the current economic agent's decisions. As an example, areas initially occupied can facilitate access to new agents and to deforestation, as well as public policies with subsidized credit and settlement programs, which have an effect that may not occur at the time of adoption but only in future periods.

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

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

2. Methodology

2.1 Database

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

As economic development proxy, we will use the municipalities per capita GDP, in line with the literature. In addition, per capita GDP are also included in its square and cube version in econometric modeling, in order to seek for the existence of other formats for EKC, that is, a quadratic or cubic function. The variables described, as well as the variables used in the present paper are in Chart 2.1. The aim of the inclusion are to improve the econometric model specification, as well as to better represent structurally the region and to identify possible relationships that they may have with deforestation in the Legal Amazon. In addition, we deflate the per capita GDP and rural credit variables to year 2010 BRL, which are expressed as an index with base year 2010 using the *IPCA (Índice de Preços ao Consumidor Amplo)* made available by *IPEA (Instituto Pesquisa Econômica Aplicada)*. The adopted procedure seeks to capture the real values in income growth and concessions in rural credit, since nominal values not affect the resources restrictions that the economic agents face in the decision making process (ASSUNÇÃO and ROCHA, 2019).

Chart 1 – Variables used for the period 2000 to 2015.

Abbreviation	Description	Unit	Source
DEFOREST	Deforested area	km²	PRODES/ INPE
GDP	Per capita GDP	R$ (BRL)	SIDRA/IBGE
GDP²	Per capita GDP - Square	-	-
GDP³	Per capita GDP - Cube	-	-
RURAL CREDIT	Total rural credit	R$ (BRL)	BACEN
DEM.DENSITY	Demographic density (inhabitants/km2)	km²	SIDRA/IBGE
AGRIC.GDP	Agricultural participation in GDP	%	SIDRA/IBGE
CATTLE	Cattle herd increase	count	SIDRA/IBGE
A.SUGARCANE	Increase in sugar cane plantation.	ha	SIDRA/IBGE
A.SOYBEAN	Increase in soybean plantation.	ha	SIDRA/IBGE
A.MAIZE	Increase in maize plantation.	ha	SIDRA/IBGE
EXTRAC.WOOD	Extraction of wood (charcoal, firewood and wood)	m³	SIDRA/IBGE
SILVICULTURE	Silviculture (Wood)	m³	SIDRA/IBGE
SUGARCANE.PROD	Sugarcane Productivity	kg/ha	SIDRA/IBGE
MAIZE.PROD	Maize Productivity	kg/ha	SIDRA/IBGE
SOYBEAN.PROD	Soy Productivity	kg/ha	SIDRA/IBGE
FOREST.COVER	Remaining forest cover in $(t-1)$	km²	PRODES/INPE

Source: research data.

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

2.2 Descriptive Statistics

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

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

[3] Considering 2010 as year base.

Table 1 – Descriptive statistics.

	Initial (1)	Final (2)	Difference (3)
DEFOREST	71.73	8.08	-63.64
	(185.50)	(26.65)	(179.04)
GDP	6,458.96	11,028.51	4,570.416
	(5,785.78)	(10,190.61)	(7,318.84)
RURAL CREDIT	17,412,287.86	8,393,500.06	-9,018,787.80
	(45497021.66)	(26,537,497.88)	(49,043,623.92)
DEM.DENSITY	20.39	25.34	4.96
	(106.49)	(131.77)	(27.87)
AGRIC.GDP	26.76	25.16	-1.60
	(15.03)	(15.25)	(12.02)
CATTLE	5,462.83	2,621.43	-2,841.40
	(26,531.83)	(13,207.83)	(27,964.53)
AREA.SUGARCANE	47.42	5.53	-41.89
	(555.92)	(600.20)	(798.84)
AREA.SOYBEAN	371.40	885.30	513.90
	(6,429.94)	(4,582.05)	(7,939.80)
AREA.MAIZE	-205.94	295.82	501.75
	(3,109.49)	(3,580.08)	(4,905.87)
EXTRAC.WOOD	12,677.83	8,232.87	-4444.96
	(31,742.70)	(23,564.69)	(29,358.98)
SILVICULTURE	7,791.39	35,835.74	2,8044.35
	(150,327.85)	(262,323.58)	(268,716.25)
SUGARCANE.PROD	16,323.99	16,378.49	54.49
	(19,961.67)	(23,670.77)	(23,549.50)
MAIZE.PROD	1,649.32	2,792.33	1,143.01
	(1,053.69)	(1,948.97)	(1,433.02)
SOYBEAN.PROD	478.40	1,137.56	659.16
	(1,027.09)	(1,463.95)	(1,219.45)
FOREST.COVER	4,439.49	3,907.86	-531.63
	(12,921.10)	(11,880.98)	(1,682.58)

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

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

Finally, we can mention a recurrent problem in the EKC model: multicollinearity, which can invalidate statistical inferences. According to Lieb (2003), Carson (2010) and Stern (2004; 2017), most of the additional variable included in the model are highly correlated with per capita income. We check this possibility and notice no extremely high correlations that could compromise the estimations.

2.3 Empirical Design

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

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

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

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

Regarding the possible econometric problems, we highlight the presence of sample heterogeneity and / or spatial dependence, which can potentially cause bias and inconsistency in the estimated parameters. The heterogeneity problem is recurrent in EKC, especially with geographical units, such as municipalities, since each place potentially has unique characteristics (LIST and GALLET, 1999; DE BRUYN, 2000; LIEB, 2003; STERN, 2004). Therefore, we used in this paper the advantage of the panel structure to control the municipalities fixed effects, as well as fixed effects for each specific year. These procedures can filter intrinsic municipality's characteristics, unusual shocks, heterogeneous initial conditions and different municipal dynamics, making estimates more consistent. On the other hand, when working with regional data, according to Almeida (2012), normally we have spatial autocorrelation. Thus, it is necessary to adopt techniques to identify and control this spatial effect in order to avoid econometric problems that can invalidate statistical inferences. For the identification and treatment of spatial dependence, we used Exploratory Spatial Data Analysis (ESDA) and Spatial Econometrics techniques. In the next subsection, we detail the methodological procedures mentioned.

2.4 Exploratory Spatial Data Analysis (ESDA)

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

The Moran's I are a statistics that seeks to capture the spatial correlation degree between a variable across regions and are represented by

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

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 in the present paper.

However, the Moran's I statistic, according to Anselin (1995), can only capture the global autocorrelation, not identifying the spatial association at a local level. To capture local spatial autocorrelation and the existence of local spatial clusters, we used LISA (Local Indicator of Spatial Association) statistic. The Moran's I statistic (LISA) are

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

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

2.5 Dynamic Spatial Panel

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

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

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

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

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

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

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

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

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

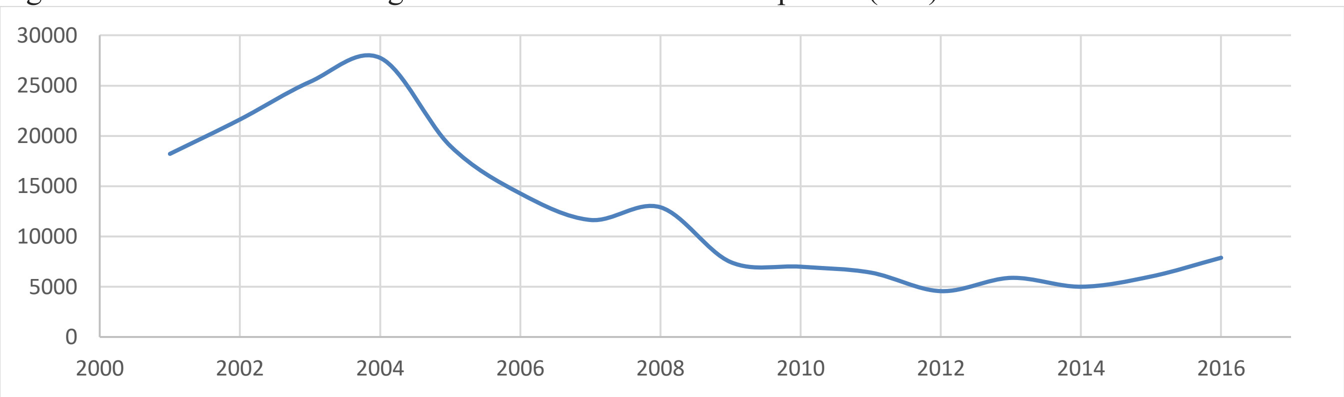
$$\ln L_{n,T}(\theta) = -\frac{nT}{2}\ln 2\pi - \frac{nT}{2}\ln\sigma^2 + T\ln|S_n(\lambda)| - \frac{1}{2\sigma^2}\sum_{t=1}^{T}\tilde{V}'_{nt}(\zeta)\,\tilde{V}_{nt}(\zeta) \qquad (8)$$

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

3. Results and Discussion

Deforestation in the Legal Amazon has significant negative impacts on the environment, affecting adjacent localities and potentially global climatic stability. Therefore, the search for its determinants are fundamental for the development of inhibitory measures. The Figure 1 shows the deforestation's rate in the Legal Amazon in the 2001-2016 period – cleared area in km². We can notice that deforestation reached a peak in 2004, when we had about 28,000 square kilometers (km²) of forest clearing. According to Araújo et al. (2009), the 2004 peak are related to the agricultural prospects booming due to the exchange rate depreciation and rise of agricultural commodities' prices, especially soybean. Since then, deforestation decreased considerably to approximately 8,000 km² in 2016, a drop of more than 70% (INPE, 2018).

Figure 1 – Deforestation in Legal Amazon in the 2001-2016 period (km²).



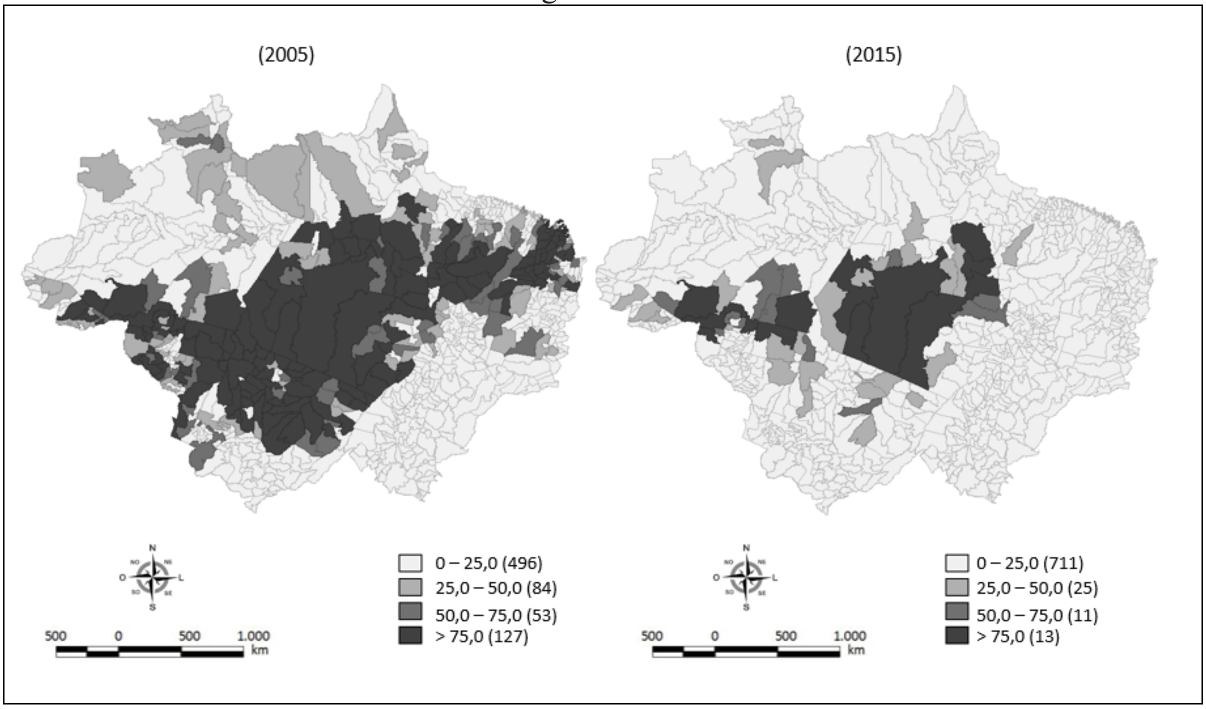
Source: research data.

Assunção et al. (2015) highlight three main factors that led to this scenario. The fall in agricultural commodities' prices after the mid-2000s, the implementation of the *Plano de Ação para a Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm)* in 2004 and the agricultural credit

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

conditionality of environmental preservation. However, the 8,000 km² of cleared area in 2016 is considerably higher than the 4,500 km² value from 2012. This scenario indicates that the "decoupling" process supported by Caviglia-Harris et al. (2016) and Silva et al. (2017) may be losing ground in the Amazon. The Figure 2 shows the deforestation spatial distribution in the Legal Amazon in 2005 and 2015 among the municipalities in the region.

Figure 2 - Distribution of deforestation in the Legal Amazon in 2005[5] and 2015[6].



Source: research data.

Comparing the initial period (2005) *versus* the final (2015), there is a relatively similar spatial disposition, with the permanence of some municipalities that, *a priori*, had a preponderant participation in the deforestation in the Legal Amazon. According to Igliori (2006b), Fearnside (2007) and Araújo et al. (2009), this region is known as the "Deforestation Arc", which is characterized by the agricultural frontier expansion. However, deforestation decrease sharply in the period. For example, in 2005, approximately 35% of the municipalities cleared an area greater than 25 km², a value that decrease to only 6,5% in 2015. Considering deforestation above 75 km², we had 16,7% in the initial period compared to 1,7% ten years later. Theoretically, this deforestation spatial concentration process may result from spatial interactions, which can reinforce deforestation. This phenomenon are also evidenced by several empirical papers for Legal Amazon (IGLIORI, 2006; AGUIAR et al., 2007; PFAFF et al., 2007; OLIVEIRA and ALMEIDA, 2011; OLIVEIRA et al., 2011; ANDRADE DE SÁ et al., 2015; JUSYS, 2016; AMIN et al., 2019).

Table 2 **-** Moran's I for deforestation in the Legal Amazon in 2005 and 2015.

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

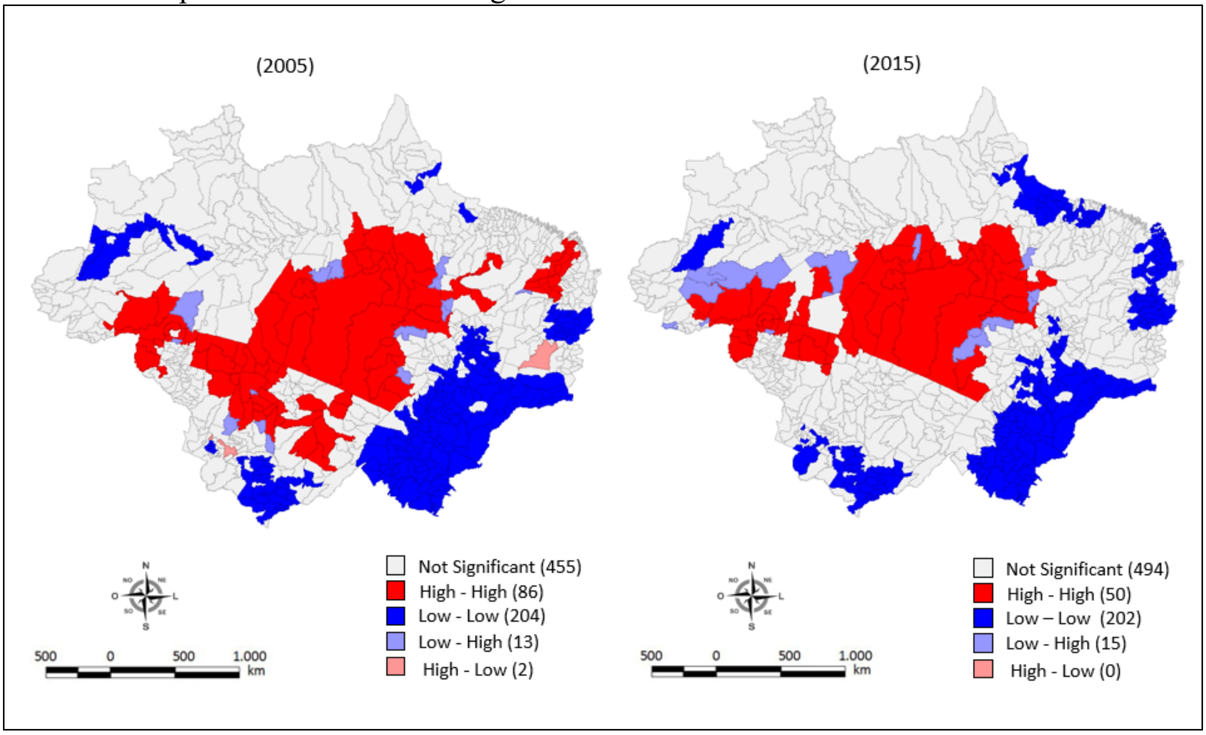
Source: research data. *Note:* * Level of significance of 1%.

Figure 3 confirms this spatial phenomenon for deforestation in the municipalities of the Legal Amazon, with the consolidation of a large High-High cluster located in the "Arc of Deforestation". As in

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

Figure 2, there is a decrease in the size of this Cluster in the municipalities in the south; while, on the other hand, there is an advance to northern locations, possibly indicating the consolidation and advancement of the agricultural frontier in the region.

Figure 3 – LISA map for deforestation in Legal Amazon in 2005 and 2015.



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

With the basic deforestation characteristics in the Legal Amazon identified, in terms of its spatial distribution, the next step is to find its determinants. To this end, Table 3 shows the Environmental Kuznets Curve results estimated with the Dynamic Spatial Autoregressive model (DSAR) and the Dynamic Spatial Durbin Model (DSDM) for the period from 2000 to 2015. Prior to the estimations, we applied the Hausman test to the fixed and random effects models to verify the sample's suitability to the method used and it reject the null hypothesis that there are no systematic differences in the estimated coefficients[7], making the fixed effect model the best to capture the deforestation determinants. In addition, following Baumont (2004), we chose the spatial lag matrix that generated the largest Moran's I coefficient for the fixed effect (2) model residues to estimate the Dynamic Spatial Panel Model, opting for the queen matrix. Moreover, we identified the presence of heteroscedasticity and in order to control the problem, we estimated the spatial dynamic models using the standard robust error of Huber/White/Sandwich (HUBER, 1967).

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

According to Grossman and Krueger (1995) and De Bruyn et al. (1998), the choice between the quadratic and cubic model, in the EKC context, is determined by selecting the one that presented statistical significance for the per capita income variable. Therefore, the model in its quadratic format, DSDM (2), are the most appropriate, since the cubic (3) did not presented statistical significance. The coefficients' signs, $\beta_1 > 0$ and $\beta_2 < 0$ indicate that we have an inverted-"U" format, demonstrating that deforestation will increase until a certain threshold as the region grows economically, from which it begins to fall. This

[7] Chi² statistics: 212.8, with a probability of 0,000.

empirical evidence is in line with Gomes and Braga (2008), Prates (2008), Santos et al. (2008), Polomé and Trotignon (2016), Tritsch and Arvor (2016) who also found that economic development induces deforestation slowdown in the long run.

Table 3 – Dynamic Spatial Autoregressive model (DSAR) and Dynamic Spatial Durbin Model (DSDM) for EKC in Legal Amazon, from 2000 to 2015,

VARIABLES	DSAR (2)	DSAR (3)	**DSDM (2)**	DSDM (3)
DEFOREST $(\gamma)_{t-1}$	0.1371***	0.1372***	**0.1365*** **	0.1366***
W_DEFOREST $(\rho)_t$	1.3768***	1.3775***	**1.3237*** **	1.3244***
GDP	0.0002	-3.42E-06	**0.0003*** **	0.0001
GDP²	-1.66E-09	3.08E-09	**-2.36E-09** **	1.57E-09
GDP³	-	-2.49E-14	**-**	-2.07E-14
A.SUGARCANE	-0.0001	-0.0001	**-0.0002**	-0.0001
A.MAIZE	-0.0001	-0.0001	**-0.0001**	-0.0001
A.SOYBEAN	7.04E-06	9.73E-06	**2.68E-05**	2.89E-05
CATTLE	0.0001***	0.0001***	**0.0001*** **	0.0001**
FOREST.COVER	0.0010***	0.0010***	**0.0011*** **	0.0011**
DEM.DENSITY	0.0131	0.0127	**0.0064**	0.0059
SILVICULTURE	-3.85E-07	-4.08E-07	**-3.22E-07**	-3.30E-07
EXTRAC.WOOD	3.27E-05**	3.33E-05**	**3.33E-05** **	3.37E-05**
AGRIC.GDP	0.0344	0.0393	**0.1089** **	0.1126**
MAIZE.PROD	-0.0012***	-0.0011***	**-0.0009** **	-0.0009**
SOYBEAN.PROD	-0.0008	-0.0008	**-0.0005**	-0.0005
SUGARCANE.PROD	1.82E-05	1.83E-05	**-5.62E-06**	-5.42E-06
RURAL CREDIT	1.40E-08*	1.42E-08*	**1.28E-08* **	1.29E-08*
D.OUTLIER	102.5200***	102.5083***	**100.4746*** **	100.4636***
W_GDP	-	-	**-0.0007*** **	-0.0007***
W_A.SUGARCANE	-	-	**0.0007**	0.0007
W_A.MAIZE	-	-	**0.0005**	0.0005
W_A.SOYBEAN	-	-	**-4.99E-05**	-4.93E-05
W_CATTLE	-	-	**1.51E-05**	1.44E-05
W_FOREST.COVER	-	-	**-0.0007**	-0.0007
W_DEM.DENSITY	-	-	**0.0049**	0.0060
W_SILVICULTURE	-	-	**5.95E-06**	5.62E-06
W_EXTRAC.WOOD	-	-	**0.0001**	0.0001
W_AGRIC.GDP	-	-	**-0.5480*** **	-0.5456***
W_MAIZE.PROD	-	-	**-0.0008**	-0.0008
W_SOYBEAN.PROD	-	-	**-0.0040** **	-0.0039**
W_SUGARCANE.PROD	-	-	**0.0003*** **	0.0003***
W_RURAL CREDIT	-	-	**9.81E-09* **	1.00E-08*
W_D.OUTLIER	-	-	**62.9460*** **	62.8907***
Akaike	99019.06	99017.62	**98965.63**	98964.66

Source: research data. *Note:* Significant at *** 1%; ** 5%. * 1%. D.OUTLIER is a dichotomous variable for the municipalities that are leverage points detected in the ESDA. They reinforce the deforestation pattern observed.[8]

Using $\tau = -\beta_1/2\beta_2$ to calculate the EKC "turning point", where the curve reaches its maximum value, we find a value of annual per capita GDP of R$66.059,32 with 2010 as base year. This income, however, is considerably large than the Legal Amazon average of R$11.028,51 and only four municipalities in the region is above this turning point threshold. In other words, despite the fact that we got an inverted "U" curve for EKC, the majority of the region's counties are far below this turning point, which means that income growth will continue to induce deforestation on the Amazon. In addition, the per capita GDP growth

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

presented a negative spatial spillover effect, reducing deforestation in its neighbors, a fact that can minimize the high turning point. However, even in the long run, the economic growth may not be a sufficient factor to generate biome protection, since there are other variables that also impacts deforestation. This translates into a trade-off among development and forest conservation, as supported by Igliori (2006b), Celentano et al. (2012) and Chagas and Andrade (2017).

Among the other results, we have the dependent variable temporarily lagged, $\mathrm{DEFOREST}_{t-1}$, which presented a coefficient (γ) statistically significant at the 1% level, with a positive impact on deforestation. Therefore, this fact corroborates the hypotheses and empirical evidence from Andrade de Sá et al. (2015) and Amin et al. (2019) that deforestation in t is positively influenced by its value in $t-1$, and have greater importance to explain environmental degradation in the municipalities of the Legal Amazon. This scenario helps to explain the dynamics presented by deforestation in Figure 2 and 3, where it is evident that some regions that deforested the most in 2005 continued to do it in 2015, evidencing an inertial component in environmental degradation. Thus, the evidence presented here demonstrates the need and importance in incorporating the deforestation temporal inertia in the analysis of its determinants in the EKC model.

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

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

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

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

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

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

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

Therefore, the expansion of cultivated area for both soy and sugarcane causes cattle rearing displacement to counties usually in the agricultural frontier, inducing deforestation (ANDRADE DE SÁ et al., 2012; ANDRADE DE SÁ et al., 2013; GOLLNOW e LAKES, 2014). In summary, cattle herd growth may also encompass the indirect soy and sugarcane influence along with its own determinants. A possible solution for the problem is to incentive production intensification in existing agricultural areas, which would enable Brazil to reduce significantly its deforestation and greenhouse gas emissions and still maintain agricultural growth (COHN et al., 2014; CORTNER et al., 2019). Although sugarcane is not a predominant crop in the region and has no important area effect, its productivity growth have positive spillover effects in its neighbors, corroborating the Assunção and Rocha (2019) affirmation that recent expansion of Brazilian ethanol production leads to direct deforestation in the Amazon.

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

4. Final Considerations

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

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

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

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

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

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

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

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

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

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

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