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RESEARCH ARTICLE

Testing Kuznets' environmental hypothesis for the Legal Amazon: a nonlinear approach

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Abstract
This study tests the null hypothesis that no significant differences exist in the relationship between economic growth and deforestation, based on the levels of growth and agricultural productivity in the municipalities of the Brazilian Legal Amazon. Grounded in the environmental Kuznets curve theory, this study employs a non-linear methodological approach to estimate the relationship between economic growth and deforestation. The results reject the null hypothesis, indicating that the relationship between growth and deforestation varies with the municipalities' productive performance. Furthermore, the findings conclude that a negative monotonic relationship exists between economic growth and deforestation in the Brazilian Legal Amazon, suggesting that reductions in deforestation are achievable even during periods of economic expansion.

Keywords: deforestation; economic growth; environmental Kuznets curve; Legal Amazon

JEL classification: Q50; Q56; Q57

1. Introduction

This paper addresses the question of how deforestation is influenced by the economic growth of municipalities located in one of the richest, most complex and important ecosystems for the functioning of the planet. The economic literature indicates that intensive agricultural activities in the use of natural resources play a significant role in deforestation. This phenomenon prompts various discussions about the advancement of agricultural frontiers in developing countries, such as Brazil. In this context, it is questioned whether the hypothesis of sustainable equilibrium specifically applies to agricultural activities (Danfeng, Dawson and Baoguo, 2006; Ibáñez *et al.*, 2007; Garnett, 2009; Taheripour and Tyner, 2013; Caro *et al.*, 2014; Slade, 2018; Marques *et al.*, 2020; Hong *et al.*, 2021).

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Since the formalisation of the environmental approach of the Kuznets hypothesis (Grossman and Krueger, 1991), the idea of a turning point in the relationship between growth and deforestation has been empirically tested in various economies. The results vary depending on the economy studied and the method employed for hypothesis testing. For example, a minimum point was identified by Hill and Magnani (2002), while Shafik (1994), Holtz-Eakin and Selden (1995), Al-Mulali *et al.* (2015) and Nasir *et al.* (2019) observed a positive linear relationship. On the other hand, Roberts and Grimes (1997) found mixed and inconclusive results for this relationship.

Additionally, Sirag *et al.* (2018) suggested a further assumption for the relationship proposed in the environmental hypothesis of Kuznets. According to this assumption, in addition to the potential existence of a turning point, there could be a level of economic growth capable of causing a break in how growth impacts deforestation. If this assumption is validated, then the EKC would transition from a continuous linear relationship to a discontinuous nonlinear relationship.

Based on these considerations, the main objective of this study is to test the null hypothesis that there are no significant differences in the relationship between economic growth and deforestation as the productivity of agriculture and livestock increases. For this purpose, we direct the study to a portion of Brazilian territory known as the Legal Amazon.[1] We use this territory as the subject of the study because the Legal Amazon contains the vast majority of Brazil's environmental preservation areas and is the location where most governmental efforts to develop activities to contain deforestation are concentrated, while the region experiences an expansion of agricultural activities.

This investigation contributes to exploring the interaction between economic growth and deforestation from a distinctive theoretical perspective and pinpoints the growth phases during which enhancements in production prompt significant environmental transformations. Additionally, it extends the discussion concerning growth-environment relationships for emerging economic sectors in the Brazilian Amazon.

The results indicated that the null hypothesis of the study, as well as the "inverted U" functional form proposed in the EKC, should be rejected for the agriculture and livestock of the Brazilian Legal Amazon, since the relationship between growth and deforestation obtained in the research was negative. In other words, we conclude that the growth of agricultural activities in the Legal Amazon can occursimultaneously as the levels of deforestation decrease.

In addition to this introduction, in the second section, we present the methodology, explaining the area studied, the data and the estimation strategy used in the EKC. In the third section, we discuss the results obtained, and finally, we describe the conclusions.

[1]The Legal Amazon was initially defined by Law No. 1,806 of 1953 and expanded by Law No. 5,173 of 1966 to include parts of various states and federal territories. The area was further enlarged in 1977 by Complementary Law No. 31 to encompass the entire State of Mato Grosso. Significant institutional reforms occurred with Provisional Measure No. 2,146-1 of 2001 and Complementary Law No. 124 of 2007, which restructured the regional development bodies, notably Superintendence of Amazonian Development - SUDAM (IBGE, 2024).

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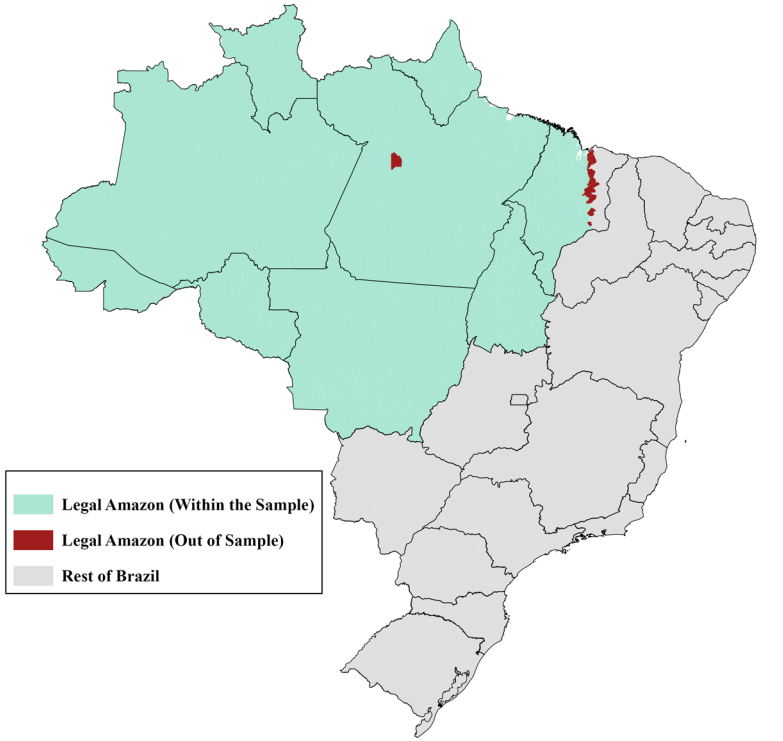


Figure 1. Territorial delimitation of the study area.
Source: Elaborated by the authors.

2. Methodology

2.1. Study area

This work is specifically directed to the region known as the Brazilian Legal Amazon. According to IBGE (2022a), this territory encompasses approximately 5.2 million square kilometres, covering the entire area of the Legal Amazon, along with 20 per cent of the Cerrado Biome area and part of the Pantanal Mato-Grossense. The territorial extension of the Brazilian Legal Amazon represents about 61 per cent of Brazil's territory. In total, the Brazilian Legal Amazon comprises 52 municipalities in the state of Rondônia, 22 in Acre, 62 in Amazonas, 15 in Roraima, 144 in Pará, 16 in Amapá, 139 in Tocantins, 181 in Maranhão and 141 in Mato Grosso. Figure 1 illustrates the geographic distribution of the municipalities that make up the Legal Amazon within Brazilian territory.

We selected the Brazilian Legal Amazon as our study area because it is a key location where the majority of Brazil's environmental planning actions are implemented. Additionally, this region is frequently chosen as the subject of research focusing on economic and environmental issues, as evidenced by studies conducted by Caetano *et al.* (2011), Mendes *et al.* (2012), Assunção *et al.* (2020), Stabile *et al.* (2020) and Do Prado *et al.* (2020).

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2.2. Data

The data used in this study span from 2005 to 2018 and comprise an unbalanced panel of data[2] for 733 municipalities within the Brazilian Legal Amazon. The period was chosen based on the availability of data for the variables constituting the database. However, the number of municipalities included is less than the total in the Brazilian Legal Amazon due to missing data on certain key variables, meaning the database only covers those municipalities where information is available for all necessary variables to estimate the EKC.

To measure deforestation, we calculate the ratio of the annual increase in deforestation (in square kilometres) to the total territorial area of each municipality.[3] This information is sourced from INPE (2022). To represent economic growth, we use the per capita Gross Domestic Product (GDP) for each municipality, provided annually by IBGE (2022e).

The matrix of control variables includes data on the demographic density of the municipalities, sourced from IBGE (2022b), along with information on the average price of key agricultural activities conducted in each municipality. The rationale for incorporating agricultural prices into the matrix is based on the hypothesis by Assunção *et al.* (2020), which suggests that price fluctuations in these activities directly impact the economic growth of the Legal Amazon. To mitigate endogeneity issues arising from the causality between prices and growth, this study employs the price estimation strategy outlined by Assunção, Gandour and Rocha (2015). This strategy posits that prices in other regions are closely correlated with those in the Legal Amazon, yet prices outside the region of interest remain completely exogenous to local market indicators. Consequently, Assunção, Gandour and Rocha (2015) suggests that an accurate and exogenous estimate of agricultural prices for the target area can be derived from the prices in other markets, weighted by the contribution of specific activities to agriculture and/or livestock in general.

Given the available information on planted areas and the representativeness of production in the municipalities comprising the sample, it was decided to include the prices of corn, cassava and rice in the control matrix.[4] To illustrate the estimation of exogenous agricultural prices, consider j as the index for the $j-th$ activity and i as the index for the $i-th$ municipality. Let Pf represent the price practised outside the Legal

[2]It is important to note that some studies suggest the possibility of selection bias in statistical procedures that utilise unbalanced data panels (Verbeek and Nijman, 1992; Lokshin, 2009). Nonetheless, the primary aim of the EKC is not to establish a pure cause-and-effect relationship, but rather to indicate the direction of the relationship between growth and deforestation at different stages of economic development. In essence, the main focus of EKC estimation lies in the sign of the coefficients, rather than their magnitudes. Therefore, the bias stemming from the unbalanced data panel will only critically impact the testing of the EKC hypothesis if it is substantial enough to reverse the sign of the estimated coefficients. Generally, the literature tends to dismiss this concern.

[3]Examples of studies using this approach include Ehrhardt-Martine Crenshaw and Jenkins (2002), Culas (2007) and Chiu (2012).

[4]Product prices serve as an incentive for local producers to either increase or decrease their production levels, which, in turn, could alter patterns of deforestation. As product quotations are not available for the municipalities of the Legal Amazon, the most practical method for acquiring these values was to estimate prices exogenous to those practised in the study area, using a method recognised by the literature.

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Amazon, P the estimated exogenous price and A the proportion of the $j-th$ planted area relative to the total planted area of a specific municipality; then:

$$P_i = Pf_{j,i} * A_{j,i} \tag{1}$$

Regarding the prices of activities related to livestock, the control matrix includes information on the price of milk and the price of fat cattle. Let R represent the cattle herd and V denote the number of cows milked; the estimated exogenous price for fat cattle is then calculated as follows:

$$P_i = Pf_{j,i} * \left[\frac{R_{j,i} - V_{i,j}}{R_{j,i}}\right] \tag{2}$$

And the estimated exogenous price of milk is calculated as follows:

$$P_i = Pf_{j,i} * \left[\frac{V_{i,j}}{R_{j,i}}\right] \tag{3}$$

We estimate prices separately for each year included in the sample. Following the methodology of Assunção, Gandour and Rocha (2015), we use price data from the state of Paraná[5] to represent the prices of products practised outside the Legal Amazon. For this purpose, we utilise the historical price series from the Center for Advanced Studies in Applied Economics at the University of São Paulo (CEPEA/USP, 2022). The data on planted areas were sourced from IBGE (2022c), and information on the cattle herd and the number of milked cows was obtained from IBGE (2022d).

Prices serve as an incentive for producers to increase their production levels, thereby affecting deforestation in the region. It is important to note that if there is a reduction in the planted area within the Legal Amazon, then for the estimated prices to rise, the prices outside the Legal Amazon must not decrease by a greater magnitude than the increase in the area planted in the study area. The same principle applies to livestock: if the internal proportion of the herd designated for milk production (or beef cattle) decreases, then estimated prices will only increase if the prices practised outside the Legal Amazon do not fall in a proportion greater than the changes in domestic prices.

To control for the effects resulting from government interventions on the environment, the matrix of control variables includes data on the number of environmental fines, the number of environmental infraction notices and the number of environmental embargoes. This information was sourced from the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA, 2022). All monetary values have been adjusted to December 2020 levels using the Broad Consumer Price Index (IPCA).

Assunção *et al.* (2020) showed that rural credit can impact deforestation and environmental degradation in the Brazilian Legal Amazon. To control for effects arising from this variable, the control matrix includes information on the amount of rural credit allocated to producers in the municipalities comprising the sample for each hectare of planted area. Additionally, Piguet (2010) and Stef and Ben (2020) suggested that climate change directly affects environmental degradation. Consequently, the matrix of control variables incorporates values for average annual temperature,

[5]See https://educa.ibge.gov.br/images/vamoscontar/atividades/populacao_total_uf_2010.jpg.

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average annual precipitation, the deviation of the average annual temperature from the period's average and the deviation of the average annual precipitation from the period's average. Climatic variable data were sourced from the research of Camarillo-Naranjo *et al.* (2019).

We aim to investigate whether production gains in municipalities experiencing higher growth patterns lead to significant changes in the deforestation of the Legal Amazon. For this hypothesis, it is prudent to consider that the EKC exhibits a threshold where the relationship between economic growth and deforestation becomes discontinuous. Identifying this threshold could aid in the strategic planning of production and environmental preservation within the study area.

To enhance the relevance of our results, we conducted three separate estimates, each utilising a different threshold variable: GDP per capita, land productivity in agriculture and dairy farming productivity. For agriculture, land productivity is measured by the ratio of total production value to planted area in each municipality. In the case of livestock, we assess dairy productivity by the ratio of total milk production (in litres) to the number of cattle in each municipality. We utilised data from IBGE (2022c) for calculating land productivity and from IBGE (2022d) for dairy productivity.

2.3. EKC estimation

To estimate the EKC, we initially employ the functional form defined by Ozcan (2013). This model posits that the deforestation in the $i-th$ municipality during the $t-th$ period $(Desm_(i,t))$ is influenced by the deforestation that occurred in the previous period. Specifically, it suggests:

$$log(Desm_{i,t}) = \beta log(Desm_{i,t-1}) + \theta_1 log(Pib_{i,t}) + \theta_2 log(Pib_{i,t})^2 + \theta_3 + \gamma X_{i,t} + \varepsilon_{i,t} \quad (4)$$

where X is the array of control variables. In this case, $log(Desm_(i,t-1))$ is considered to be endogenous in the model, while the other components of equation 4 are considered exogenous. To consider the threshold in the EKC and resolve any problems associated with endogeneity in the estimation of equation 4, we use the specification of a dynamic panel with threshold proposed by Kremer *et al.* (2013). This procedure consists of estimating the EKC according to the following specification:

$$\begin{aligned} log(Desm_{i,t}) = \beta log(Desm_{i,t-1}) + \tau_1 log(Pib_{i,t}) I(log(TH_{i,t}) \leq \lambda) + \\ \tau_2 log(Pib_{i,t}) I(log(TH_{i,t}) > \lambda) + \gamma X_{i,t} + \varepsilon_{i,t} \end{aligned} \quad (5)$$

Where TH is the threshold variable, which in this study includes the productivity of land in the agricultural sector and the productivity of dairy farming; λ represents the threshold; β, τ and γ are the estimated model parameters; and ε is the error term of the estimate. This functional form allows us to identify the point at which the threshold variable causes the EKC to reach an inflection point and the relationship between growth and deforestation to start changing direction. It is important to note that in the threshold estimates, a set of variables that are both dependent and independent of the threshold is considered. In this study, GDP per capita is the variable that depends on the threshold, enabling the exploration of the relationship between growth and deforestation both before and after the threshold is reached, despite the threshold variable not directly representing economic growth.

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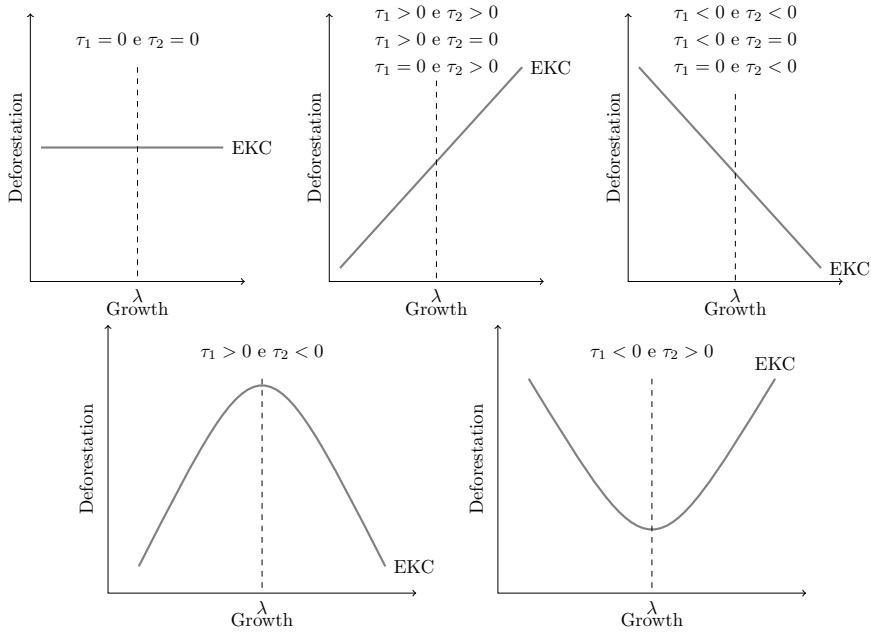


Figure 2. Possible formats for EKC with threshold.
Source: Elaborated by the authors.

To test the null hypothesis that there is no discontinuity in the relationship between economic growth and deforestation in the Brazilian Legal Amazon, it is posited that a single threshold accurately represents the abrupt changes in the responses of deforestation to changes in economic growth. This assumption suggests that, if present, there is a single threshold across the entire span of the EKC. Based on this assumption, nine specific scenarios can occur, each represented in figure 2.

It is important to emphasise that a conventional estimate of a second-order polynomial equation could accurately represent the relationship between growth and deforestation in the Legal Amazon. However, the nonlinear approach offers the advantage of testing the hypothesis concerning the EKC while it facilitates the examination of whether municipalities in more advanced stages of growth can achieve additional production gains without abrupt changes in deforestation levels. In essence, the nonlinear approach enables the estimation of the EKC and the verification of whether the resulting curve from the estimate is continuous.

It is also important to emphasise that this technique captures the non-linearity of the EKC more effectively than the conventional quadratic approach (Ozcan, 2013; Sirag *et al.*, 2018). Additionally, the threshold dynamics panel we employ allows us to precisely identify the turning point of the EKC.

To address the issues associated with fixed effects, we employed the direct orthogonal deviation transformation technique proposed by Arellano and Bover (1995). Essentially, this method involves eliminating the serial correlation in the transformed error terms by subtracting the mean of all future observations. The direct orthogonal

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deviation transformation technique is formulated as follows:

$$\varepsilon_{it}^{*} = \sqrt{\frac{T-t}{T-t+1}}\left[\varepsilon_{it} - \frac{1}{T-t}\left(\varepsilon_{i(t+1)} + \cdots + \varepsilon_{iT}\right)\right] \tag{6}$$

In this equation, ε_{it} represents the transformed error vector, and T denotes the number of periods. The advantage of using this transformation is that it allows the correlation between the residuals to remain zero over time.

The procedure for estimating the EKC and the estimation threshold follows a methodology similar to that employed by Kremer *et al.* (2013) and Sirag *et al.* (2018). Initially, the endogenous components of equation 6 are regressed using the instruments contained in the matrix $X_{i,t}$ through the Generalised Method of Moments. Subsequently, the predicted values are substituted into the EKC equation, and the threshold λ is calculated using an Ordinary Least Squares estimate, determined by minimising the sum of squared residuals. The statistical significance of the threshold is assessed using a likelihood ratio test with a 95 per cent confidence interval, as suggested by Hansen (1999) and Caner and Hansen (2004).

3. Results

Before conducting the estimations, it is crucial to comprehend the fundamental characteristics of the data. Table 1 presents the descriptive statistics of the variables employed in estimating the EKC. The dataset comprises 8,781 observations, constituting an unbalanced panel featuring 760 municipalities and spanning 14 years from 2005 to 2018. The results reveal that, on average, each municipality in the sample possesses a population density of around 13.31 inhabitants per square kilometre and a GDP per capita of approximately R$ 16,864.80 per inhabitant. Additionally, it can be observed that the average deforestation increase for each municipality is about 13.04 square kilometres between 2005 and 2018.

The descriptive statistics also reveal that the estimated mean price of corn in the Legal Amazon during the study period was roughly R$ 9.04 per 60 kg sack, while the price of a 60 kg sack of rice averaged approximately R$ 9.04. The calculated average price per arroba of live cattle stood at approximately R$ 144.68, whereas the mean price per litre of milk was about R$ 0.08. In terms of productivity metrics, the findings show that, on average, each milked cow yielded around 0.70 litres of milk over the study period, while land productivity amounted to roughly R$ 3,964.30 per cultivated hectare.

Climate-related statistics depict that the mean temperature in the Brazilian Legal Amazon between 2005 and 2018 hovered around 27.17 °C, with a variation from the period's mean of about 0.76 °C. As for precipitation, the descriptive statistics indicate an average rainfall volume of approximately 1849.44 mm in the Legal Amazon throughout the studied period, with a divergence from the historical mean of about 14.65 mm. These results underscore that climate fluctuations in the study region are more closely associated with temperature change, as the precipitation volume shows minimal variability over the years.

In order to enhance our comprehension of the primary data underlying this analysis, figure 3 illustrates the variability in data pertaining to deforestation (panel (a))

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Table 1. Descriptive statistics of variables

	Average	Standard deviation	Minimum	Maximum
Rural credit	4,373.96	14,161.53	0.00	440,667.72
Demographic density	13.31	20.83	0.15	271.28
Precipitation deviation	-14.65	303.91	-1,805.43	1,096.04
Temperature deviation	0.76	0.60	-2.11	6.64
Embargoes	4.50	16.92	0.00	599.00
Increase in deforestation	13.04	42.80	0.00	1,407.90
Notices of infractions	11.13	31.67	0.00	904.00
Environmental fines	17.43	63.42	0.00	1,765.00
Rice price	9.04	8.93	0.00	55.33
Fat ox price	144.68	22.23	12.69	188.87
Per capita GDP	16.86	16.40	2.72	318.77
Milk price	0.08	0.07	0.00	1.18
Manioc price	68.96	86.56	0.01	593.55
Corn price	9.94	6.96	0.01	46.99
Precipitation	1,849.44	496.41	571.00	3,782.70
Livestock productivity	0.70	0.38	0.06	2.89
Land productivity	3.96	3.05	0.40	58.51
Temperature	27.17	0.95	23.21	33.69

Source: Prepared by the authors.
Notes: We calculate exogenous prices according to Assunção, Gandour and Rocha (2015). The number of observations for all the variables is 8,781.

and economic growth (panels (b)–(d)). It is noteworthy that in each year encompassed within the analysis, the mean value of this data (depicted by the green line) closely approximates the minimum values for each variable. This outcome indicates that when comparing all municipalities within the Legal Amazon, the majority of them exhibit a limited degree of economic growth while, concurrently, most of these municipalities register relatively low levels of deforestation.

However, it is important to note that certain municipalities are experiencing significantly higher levels of growth compared to the Legal Amazon's average. Consequently, there is a potential for deforestation in these municipalities to respond to growth-related changes in a manner distinct from what is observed in areas with relatively lower economic growth. Moreover, given that these municipalities have already reached an advanced stage of growth, achieving further production gains may necessitate a sudden shift in deforestation.

Table 2 presents the outcomes of EKC estimations employing a threshold approach, as proposed by Kremer *et al.* (2013). We conducted three distinct estimations, each utilising a different threshold variable: GDP per capita, land productivity and dairy cattle productivity. The findings allow us to conclude that while each estimation defines a specific threshold beyond which the relationship between economic growth and

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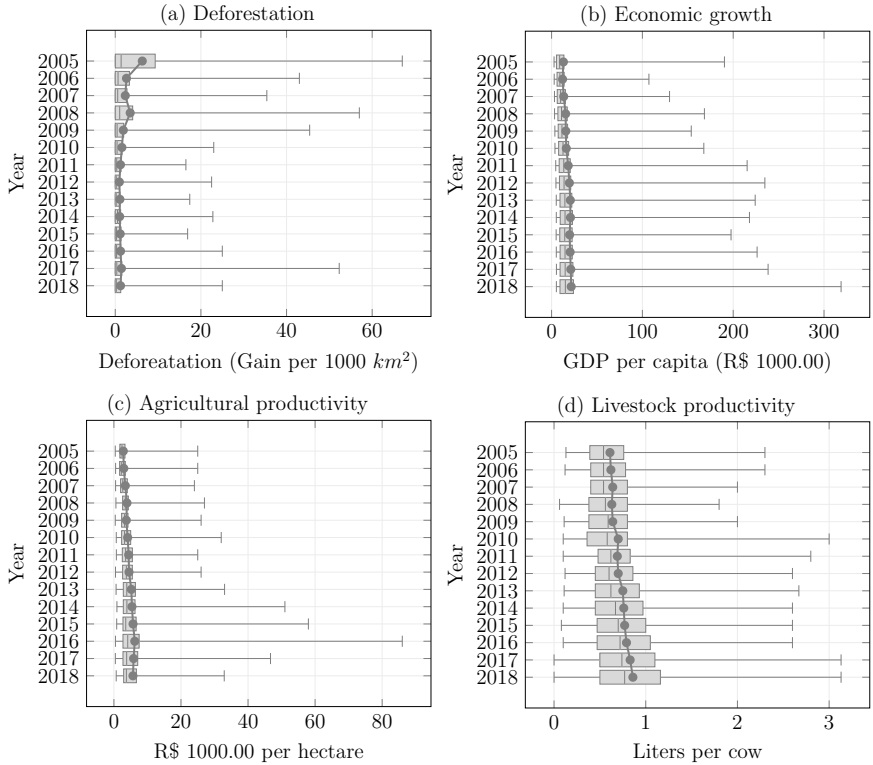


Figure 3. Summary of growth and deforestation in the Legal Amazon.
Source: Elaborated by the authors according to research data.

deforestation undergoes a change, the overall directional trend of this relationship remains consistent both above and below the threshold.

In simpler terms, during the initial stages of growth in the Legal Amazon, it is conceivable that deforestation levels may decrease, even as economic growth continues to accrue. Once a certain threshold of growth (or agricultural productivity) is reached, the sensitivity of deforestation in response to changes in growth levels does shift; however, the fundamental relationship between growth and deforestation remains negative. Hence, the EKC retains a negative slope throughout its entire range, with the only variation occurring in the degree of slope before and after the threshold point.

The analysis of the time lag in deforestation reveals a persistent trend over time. This indicates that increases in deforestation in previous periods invariably lead to a corresponding rise in the present period. In other words, deforestation tends to persist in municipalities with a history of substantial deforestation. This suggests that in areas with a historical pattern of increasing deforestation, transitioning from conventional production methods to 'clean production' methods offers limited scalability benefits. Consequently, it may still be more economically viable for producers to prioritise higher levels of production, even at the expense of increased deforestation, rather than entering the market for environmentally sustainable products.

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Table 2. Results of the estimates

Variable	Per capita GDP	Agriculture	Livestock
τ_1	-0.6379 (0.2155)	-1.0623 (0.1653)	-1.6288 (0.1590)
τ_2	-1.1476 (0.1638)	-1.2790 (0.1584)	-1.4057 (0.1635)
$log(Desm_{i,t-1})$	0.3214 (0.0337)	0.2897 (0.0322)	0.2844 (0.0338)
log(Demographic density)	-2.0525 (0.4753)	-2.7914 (0.4884)	-1.3345 (0.4932)
log(Infraction notices)	0.3393 (0.0588)	0.3273 (0.0596)	0.3186 (0.0557)
log(Environmental fines)	-0.1044 (0.0303)	-0.1323 (0.0313)	-0.0155 (0.0318)
log(Environmental embargoes)	-0.4007 (0.0622)	-0.3410 (0.0609)	-0.4170 (0.0605)
log(Corn price)	0.1610 (0.0627)	0.1863 (0.0579)	0.2499 (0.0566)
log(Manioc price)	0.2589 (0.0325)	0.2299 (0.0355)	0.2352 (0.0331)
log(Rice price)	-0.1777 (0.0410)	-0.2137 (0.0402)	-0.0906 (0.0405)
log(Fat ox price)	0.8696 (0.1108)	0.8949 (0.1078)	0.7680 (0.1027)
log(Milk price)	-0.7626 (1.1583)	0.0546 (1.2227)	-1.1089 (1.2444)
log(Rural credit)	-0.1844 (0.0297)	-0.2034 (0.0291)	-0.1806 (0.0298)
log(Precipitation)	0.8369 (0.3071)	0.4741 (0.3137)	0.7009 (0.3172)
log(Temperature)	-158.9337 (31.5814)	-143.5384 (30.6748)	-112.7987 (29.9369)
Precipitation deviation	-0.0008 (0.0002)	-0.0006 (0.0002)	-0.0008 (0.0002)
Temperature deviation	5.3487 (1.1025)	4.7438 (1.0687)	3.7103 (1.0526)
Constant	517.9345 (103.9171)	472.1732 (100.6722)	366,9822 (98.1561)
Threshold	8.131,14 (R dollar)	3.501,35 (R dollar / hc)	0,6848 (litres/cow)

Source: Prepared by the authors based on research results.
Note: Standard deviation in parentheses.

Despite these findings, the coefficients τ_1 and τ_2 reveal that the Brazilian Legal Amazon exhibits an EKC with a negative slope. This suggests that, even though deforestation persists over time, producers can achieve greater productivity gains with decreasing rates of deforestation.[6] Consequently, the relationship between economic growth and deforestation in the Brazilian Legal Amazon is inverse, with only the sensitivity of growth to deforestation differing among municipalities situated above and below the thresholds considered in the estimations. Figure 4 provides a detailed representation of the EKC based on the results presented in table 2.

Panel (a) displays the EKC representation based on the estimation employing GDP per capita as the threshold variable. The findings reveal that in municipalities where GDP per capita is below the threshold value (R$ 8,131.14 per inhabitant), the EKC

[6]It is important to note that if deforestation increases (decreases) in the current period, the presence of temporal deforestation persistence would imply positive (negative) deforestation in the subsequent period, even if production were non-existent. Therefore, the negative slope of the EKC and the positive sign of the persistence parameter offer statistical evidence that, over time, producers in the Brazilian Legal Amazon are simultaneously increasing production gains while reducing deforestation.

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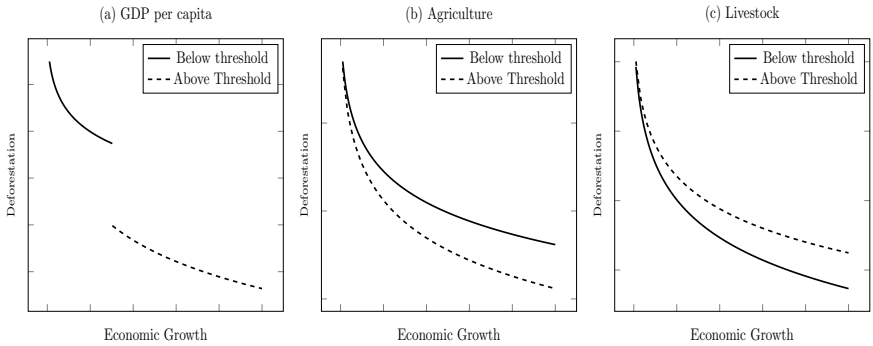


Figure 4. Representation of the EKC estimate.
Source: Prepared by the authors based on research results.

exhibits a less steep slope compared to municipalities with GDP per capita exceeding the threshold. This outcome suggests that in advanced stages of economic growth,[7] significant reductions in deforestation can be accomplished, provided economic agents accept positive rates of economic growth. Furthermore, this result also indicates that municipalities with higher growth levels are more sensitive to deforestation in relation to economic growth, implying that even with higher levels of growth, substantial reductions in deforestation can still be attained. Similar trends are observed when land productivity serves as the threshold variable. However, these patterns do not hold true for cases where the threshold variable is dairy farming productivity.

Regarding land productivity, municipalities that yield more than R$ 3,501.35 per hectare exhibit a steeper EKC, indicating a greater susceptibility to deforestation in response to economic growth, compared to municipalities with productivity below this threshold. Nevertheless, this characteristic does not persist when the threshold variable is dairy farming productivity. In this case, the difference in the EKC slope before and after the threshold is smaller. When the analysis is conducted using GDP per capita and land productivity as threshold variables, the results suggest that economic growth can be simultaneously achieved while effectively reducing deforestation in municipalities with high-growth levels and land productivity. However, when the analysis is approached from the perspective of dairy productivity, the results indicate a more pronounced negative response of deforestation to growth gains in municipalities with low productivity.

Please note that the negative slope of the EKC, associated with the logarithmic specification of the estimated equation, enables us to observe that as economic growth increases, the disparity in the sensitivity of deforestation concerning growth widens between municipalities situated above and below the threshold. It becomes evident that as economic growth escalates, there is a smoothing effect in the trajectory of the

[7]In academic literature, advanced stages of economic growth are generally characterised by economies boasting the highest technological standards, superior productivity indicators and substantial product and wealth gains. In this study, we employ municipalities with higher levels of economic growth as a proxy for such advanced economies.

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EKC, both for municipalities with growth rates below the threshold and for those with GDP per capita above the threshold. This outcome indicates that within the Brazilian Legal Amazon, deforestation exhibits a stronger response to economic growth during the initial stages of municipal growth and in municipalities with low levels of growth and agricultural productivity. Consequently, these findings may suggest that any potential intervention aimed at altering deforestation levels in the Brazilian Legal Amazon should prioritise changes in the economic growth of municipalities characterised by low growth rates or limited agricultural sector productivity.

It is crucial to emphasise that the parameters obtained in the EKC estimation should not be interpreted causally. The purpose of the estimation is solely to determine the sign of the relationship between economic growth and deforestation based on the estimated threshold. When applying this definition to the representation depicted in figure 4, it is inappropriate to assert that any potential alteration or intervention in economic growth within the Legal Amazon will yield a corresponding change in deforestation equivalent to the slope of the EKC. The estimated coefficients and the structure of the EKC can only suggest that, in a general sense, there is a possibility of reductions in deforestation in the Brazilian Legal Amazon, even when municipalities experience positive economic growth.

These results also provide insights into the sustainability of development patterns in the Legal Amazon. Since the relationship between economic growth and deforestation is negative, there are statistical indications that municipalities in the study area are progressing within an environmentally sustainable framework. This suggests that local economies can concurrently achieve continual gains in production and environmental preservation.

For the sake of comparison, table 3 displays the outcomes of EKC estimations using a quadratic polynomial functional form in a fixed effects estimator. It is worth noting that for general economic growth and dairy farming, the EKC's slope remains negative, while this slope is zero for agriculture. However, it is important to recognise that the conventional estimate does not facilitate the identification of potential discontinuity points in the curve, hindering the precise pinpointing of instances where increasing growth gains might lead to abrupt alterations in the region's deforestation.

Despite the theoretical proposition by Grossman and Krueger (1991) suggesting an "inverted U" relationship between economic growth and deforestation, this configuration is not consistently confirmed in empirical studies aimed at testing the EKC hypothesis. For instance, Marrero (2010) examined the EKC hypothesis for a selection of European countries and found that, within this specific group of countries, the connection between economic growth and deforestation is null. Consequently, this allowed the aforementioned author to reject the "inverted U" hypothesis put forth by Grossman and Krueger (1991). Other studies have also yielded conclusions contradictory to the "inverted U" shape, as demonstrated in Bölük and Mert (2014), Lapinskienė, Tvaronavičienė and Vaitkus (2014) and Abid (2017). In light of these observations, although the estimations conducted in this study do not establish the existence of an "inverted U" relationship between economic growth and deforestation in the Brazilian Legal Amazon, this outcome aligns with the patterns observed in other studies examining the same theory.

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Table 3. Standard EKC estimate

Variable	Per capita GDP	Agriculture	Livestock
Growth	0.5022(0.0369)	-0.0115(0.1136)	-0.7637(0.3669)
growth squared	-0.0778(0.0369)	0.0080(0.0280)	0.4733(0.2644)
$log(Desm_{i,t-1})$	-0.1140(0.0212)	-0.1144(0.0213)	-0.1154(0.0213)
log(Demographic density)	0.3539(0.2684)	0.2796(0.2588)	0.2804(0.2582)
log(Infraction notices)	0.0452(0.0142)	0.0464(0.0142)	0.0474(0.0142)
log(Environmental fines)	-0.0117(0.0092)	-0.0124(0.0092)	-0.0142(0.0092)
log(Environmental embargoes)	-0.0186(0.0142)	-0.0198(0.0142)	-0.0191(0.0142)
log(Corn price)	-0.0509(0.0194)	-0.0500(0.0199)	-0.0502(0.0194)
log(Manioc price)	0.0079(0.0154)	0.0087(0.0157)	0.0081(0.0154)
log(Rice price)	0.0253(0.0162)	0.0263(0.0167)	0.0252(0.0161)
log(Fat ox price)	-0.5221(0.1395)	-0.5175(0.1395)	-0.5543(0.1417)
log(Milk price)	-0.5178(0.4012)	-0.5172(0.4019)	-0.6430(0.4106)
log(Rural credit)	0.0053(0.0080)	0.0040(0.0079)	0.0034(0.0079)
log(Precipitation)	0.3461(0.1484)	0.3520(0.1495)	0.3702(0.1483)
log(Temperature)	-16.7829(12.6233)	-15.5916(12.6631)	-15.9867(12.6351)
Precipitation deviation	-0.0003(0.00009)	-0.0003(0.00009)	-0.0003(0.00009)
Temperature deviation	0.53930(0.4481)	0.5519(0.4497)	0.5672(0.4487)
Constant	54.2124(41,3970)	51.1687(41.4961)	52.7871(41.4219)

Source: Prepared by the authors based on research results.
Note: Standard deviation in parentheses.

It is essential to emphasise that consensus on the EKC format within the Legal Amazon remains elusive. Divergent results emerge from studies employing different methodologies or analysing distinct time periods concerning the EKC's shape. For instance, Araujo *et al.* (2009) identified a consistently positive relationship between growth and deforestation, while Oliveira *et al.* (2011) concluded that economic growth and deforestation in the Brazilian Legal Amazon follow an "inverted U" pattern. Consequently, the results presented here contribute to the ongoing debate regarding the impact of growth on deforestation in the Brazilian Legal Amazon. The economic literature in this area still requires further discussions, emphasising the need for cautious interpretation of the conclusions drawn from the EKC estimations in this research.

It is also noteworthy that the literature typically treats the relationship between growth and deforestation in the Brazilian Legal Amazon as linear and homogeneous. This approach restricts the comparability of the findings from this study with the existing literature. Furthermore, agriculture's role in deforestation is typically subjected to a set of control variables in studies aiming to estimate the EKC for the Brazilian Legal Amazon. Consequently, the discussion of the results concerning the current literature remains constrained, primarily due to the limited number of studies focused on estimating the EKC within this specific region and the methodological approach adopted in this work.

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The primary reason for the consistently negative pattern observed in the EKC within this study may be attributed to the theoretical framework proposed by Grossman and Krueger (1991) and the stages of environmental consciousness among producers and consumers in the Brazilian Legal Amazon. In its fundamental definition, the EKC theory posits that the relationship between economic growth and deforestation can be dissected into two effects: the scale effect and the composition effect. The scale effect arises from the tendency, especially in the early stages of growth, for economies to pursue greater growth increments through scale returns. This involves increased resource utilisation and inputs, consequently leading to heightened deforestation. On the other hand, the composition effect pertains to the phase of growth where economies have comparative advantages over similar counterparts, enabling them to adopt sustainable growth practices with a stronger emphasis on environmental education and natural resource conservation.

In this context, beyond a certain threshold of growth, the composition effect tends to surpass the scale effect, resulting in the characteristic "inverted U" shape of the EKC. Consequently, the consistently negative relationship revealed in the estimations of this research offers evidence that, within the Brazilian Legal Amazon, even in municipalities characterised by low growth levels, the composition effect tends to prevail over the scale effect. This indicates that adopting clean production practices and pursuing sustainable growth can be so efficient that they allow for increased economic growth while simultaneously reducing deforestation.

4. Concluding remarks

This study aimed to assess the null hypothesis of EKC continuity in the Brazilian Legal Amazon concerning levels of agricultural productivity. To achieve this goal, we utilised an unbalanced panel dataset spanning from 2005 to 2018, encompassing data from 733 municipalities. To fulfil our research objectives, we employed a nonlinear estimation approach, calculating a productivity threshold that delineated the points at which the relationship between economic growth and deforestation changed in the stages before and after this threshold.

Our findings led to the rejection of the null hypothesis, signifying significant disparities in the relationship between economic growth and deforestation contingent on agricultural productivity levels and the economic growth pattern within Legal Amazon municipalities. Moreover, the results indicated that the relationship between growth and deforestation in the Brazilian Legal Amazon follows a consistently negative trend. This implies that, irrespective of the level of economic growth, further growth gains can be attained even in scenarios with reduced levels of deforestation.

Despite the uniformity of the relationship across different threshold variables, our results suggest that the slope of the EKC may vary depending on productivity levels when the threshold is derived from land and dairy farming productivity. To summarise, when dairy farming productivity serves as the threshold variable, the EKC exhibits a steeper slope in municipalities with higher productivity levels. Conversely, when land productivity is the threshold variable, the EKC slope is more pronounced in municipalities with lower productivity levels. These outcomes imply that an economic

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growth shock can have more significant impacts on deforestation in municipalities specialising in dairy farming and less in agriculture within the Brazilian Legal Amazon.

In conclusion, our findings demonstrate that when the EKC theory is tested using a nonlinear functional form in the Brazilian Legal Amazon, the "inverted U" hypothesis is not supported, resulting in a consistently negative monotonic EKC relationship. This conclusion contributes to the ongoing discussion in the literature on how growth influences deforestation while expanding the discourse on the environmental consequences of economic growth in the Legal Amazon. Future research endeavours may further contribute to this area by examining the hypothesis of the existence of multiple thresholds within the EKC.

Competing interests. The authors declare none.

References

Abid M (2017) Does economic, financial and institutional developments matter for environmental quality? A comparative analysis of EU and MEA countries. *Journal of Environmental Management* **188**, 183–194.

Al-Mulali US B and Ozturk I (2015) Investigating the environmental Kuznets curve hypothesis in Vietnam. *Energy Policy* **76**, 123–131.

Araujo C, Bonjean CA, Combes J, Motel PC and Reis EJ (2009) Property rights and deforestation in the Brazilian Amazon. *Ecological Economics* **68**, 2461–2468.

Arellano M and Bover O (1995) Another look at the instrumental variable estimation of error-components models. *Journal of Econometrics* **68**, 29–51.

Assunção J, Gandour C and Rocha R (2015) Deforestation slowdown in the Brazilian Amazon: prices or policies?. *Environment and Development Economics* **20**, 697–722.

Assunção J, Gandour C Rocha R and Rocha R (2020) The effect of rural credit on deforestation: evidence from the Brazilian Amazon. *The Economic Journal* **130**, 290–330.

Bölük G and Mert M (2014) Fossil & renewable energy consumption, GHGs (greenhouse gases) and economic growth: Evidence from a panel of EU (European Union) countries. *Energy* **74**, 439–446.

Caetano MAL, Gherardi DFM and Yoneyama T (2011) An optimized policy for the reduction of CO2 emission in the Brazilian Legal Amazon. *Ecological Modelling* **222**, 2835–2840.

Camarillo-Naranjo JM, Alvarez-Francoso JI, Limones-Rodriguez N, Pita-Lopez MF and Aguilar-Alba M (2019) The global climate monitor system: from climate data-handling to knowledge dissemination. *International Journal of Digital Earth* **12**, 394–414.

Caner M and Hansen BE (2004) Instrumental variable estimation of a threshold model. *Econometric Theory* **20**, 813–843.

Caro D, Davis SJ, Bastianoni S and Caldeira K (2014) Global and regional trends in greenhouse gas emissions from livestock. *Climatic Change* **126**, 203–216.

CEPEA/USP (2022) Preços agropecuários. Available at https://www.cepea.esalq.usp.br/br.

Chiu Y (2012) Deforestation and the environmental Kuznets curve in developing countries: a panel smooth transition regression approach. *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie* **60**, 177–194.

Culas RJ (2007) Deforestation and the environmental Kuznets curve: An institutional perspective. *Ecological Economics* **61**, 429–437.

Danfeng S, Dawson R and Baoguo L (2006) Agricultural causes of desertification risk in Minqin, China. *Journal of Environmental Management* **79**, 348–356.

Do Prado T, Tarik M, Miyajima DN, Magalhães AS, Domingues EP and Carvalho TS (2020) The impacts of climate change on agricultural production, land use and economy of the legal Amazon Region between 2030 and 2049. *EconomiA* **21**, 73–90.

Ehrhardt-Martinez K, Crenshaw EM and Jenkins JC (2002) Deforestation and the environmental Kuznets curve: A cross-national investigation of intervening mechanisms. *Social Science Quarterly* **83**, 226–243.

https://doi.org/10.1017/S1355770X25000063 Published online by Cambridge University Press

Garnett T (2009) Livestock-related greenhouse gas emissions: impacts and options for policy makers. *Environmental Science & Policy* **12**, 491–503.

Grossman GM Krueger AB (1991) Environmental impacts of a North American free trade agreement. Available at https://www.nber.org/papers/w3914.

Hansen BE (1999) Threshold effects in non-dynamic panels: Estimation, testing, and inference. *Journal of Econometrics* **93**, 345–368.

Hill R and Magnani E (2002) An exploration of the conceptual and empirical basis of the environmental Kuznets curve. *Australian Economic Papers* **41**, 239–254.

Holtz-Eakin D and Selden TM (1995) Stoking the fires? CO2 emissions and economic growth. *Journal of Public Economics* **57**, 85–101.

Hong C, Burney JA, Pongratz J, Nabel J, Mueller ND, Jackson RB and Davis SJ (2021) Global and regional drivers of land-use emissions in 1961–2017. *Nature* **589**, 554–561.

IBAMA (2022) IBAMA: Dados abertos. Available at http://www.ibama.gov.br/dados-abertos.

Ibáñez J, Martínez J and Schnabel S (2007) Desertification due to overgrazing in a dynamic commercial livestock–grass–soil system. *Ecological Modelling* **2005**, 277–288.

IBGE (2022a) Amazônia Legal. Available at https://www.ibge.gov.br/geociencias/cartas-e-mapas/mapas-regionais/15819-amazonia-legal.html?=&t=acesso-ao-produto.

IBGE (2022b) Estimativas de População. Available at https://sidra.ibge.gov.br/tabela/6579.

IBGE (2022c) Pesquisa Agrícola Municipal. Available at https://sidra.ibge.gov.br/pesquisa/pam/tabelas.

IBGE (2022d) Pesquisa Pecuária Municipal. Available at https://sidra.ibge.gov.br/pesquisa/ppm/quadros/brasil/2020.

IBGE (2022e) Produto Interno Bruto dos Municípios. Available at https://sidra.ibge.gov.br/pesquisa/pib-munic/tabelas.

IBGE (2024) Amazônia Legal. Available at https://www.ibge.gov.br/geociencias/cartas-e-mapas/mapas-regionais/15819-amazonia-legal.html?=&t=legislacao-relacionada.

INPE (2022) Monitoramento da Floresta Amazônica Brasileira por Satélite. Available at http://www.obt.inpe.br/OBT/assuntos/programas/amazonia/prodes.

Kremer S, Alexande B and Nautz D (2013) Inflation and growth: new evidence from a dynamic panel threshold analysis. *Empirical Economics* **44**, 861–878.

Lapinskienė G, Tvaronavičienė M and Vaitkus P (2014) Greenhouse gases emissions and economic growth–evidence substantiating the presence of environmental Kuznets curve in the EU. *Technological and Economic Development of Economy* **20**, 65–78.

Lokshin B (2009) Further results on bias in dynamic unbalanced panel data models with an application to firm R&D investment. *Applied Economics Letters* **16**, 1227–1233.

Marques GM, Teixeira C, Sousa T, Morais TG, Teixeira RFM and Domingos T (2020) Minimizing direct greenhouse gas emissions in livestock production: The need for a metabolic theory. *Ecological Modelling* **434**, 109259.

Marrero GA (2010) Greenhouse gases emissions, growth and the energy mix in Europe. *Energy Economics* **32**, 1356–1363.

Mendes C, Cassandro M and Junior SP (2012) Deforestation, economic growth and corruption: a nonparametric analysis on the case of Amazon forest. *Applied Economics Letters* **19**, 1285–1291.

Nasir MA, Huynh TLD and Tram HTX (2019) Role of financial development, economic growth & foreign direct investment in driving climate change: A case of emerging ASEAN. *Journal of Environmental Management* **242**, 131–141.

Oliveira RC, Almeida E, Freguglia RS and Barreto RC (2011) Desmatamento e crescimento econômico no Brasil: uma análise da curva de Kuznets ambiental para a Amazônia legal. *Revista de Economia e Sociologia Rural* **49**, 709–739.

Ozcan B (2013) The nexus between carbon emissions, energy consumption and economic growth in Middle East countries: a panel data analysis. *Energy Policy* **62**, 1138–1147.

Piguet E (2010) Linking climate change, environmental degradation, and migration: a methodological overview. *Wiley Interdisciplinary Reviews: Climate Change* **1**, 517–524.

Roberts JT and Grimes PE (1997) Carbon intensity and economic development 1962–1991: A brief exploration of the environmental Kuznets curve. *World Development* **25**, 191–198.

Shafik N (1994) Economic development and environmental quality: an econometric analysis. *Oxford Economic Papers* **46**, 757–773.

https://doi.org/10.1017/S1355770X25000063 Published online by Cambridge University Press

Sirag A, Matemilola BT, Law SH and Bany-Ariffin AN (2018) Does environmental Kuznets curve hypothesis exist? Evidence from dynamic panel threshold. *Journal of Environmental Economics and Policy* **7**, 145–165.

Slade P (2018) The effects of pricing Canadian livestock emissions. *Canadian Journal of Agricultural Economics/Revue Canadienne d'agroeconomie* **66**, 305–329.

Stabile MCC, Guimarães AL, Silva DS, Ribeiro V and Macedo MN, Coe MT, Pinto E, Moutinho P and Alencar A (2020) Solving Brazil's land use puzzle: Increasing production and slowing Amazon deforestation. *Land Use Policy* **91**, 104362.

Stef N and Ben JS (2020) Climate change legislations and environmental degradation. *Environmental and Resource Economics* **77**, 839–868.

Taheripour F and Tyner WE (2013) Induced land use emissions due to first and second generation biofuels and uncertainty in land use emission factors. *Economics Research International* **2013**, 1–12. https://doi.org/10.1155/2013/315787.

Verbeek M and Nijman T (1992) Testing for selectivity bias in panel data models. *International Economic Review* **33**, 681–703.

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