# The determinants of forest area in Brazil: U-shaped relationship for GDP per capita and for value of agricultural production per hectare

Ben Youssef, Slim

University of Manouba, ESCT, QuAnLab (LR24ES21), Manouba 2010, Tunisia

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**Slim Ben Youssef**
University of Manouba, ESCT, QuAnLab (LR24ES21), Manouba 2010, Tunisia
slim.benyoussef@esct.uma.tn
https://orcid.org/0000-0002-4297-3367

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**Abstract:** We evaluate the impact of gross domestic product per capita (GDPC), the value of agricultural production (VAP), and the value of agricultural production per hectare (VAPH) on the forest area in Brazil by considering annual time series data ranging from 1990 to 2022. The autoregressive distributed lag approach is used to estimate our long-run elasticities. The increase in the value of agricultural production reduces forest area in the long-run. However, the value of agricultural production per hectare and the gross domestic product per capita both have a U-shaped relationship with forest area. Indeed, with an increase in the VAPH (resp. GDPC), forest area decreases, then after a threshold point begins to increase. In Brazil, deforestation can be reversed by continuous economic growth accompanied by more propagation of environmental education within the population. Also, agricultural green technologies, as aeroponics for vegetable culture or smart agriculture, should be encouraged through subsidies or advantageous credits, as they increase the VAPH.

**Keywords: Forest area;** Value of agricultural production; Value of agricultural production per hectare; Gross domestic product per capita; U-shaped hypothesis; Autoregressive distributed lag; Brazil.

**Jel classification:** C32; O44; 054;Q15.

## 1. Introduction

Deforestation is mostly caused by agriculture, which clears trees for pasture and crops to supply the demand for food, animal feed, biofuels, and lumber. Significantly detrimental effects on the ecosystem result from this deforestation, such as decreased soil quality, biodiversity loss, and greenhouse gas emissions that contribute to climate change. Large-scale livestock ranching, the production of lumber, and the development of monoculture crops like soy and palm oil are important agricultural practices that contribute to this negative impact.

According to Mondal et al. (2025), forest ecosystems, which make up 31% of the world's land and are essential for biodiversity, water control, and carbon sequestration, are greatly impacted by climate change, which is caused by greenhouse gas emissions. The health, composition, and distribution of forests are disrupted by rising temperatures, changing rainfall patterns, extreme weather events, and increased $CO_2$ levels. Communities that depend on forests incur socioeconomic hazards due to changes in the forestry sector and livelihoods. Sustainable forestry methods, replanting, conservation initiatives, efficient policy integration, and monetary rewards like carbon credits are examples of mitigation and adaptation solutions.

Barbier et al. (2017) define forest transition as the period during which a long-term decline in forest area is eventually replaced by a phase of forest recovery. The initial reduction in natural forest cover typically accompanies economic expansion and population growth. Over time, this decline tends to decelerate as pressures on primary forests diminish and environmental protection measures are strengthened, contributing to the stabilization of remaining forest areas. With continued economic development, rising demand for both wood products and non-market ecosystem services derived from forested landscapes may stimulate a reversal of forest loss. This recovery phase can involve multiple processes, including the conservation of residual primary forests, natural regrowth on previously cleared land, active reforestation efforts, and the establishment of forest plantations.

Brazil’s forest area is impacted by several economic activities, including soybean and beef production, timber exploitation, mining activities, and, in particular, bauxite mining. Forest area has continuously declined from 5888980 $km^2$ in 1990 to

4941960,222 km2 in 2022. In the same period, the value of agricultural production (VAP) has increased, passing from 67 billion constant 2014-2016 US$ to 198 (World Bank, 2025). Some efforts have been taken to reduce deforestation, as forest plantations in states like Minas Gerais have produced positive socio-economic impacts, as poverty reduction, but this conversion can lead to biodiversity loss. Other efforts include the establishment of protected areas and a Brazilian Forest Code.

According to Kauano et al. (2020), the Brazilian Amazon contains approximately 70% of the world's tropical forests and plays a crucial role in the national economy by preserving biodiversity, supporting the livelihoods of Indigenous peoples and local communities, and providing essential ecosystem services, including climate and water regulations, soil stabilization, and flood mitigation. Over the past three decades, the Brazilian government has established an extensive network of regional protected areas (PAs), which now encompasses nearly 48% of the Amazon region. Nevertheless, despite their ecological and social significance, certain sectors of Brazilian society contend that the expansion of PAs constrains local economic development by limiting the land available for non-forest economic activities such as large-scale agriculture, mining, and energy production.

According to Silva et al. (2022), it would cost at least 1.7–2.8 billion US$ annually in ongoing management and system-wide expenses, plus an initial investment of 1.0–1.6 billion US$ for establishment costs, to keep about 80% (3.5 million km$^2$) of the Brazilian Amazon region within conservation areas.

Lopes and Chiavari (2024) emphasize that landscape-scale restoration in Brazil demands an innovative regulatory framework that considers diverse land tenure categories and restoration approaches. Such a framework should encourage the integration of both mandatory and voluntary restoration initiatives. Consequently, effective governance is essential to coordinate multiple stakeholders and reconcile differing interests. The ongoing revision of PLANAVEG (the National Plan for Native Vegetation Recovery), originally adopted in 2017, presents an important opportunity for the federal government to address these considerations.

The industrial soy farmers of Tocantins, a Brazilian state in the Cerrado ecoregion with significant rates of soy-driven deforestation, are the subject of a study by Andrade

Aragão et al. (2024). They conduct a focus group with soy farmers in Tocantins, based on background conversations with them and an analysis of the land-use change literature in Brazil. According to their findings, Brazilian soy farmers are wary of foreign actors and extremely doubtful of environmental standards.

The influence of the Atlantic Forest Restoration Pact on Brazilian forest restoration is estimated by Toto et al. (2025). To isolate the causal influence of restoration support, they compare forest change on Pact-supported sites to change on comparable lands before and after the program began. They demonstrate that the intervention enhanced the amount of restored forest cover by 10–20%, probably as a result of assisting private landowners in overcoming significant financial and informational obstacles. Greater distances to cities and increased state-level environmental enforcement are linked to larger effects.

In this paper, we will try to evaluate the impact of economic and agricultural activities on the forest area in Brazil. Particularly, we will verify whether the environmental Kuznets curve (EKC) hypothesis is verified for deforestation by considering gross domestic product (GDP) per capita and value of agricultural production per hectare (VAPH). We also evaluate the impact of the value of agricultural production on forest area. This research is worth considering, as, to the best of our knowledge, there is no temporal series analysis about the impact of GDP on forest area or deforestation in Brazil. Also, no temporal series analysis has considered the impact of agriculture on deforestation, even in countries other than Brazil. The autoregressive distributed lag (ARDL) method and annual data ranging from 1990 to 2022 will be used.

Our paper is organised as follows: Section 2 is a literature review. Section 3 is for data, econometric analysis, and discussions. Section 4 is a conclusion with policy recommendations.

## 2. Literature review

Several studies have been concerned with the factors impacting forest area. Some are related to Brazil and others to other countries.

### 2.1. *Countries other than Brazil*

Previous studies have evaluated the long-run relationship of forest area with GDP per capita with different conclusions depending on the country or panel of countries considered, or regions within the same country: a linear and positive relation (Tan and Tachibana, 2025), a U-shaped relation (Pablo-Romero et al., 2023), inverted U-shaped (Halkos and Skouloudis, 2020; Aydin et al., 2024; Tan and Tachibana, 2025), N-shaped (Halkos and Skouloudis, 2020; Benedek and Fertő, 2020), or inverted N-shaped (Bhattarai and Hammig; 2001).

Bhattarai and Hammig (2001) consider three panels of countries from Africa, Latin America, and Asia, and annual data from 1972 to 1991. For Latin America and Africa, the environmental Kuznets Curve (EKC) relationship, and even the N-shaped relationship, are verified between deforestation, defined as the annual percentage change in forest and woodland area, and per capita income. However, the inverted N-shaped relationship is found for Asia. In addition, political institutions and governance reduce deforestation. Barbier et al. (2017) develop a straightforward model of forest transition that explains how a nation or region's long-term land-use trends can change from one of net forest area loss to net increase. High-income economies have seen this kind of forest rebound, and developing nations are seeing it more and more. Ajanaku and Collins (2021) use the Generalized Method of Moments (GMM) estimators on a panel of 45 African countries with data between 1990 and 2016. They validate the EKC hypothesis for deforestation in Africa and estimate the turning point to 3000 US$ per capita.

Tan et al. (2022) pointed out that, as the World's forest area is continuously declining, China's forest area has steadily increased since the 1980s. They use time series data on forest area and socioeconomic factors in China, and the ARDL model. They conclude that GDP per capita growth has a positive impact on forest area growth in the short-run and a negative one in the long-run, while rural population growth has a negative impact in both the short- and long-run. In the short-run, both the urban population and foreign direct investment growth have a positive impact on forest coverage rates. Caravaggio (2022) points out that Latin America's forests in the past decades have experienced a decrease in the rates of deforestation. He empirically investigates the existence of a forest transition on a panel of 21 Latin American countries and data between 1982 and 2015. He concludes that countries in early and pre-transition stages have a U-shape relationship of forest cover with GDP per capita and a turning point at 7150 US$. On the other hand, countries in late and post-transition stages show an inverted U-shape opposite curve with a much higher turning point of 38750 US$.

The impact of agricultural activity on forest area has also been considered by other studies. Some research shows that agriculture increases deforestation (Maertens et al., 2006), others conclude that the impact of agricultural activity is insignificant (Angelsen, 2010; Pablo-Romero et al., 2023; Pratzer et al., 2023), or even is beneficial when Indigenous land management is common (Pratzer et al., 2023). Maertens et al. (2006) note that the Lore Lindu region in Indonesia, similar to many forest frontier areas in Southeast Asia, has undergone rapid deforestation driven by agricultural expansion in upland areas along forest margins. This expansion has intensified problems such as soil erosion and reduced water availability, posing risks to agricultural productivity. Meanwhile, technological advances are encouraging agricultural intensification in the lowlands. Using data from an extensive village survey combined with geographic information system data, the authors develop a theoretical framework based on a Chayanov-type agricultural household model. Their empirical results demonstrate how technological progress in lowland agriculture influences land use at the forest margins and how these impacts vary according to the factor intensity of the technology.

Angelsen (2010) notes that agricultural production in developing countries has grown by approximately 3.3–3.4% per year over the past two decades, while gross deforestation has expanded agricultural land by only about 0.3%. This indicates that overall agricultural growth has played a relatively minor role in forest conversion. Pablo-Romero et al. (2023) show that crop yield has an insignificant impact on forest area per capita in their study about a sample of 19 Latin American and Caribbean countries during the period 1991–2014. Pratzer et al. (2023) examine how agricultural intensification affects deforestation in the world's understudied and endangered tropical dry forests using a multilevel Bayesian regression approach. They discover that, generally, intensification has not reduced deforestation in tropical dry forests, especially in nations where the production of commodity crops predominates—a situation common in many regions where agriculture is growing. However, in regions where Indigenous land management is common, intensification at the national level decreased deforestation.

Several studies consider other factors, including demographic, social, economic, geographic, and geophysical ones that impact forest area (Huang et al., 2010; Hu et al., 2014; Toledo et al., 2022; Xu et al., 2025). Nagendra (2007) uses a dataset of 55 woods from Nepal's Terai plains and middle hills to investigate the variables related to forest regeneration or destruction. The findings support the notion that local monitoring and tenure regimes are crucial for forest recovery. Additionally, one significant, independent explanator of forest change is the size of user groups per unit of forest area. These factors can also be linked to particular behaviors that further impact forest transformation, like resolving social conflicts, implementing new technology to lessen forest stress, and involving users in forest care initiatives. Based on data gathered from 54 countries and regions between 2000 and 2020, Xiao et al. (2022) examine the African region, which is undergoing unprecedented deforestation. The main research tools have been the geographic detector model, global principal component analysis, and spatial autocorrelation analysis. They discovered that over the past 20 years, the forest area in Africa has decreased due to the incredibly uneven distribution of forests. North Africa has had the least amount of forest loss, whereas Central Africa has seen the most. Furthermore, the primary determinants of the temporal evolution of forest cover change in Africa include the continent's total population, land area, cultivated land, urban population, consumer price index, and birth rate.

### *2.2. Studies about Brazil*

Studies about Brazil and evaluating the impact of economic growth on forests are panel studies using municipal data from some regions of Brazil. While some research concludes that economic growth increases deforestation (Faria and Almeida, 2016), others find that economic growth can be reconciled with a reduction in deforestation (Souza and Barbosa, 2025). Carvalho and Domingues (2016) use a dynamic interregional Computable General Equilibrium (CGE) model for the Legal Amazon region and consider the period 2006-2030. Their computations show that regions with higher growth and deforestation would be those located in the arc of deforestation (Mato Grosso, Pará e Rondônia), in particular areas of cattle and soybean production. Tritsch and Arvor (2016) validate the EKC hypothesis between deforestation and GDP per capita using a sub-municipal analysis in the Brazilian Amazon and data between 2000 and 2010. Sousa et al. (2022) consider the Atlantic Forest in the state of Ceará and estimate a panel Tobit model by considering data about its municipalities from 2011 to 2017. They show that the relationship between deforestation and GDP per capita has an N format.

About the impact of agriculture on deforestation, panel studies about some municipalities or regions of Brazil show that cattle and soybean production may increase deforestation (Carvalho and Domingues, 2016; Faria and Almeida, 2016), while Sousa et al. (2022) show that cattle farming reduces deforestation.

Other variables have been shown to reduce deforestation as a decrease in poverty (Afonso and Miller, 2021), protected area (Espindola et al., 2021), and population density (Sousa et al., 2022), but others increase deforestation as trade openness (Faria and Almeida, 2016). Barros and Stege (2019) use data for the year 2010 about 337 municipalities of Matopiba, a Brazilian agricultural frontier, exploratory spatial data analysis (ESDA), and spatial econometrics, to support the EKC hypothesis between deforestation and the Human Development Index. Silveira et al. (2025) investigate the relationship between deforestation and regional economic complexity (ECI-R) in municipalities of the Brazilian Amazon by considering data between 2006 and 2021. Their results suggest an inverted U-shaped curve.

Our literature review shows that there is no temporal series analysis about the impact of GDP on forest area or deforestation in Brazil. Also, no temporal series analysis has considered the impact of agriculture (or the value of agricultural production) on deforestation, even in other countries. In addition, the impact of agricultural yield or VAPH on forest area has not been evaluated econometrically by previous literature. Therefore, our research could be of great importance to understand the macroeconomic impact of economic growth and agricultural activity on deforestation in Brazil.

## 3. Econometric methodology

### *3.1. Data and unit root tests*

Annual data about Brazil from 1990 to 2022 are obtained and include: *i)* Forest area (FA) in km$^2$; *ii)* Gross domestic product per capita (GDPC, yc) in US$ 2015 prices; *iii)* Value of agricultural production (VAP, vap) in constant 2014-2016 thousand US$; *iv)* Value of agricultural production per hectare (VAPH, vaph) are obtained in US$ PPP (purchasing power parity) and are divided by the GDP deflator for the USA base year 2015 then multiplied by 100 to get their value in US$ PPP constant 2015. Data about FA and GDP deflators are obtained from the World Bank (2025), and data about GDPC, VAP, and VAPH are obtained from the Food and Agriculture Organisation (FAO, 2025). We apply the natural logarithmic transformation to our variables before the econometric computations, which are done with EViews 13 software.

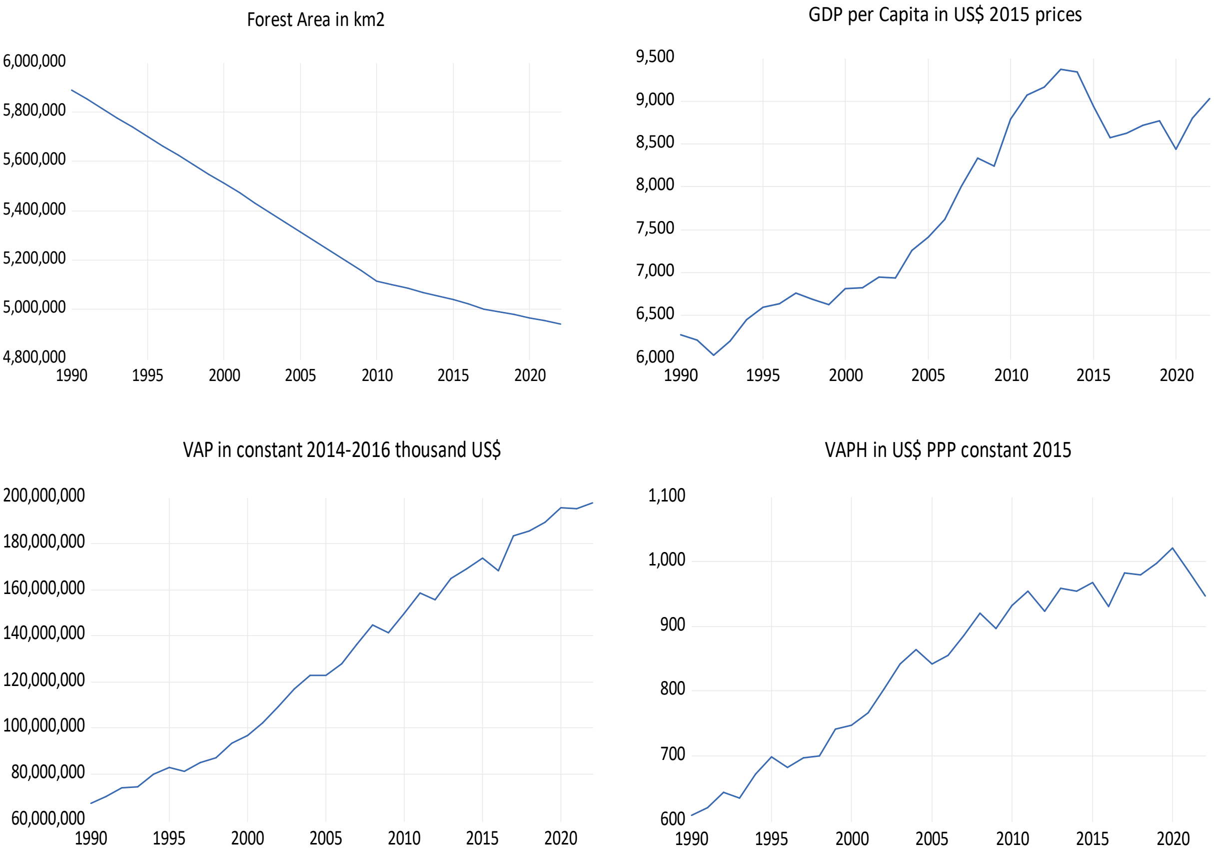

**Fig. 1. Plots of variables**

Fig. 1 shows that the forest area in Brazil has continuously decreased, passing from 5888980 km$^2$ in 1990 to 4941960 km$^2$ in 2022, meaning a decrease of 16% during this period. In the same period, the value of agricultural production has a net increasing trend, passing from nearly 67 billion constant 2014-2016 US$ to 198, signifying an increase of 195%. The value of agricultural production per hectare has also an upward tendency, passing from 608 US$ PPP constant 2015 to 947, meaning an increase of 56%. Between 1990 and 2022, GDP per capita has globally increased, with a peak in 2013, and passed from 6279 US$ 2015 prices to 9032, implying an increase of 44%.

**Table 1. Descriptive statistics**

| | FA | YC | VAP | VAPH |
|---|---|---|---|---|
| Mean | 5328353 | 7713.057 | 1.30E+08 | 837.9384 |
| Median | 5273839 | 7622.039 | 1.28E+08 | 863.5457 |
| Maximum | 5888980 | 9366.738 | 1.98E+08 | 1021.596 |
| Minimum | 4941960 | 6036.717 | 67379459 | 607.9238 |
| Std. Dev. | 306863.8 | 1111.097 | 43112412 | 130.4644 |
| Skewness | 0.366722 | 0.015951 | 0.071672 | -0.371829 |
| Kurtosis | 1.740541 | 1.426486 | 1.615609 | 1.696705 |
| Jarque-Bera | 2.920745 | 3.405828 | 2.663491 | 3.095958 |
| Probability | 0.232150 | 0.182152 | 0.264016 | 0.212677 |
| Sum | 1.76E+08 | 254530.9 | 4.30E+09 | 27651.97 |
| Sum Sq. Dev. | 3.01E+12 | 39505144 | 5.95E+16 | 544670.4 |
| Observations | 33 | 33 | 33 | 33 |

We begin our econometric computations by evaluating the stationary properties of our series. The Zivot and Andrews (1992) unit root test is an extension of conventional unit root tests, such as the Augmented Dickey–Fuller (ADF, 1979) test, that permits the presence of a structural break at an unknown point. Traditional unit root tests may mistakenly fail to reject the null hypothesis of a unit root if the data show a structural break, misinterpreting a one-time level or trend shift as proof of non-stationarity. Zivot and Andrews (1992) endogenously determine the most likely break date, instead of assuming it a priori. The null hypothesis states that the series has a unit root without any structural break, while the alternative hypothesis states that the series is trend-stationary with a single structural break. This test enhances the reliability of stationarity testing in financial and macroeconomic time series that may have undergone economic crises, policy changes, or regime changes by accounting for any breaks. Table 2 shows that all our series are not stationary at the level, but they become stationary after first-difference at the 1% significance level. Thus, all our variables are integrated of order 1, i.e., are I(1).

**Table 2. Zivot and Andrews (1992) stationary test**

| variables | fa | vap | vaph | Vaph2 | yc | Yc2 |
|---|---|---|---|---|---|---|
| ZA (L) | -1.10 | -3.30 | -2.24 | -2.31 | -3.18 | -3.21 |
| Break point (L) | 2017 | 2002 | 2002 | 2002 | 2007 | 2007 |
| ZA (FD) | -10.82[a] | -8.74[a] | -5.80[a] | -5.75[a] | -5.55[a] | -5.56[a] |
| Break point (FD) | 2011 | 1999 | 1999 | 1999 | 2014 | 2014 |
| Integration order | I(1) | I(1) | I(1) | I(1) | I(1) | I(1) |

ZA (L) is the Zivot-Andrews test statistic at level, and ZA (FD) is the Zivot-Andrews test statistic after first-difference. Break point (L) and Break point (FD) are the break points for the variables at the level and after the first difference, respectively. Statistical significance levels at 1% are denoted by superscripts a. This test is conducted with an intercept and a maximum lag length of 4. Critical values at the 1%, 5%, and 10% are respectively -5.34, -4.93, and -4.58.

### *3.2. Cointegration and long-run estimates*

This paper tries to evaluate the impact of gross domestic product per capita and the value of agricultural production on forest area in Brazil. Following the literature on the inverted U-shaped, also called environmental Kuznets curve, hypothesis (Grossman and Krueger, 1995; Ang, 2007), we evaluate the impact of GDP per capita and the VAP per hectare on forest area. As papers Halkos and Skouloudis (2020), Aydin et al. (2024), and Tan and Tachibana (2025) in our first model, we express the forest area as a function of GDP per capita and its square:

$$fa_t = c_1 + \alpha_{11} yc_t + \alpha_{12} yc_t^2 + \varepsilon_{1t} \tag{1}$$

The second model is a novelty and expresses forest area as a function of VAP, VAP per hectare, and its square:

$$fa_t = c_2 + \alpha_{21} vap_t + \alpha_{22} vaph_t + \alpha_{23} vaph_t^2 + \varepsilon_{2t} \tag{2}$$

Since our variables are integrated of order one, we can use the autoregressive distributed lag approach introduced by Pesaran and Pesaran (1997), Pesaran and Smith (1998), and Pesaran et al. (2001). This methodology enables us to verify the long-run cointegration between our variables and to evaluate the long-run elasticities. Compared to other approaches, the ARDL bounds testing works well with mixed variables being stationary or stationary after first difference, enables the avoidance of endogeneity problems, and can give interesting estimates even with small samples.

The ARDL specifications of our two models are, respectively:

$$\Delta fa_t = c_3 + \beta_0 fa_{t-1} + \beta_1 yc_{t-1} + \beta_2 yc_{t-1}^2 + \sum_{j=1}^{p0} \lambda_{0j} \Delta fa_{t-j} + \sum_{j=0}^{p1} \lambda_{1j} \Delta yc_{t-j} + \sum_{j=0}^{p2} \lambda_{2j} \Delta yc_{t-j}^2 + \varepsilon_{3t} \tag{3}$$

$$\begin{aligned} \Delta fa_t = {} & c_4 + \lambda_0 fa_{t-1} + \lambda_1 vap_{t-1} + \lambda_2 vaph_{t-1} + \lambda_3 vaph_{t-1}^2 + \\ & \sum_{j=1}^{q0} \phi_{0j} \Delta fa_{t-j} + \sum_{j=0}^{q1} \phi_{1j} \Delta vap_{t-j} + \sum_{j=0}^{q2} \phi_{2j} \Delta vaph_{t-j} + \sum_{j=0}^{q3} \phi_{3j} \Delta vaph_{t-j}^2 + \varepsilon_{4t} \end{aligned} \tag{4}$$

Where Δ and $\varepsilon_{it}$ denote the first differences and the residual terms, respectively; $p_i$ and $q_i$ denote the number of lags that could be determined by the Akaike information criterion (AIC); $c_i$ are the constant terms, and $\beta_0$, $\lambda_0$ are the error corrections terms that should be negative; $\beta_1$, $\beta_2$, $\lambda_1$, $\lambda_2$, $\lambda_3$ are for long-run estimates, and $\lambda_{ij}$, $\phi_{ij}$ are for short-run estimates. For *i=1,2,3,* long-run coefficients are equal to $-\beta_i / \beta_0$ for equation (3), and are equal to $-\lambda_i / \lambda_0$ for equation (4).

Pesaran et al. (2001) compare the estimated Fisher-statistic (F) of the Wald test to two critical values: a lower value (LOW) and an upper value (UPP) to obtain three possible conclusions: *i)* if F>UPP, there is long-run cointegration between variables; *ii)* if F<LOW, there is no long-run cointegration between variables; *iii)* if LOW≤F≤UPP, we have an inconclusive test. The robustness of our estimates is checked by tests for normality, heteroskedasticity, and serial correlation.

Table 3 groups the cointegration results of our two estimated models and shows the presence of a long-run cointegration between forest area, gross domestic product per capita, and the square of gross domestic product per capita, statistically significant at the 1% level. Also, there is a long-run cointegration between forest area, value of agricultural production, value of agricultural production per hectare, and the square of agricultural production per hectare also significant at the statistical level of 1%. For both estimates, residues are normally distributed, homoskedastic, and independent.

**Table 3. Long-run cointegration**

| Model | Optimal lags | F-statistic | $ECT_{t-1}$ | Normality test | LM-test | BPG-test | Conclusion |
|---|---|---|---|---|---|---|---|
| fa/yc,yc2 | (1,4,4) | 109.578[a] | -0.081[a] | 0.950 | 0.309 | 0.277 | Cointegration |
| fa/vap,vaph,vaph2 | (1,4,4,4) | 13.139[a] | -0.140[c] | 0.140 | 0.181 | 0.849 | Cointegration |

The F(.) statistics are estimated for the restricted constant case. Critical values are obtained from Pesaran et al. (2001) in the case of a finite sample n=30. The maximum number of lags selected for both models and for the dependent and independent variables is 1 and 4, respectively. The Akaike information criterion (AIC) is used to fix the optimal number of lags. Diagnostic tests include the Jarque-Bera normality test, Breusch-Godfrey serial correlation LM test, and the Breusch-Pagan-Godfrey(BPG) heteroskedasticity test; the probability of rejecting the null hypothesis is given. The LM test is calculated with lag=2 for Model 3, and with lag=3 for Model 4. Statistical significance levels of 1% and 10% are denoted by [a] and [c], respectively.

Table 4 gathers our long-run coefficient estimates. All our estimated coefficients are statistically significant. For Model 1, i.e., Equation 3, all coefficients are statistically significant at the 1% level. The coefficient of GDP per capita is negative, and that of GDP per capita squared is positive, signifying that there is a U-shaped long-run relationship between per capita GDP and forest area in Brazil. It means that firstly, forest area decreases with per capita GDP increase, then at a turning point of GDPC, forest area begins to increase. If we approximate the decrease in forest area by deforestation, our results mean that there is an inverted U-shaped EKC hypothesis between deforestation and GDP per capita in Brazil. That is, deforestation firstly increases with GDP, then at a turning point of GDP per capita, it begins to decrease. The turning point is estimated to be 8062.670 US$ 2015 prices. Looking at Fig. 1 and Table 1, we can see that the GDP per capita of Brazil has surpassed the turning point and that the absolute value of the slope of the forest area curve has clearly decreased in 2010 and again in 2017. Our result may be explained by several ways: *i)* When GDP per capita becomes relatively high, citizens become more aware about protecting the environment and preserving forests, which favors forest area increase; *ii)* GDP increase is generally associated with technology advancements, in particular in the agricultural sector, implying improvement of agricultural yields and thus less pressure on agricultural land, which pleds for forest area growth; *iii)* An improvement in GDPC is sometimes followed by an increase in urbanization and thus less pressure on rural areas leading the way for forest expansion.

Our last result is worth considering, as there is no previous temporal series analysis about the impact of GDP on forest area or deforestation in Brazil. Considering studies about Brazil, our result is similar to that of Tritsch and Arvor's (2016) study on a sub-municipal analysis in the Brazilian Amazon, who validate the EKC hypothesis between deforestation and GDP per capita. However, our study differs from that of Sousa et al. (2022) about municipalities of the Atlantic Forest in the state of Ceará, concluding to an N-curve relationship between deforestation and GDP per capita. Other panel studies based on municipal data about some regions of Brazil show that economic growth enhances deforestation (Faria and Almeida, 2016), while others conclude that economic growth can be reconciled with a reduction in deforestation (Souza and Barbosa, 2025).

For Model 2, i.e., Equation (4), all coefficients are statistically significant. The value of agricultural production has a long-run negative impact on forest area. Indeed, more VAP implies more pressure on agricultural land, and thus a reduction in forest area. This result is similar to that of Carvalho and Domingues (2016) and Faria and Almeida (2016) panel studies about some municipalities or regions of Brazil and showing that cattle and soybean production may increase deforestation. Our result differs from that of Sousa et al.'s (2022) study about some municipalities of Brazil, showing that cattle farming reduces deforestation.

The coefficient for the value of agricultural production per hectare is negative, and that of the square of the value of agricultural production is positive, meaning the existence of a U-shaped relationship between forest area and VAPH in Brazil. Forest area decreases with VAPH, then after a turning point, it begins to increase. This also means that there is an inverted U-shaped EKC hypothesis between forest area and VAPH in Brazil. The turning point is estimated to be 500818.981 US$ PPP constant 2015. From Fig. 1 and Table 1, we can see that Brazil is far from reaching this turning point. The intuition behind our result is that when VAPH increases, agriculturists are motivated by agricultural activity that they develop and use more agricultural land, leading to a reduction in forest area. After a threshold point in VAPH, which is relatively very high in Brazil, agriculturists will be motivated by increasing the VAPH to increase their revenue rather than increasing the agricultural lands they are exploiting, leading to an increase in forest area. One might consider aeroponics, which is one of the most recent and sophisticated soilless cultivation techniques, or smart agriculture. Our results about the VAPH and forest area are new and very interesting, as no previous econometric study has estimated the impact of the value of agricultural production per hectare on forest area or deforestation.

**Table 4. Long-run elasticities**

| | Exogeneous variables | | | | | |
|---|---|---|---|---|---|---|
| Model/ Endogeneous variable | c | yc | Yc2 | vap | vaph | Vaph2 |
| fa/yc,yc2 | 186.839<br>(0.000)$^a$ | -38.121<br>(0.000)$^a$ | 2.119<br>(0.000)$^a$ | - | - | - |
| fa/vap,vaph,vaph2 | 61.871<br>(0.014)$^b$ | - | - | -0.222<br>(0.042)$^b$ | -12.901<br>(0.069)$^c$ | 0.983<br>(0.073)$^c$ |

Statistical significance levels of 1%, 5%, and 10% are denoted by $^a$, $^b$, and $^c$, respectively.

For both our models, long-run estimated coefficients stability is guaranteed by using the statistics cumulative sum (CUSUM) and cumulative sum of squares (CUSUMS) proposed by Brown et al. (1975). The fact that the plots of these statistics are within the 5% critical bounds signifies that the estimated parameters of our regressions are stable. Fig. 2 and 3 show that these statistics are indeed within the critical values of the 5% level of significance. Therefore, our long-term ARDL estimated coefficients are stable.

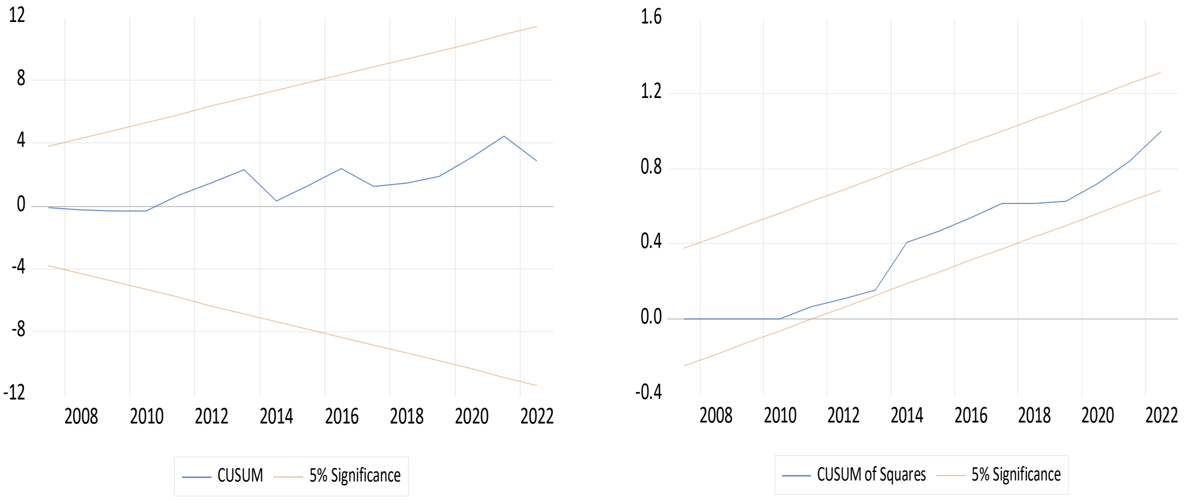

**Fig. 2. CUSUM and CUSUM of Squares for Model 1 (Equation 3)**

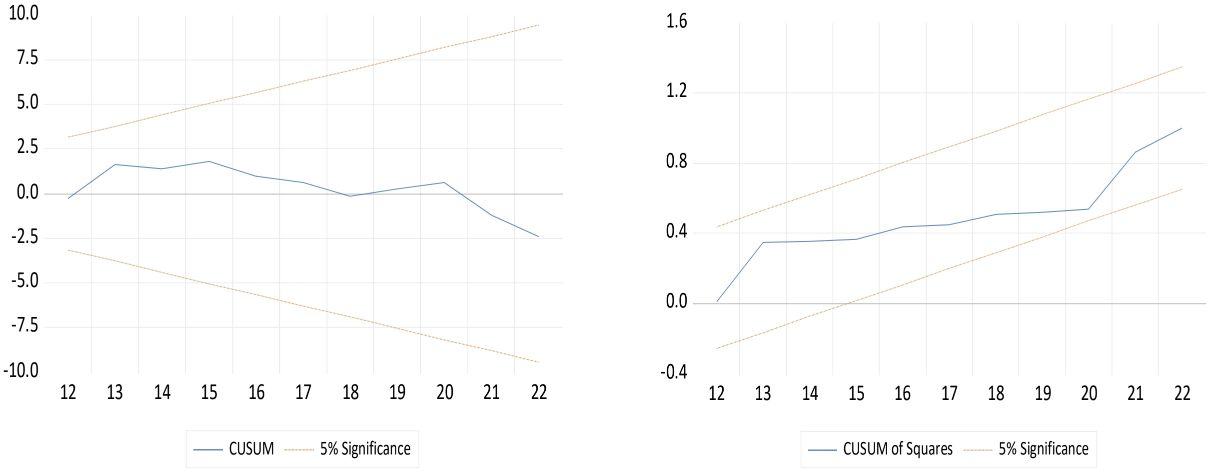

**Fig. 2. CUSUM and CUSUM of Squares for Model 2 (Equation 4)**

## 4. Conclusion and policy implications

We consider annual data about Brazil to estimate the impact of gross domestic product per capita, the value of agricultural production, and the value of agricultural production per hectare on forest area. The autoregressive distributed lag approach is used to assess the long-run cointegration between variables and to estimate long-run elasticities.

We show that the long-run impact of GDP per capita on forest area follows a U-shaped curve as forest area decreases with GDPC and after a threshold point increases. This threshold point is estimated at 8062.670 US$ 2015 prices. Considering a decrease in forest area as an increase in deforestation, our finding is equivalent to saying that the impact of GDPC on deforestation verifies the inverted U-shaped EKC hypothesis, as deforestation increases with GDPC, then decreases after a certain turning point. One explanation for this is that when GDP per capita surpasses a certain level, citizens become more aware of environmental and forest preservation, leading to forest area expansion. This result is interesting and new, as there is no previous temporal series analysis evaluating the impact of GDP on forest area or deforestation in Brazil.

Our computations conclude that the value of agricultural production reduces forest area in the long-run in Brazil. What explains this is that more VAP incites agriculturists to expand their activity and to look for more agricultural lands, leading to deforestation. This is a new result as no temporal series analysis has considered the impact of agriculture (or the value of agricultural production) on deforestation, even in countries other than Brazil.

The value of agricultural production per hectare seems to have a U-shaped relationship with forest area. Indeed, more VAPH firstly reduces forest area until a certain turning point, then forest area begins to increase. This is equivalent to saying that there is an inverted U-shaped EKC hypothesis between VAPH and deforestation. What explains this result is that the VAPH increase incites agriculturists to develop and use more agricultural lands, resulting in a reduction of forest areas. After a relatively very high turning point in the VAPH, agriculturists are more worried about increasing the VAPH of the lands they are exploiting rather than looking for other lands, and this seems to increase the forest area. This is a worthwhile result as no previous econometric study has evaluated the impact of the value of agricultural production per hectare on forest area or deforestation.

Given our econometric computations and results, several interesting conclusions are drawn: *i)* As Brazil is developing with an increasing trend in GDP per capita, we may expect that forest area will begin to increase soon. This can be seen in Fig. 1, showing that the negative slope of the forest area is decreasing in absolute value. Economic growth is not sufficient to ensure the preservation of forest areas and the associated benefits as biodiversity, combating climate change, etc. More environmental education should be propagated within the population to increase the consciousness about protecting natural resources and the environment; *ii)* The spread of high technologies, and particularly green ones, excluding pesticides and other harmful technologies, will certainly increase the yield of agricultural lands, leading to less pressure on agricultural lands and more forest preservation. Brazilian authorities should encourage the introduction of these green technologies, as aeroponics for vegetable culture, through subsidies or advantageous credits. Also, smart agriculture should be encouraged.

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