Deforestation in the Amazon and macroeconomic variables: evidence from time-series analysis (2000–2023)

O desmatamento na Amazônia e variáveis macroeconômicas: evidências de análises de séries de tempo entre 2000 e 2023

Leandro Vinicios Carvalho [1]

Jonathan Gonçalves da Silva [2]

Roselaine Bonfim de Almeida [3]

[1] PhD in Applied Economics, Professor, Faculdade de Administração, Ciências Contábeis e Economia, Universidade Federal da Grande Dourados, Dourados, MS, Brazil
Email: leandrocarvalho@ufgd.edu.br

[2] PhD in Applied Economics, Professor, Faculdade de Administração, Ciências Contábeis e Economia, Universidade Federal da Grande Dourados, Dourados, MS, Brazil
Email: jonathandasilva@ufgd.edu.br

[3] PhD in Applied Economics, Professor, Faculdade de Administração, Ciências Contábeis e Economia, Universidade Federal da Grande Dourados, Dourados, MS, Brazil
Email: roselainealmeida@ufgd.edu.br

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ABSTRACT
Building on the premise that macroeconomic variables – such as prices, agricultural income, and the real exchange rate – are associated with deforestation dynamics, this study investigates both the long-run relationship between these variables and deforestation, as well as the effects of macroeconomic shocks on its temporal evolution. The empirical strategy is grounded in a time-series framework using annual data from 2000 to 2023 and employs unit root tests, the Johansen cointegration approach, and a Vector Error Correction Model (VECM). The results provide evidence of cointegration among the variables, indicating the existence of a long-run equilibrium relationship between macroeconomic conditions and deforestation. Granger causality tests underscore the predictive relevance of the real exchange rate within the system, particularly in relation to deforestation and agricultural variables. Variance decomposition analysis reveals that exchange rate shocks account for a substantial share of the fluctuations in deforestation, whereas agricultural prices and agricultural GDP contribute to a lesser extent. Furthermore, impulse–response functions indicate that positive shocks in prices and the real exchange rate generate positive cumulative effects on deforestation over time. These findings suggest

that external competitiveness and the profitability of agricultural activities constitute key economic drivers of land-use expansion in the Amazon. At the same time, the results highlight the importance of the institutional environment, as conservation policies and monitoring mechanisms may mitigate the environmental pressures associated with favourable macroeconomic conditions. Overall, this study contributes to the literature by emphasising the interaction between macroeconomic dynamics and environmental outcomes in the Amazon region.

Keywords: Agriculture. Deforestation. Amazon. Macroeconomic Variables.

RESUMO

Partindo da premissa de que variáveis macroeconômicas – como preços, renda agrícola e a taxa de câmbio real – estão associadas à dinâmica do desmatamento, este estudo investiga tanto a relação de longo prazo entre essas variáveis e o desmatamento quanto os efeitos de choques macroeconômicos sobre sua evolução temporal. A estratégia empírica baseia-se em uma abordagem de séries temporais, utilizando dados anuais de 2000 a 2023, e emprega testes de raiz unitária, o método de cointegração de Johansen e o Modelo de Correção de Erros Vetorial (VECM). Os resultados fornecem evidências de cointegração entre as variáveis, indicando a existência de uma relação de equilíbrio de longo prazo entre as condições macroeconômicas e o desmatamento. Testes de causalidade de Granger destacam a relevância preditiva da taxa de câmbio real no sistema, particularmente em relação ao desmatamento e às variáveis agrícolas. A análise de decomposição da variância revela que choques na taxa de câmbio respondem por uma parcela substancial das flutuações no desmatamento, enquanto os preços agrícolas e o Produto Interno Bruto agrícola contribuem em menor medida. Além disso, as funções impulso-resposta indicam que choques positivos nos preços e na taxa de câmbio real geram efeitos cumulativos positivos sobre o desmatamento ao longo do tempo. Esses achados sugerem que a competitividade externa e a rentabilidade das atividades agrícolas constituem importantes motores econômicos da expansão do uso da terra na Amazônia. Ao mesmo tempo, os resultados ressaltam a importância do ambiente institucional, uma vez que políticas de conservação e mecanismos de monitoramento podem mitigar as pressões ambientais associadas a condições macroeconômicas favoráveis. De modo geral, este estudo contribui para a literatura ao enfatizar a interação entre a dinâmica macroeconômica e os resultados ambientais na região amazônica.

Palavras-chave: *Agricultura. Desmatamento. Amazônia. Variáveis Macroeconômicas.*

1 INTRODUCTION

Over the past few decades, Brazil has emerged as a key global supplier in meeting the increasing demand for food, with approximately 49% of the country's total exports originating from agribusiness (Brasil, 2024). In this context, Brazilian agribusiness plays a central role in global food provision and, importantly, has the potential to expand production without necessarily contributing to increased deforestation, particularly in the Amazon Biome. According to Abramovay (2019), between 1991 and 2017, agricultural and livestock production increased by 312%, while the total cultivated area expanded at a substantially lower rate of 61%. These figures, which refer specifically to the Amazon Biome, suggest significant gains in productivity. In addition, Rodrigues (2018) reports that only 13% of the total area allocated to grain production is located within the Amazon Biome, with most of this land already previously cleared for low-productivity pasture. Therefore, both within the Amazon Biome and across the country as a whole, there is no structural requirement for further deforestation to meet global food demand, as existing technologies enable productivity gains without expanding cultivated areas.

Moreover, Brazil has faced increasing pressure from international *trading partners* – particularly the European Union – to impose restrictions on products associated with deforestation. One prominent example is the "Soy Moratorium," a multi-stakeholder agreement involving public- and private-sector stakeholders, as well as non-governmental organisations. This initiative seeks to enhance the export potential of Brazilian agricultural and livestock products while ensuring traceability and sustainability in production processes (Abramovay, 2019).

Brazil's international commitments in recent years, especially under the Paris Agreement – ratified in 2016 – represent an additional step toward strengthening its global environmental credibility and promoting long-term policies related to deforestation, greenhouse gas emissions, and sustainability. According to the Ministry of Environment (2024), Brazil has committed to: (i) reducing greenhouse gas emissions by 37% below 2005 levels by 2025; (ii) reducing emissions by 43% below 2005 levels by 2030; (iii) increasing the share of sustainable bioenergy to 18% by 2030; and (iv) restoring approximately 12 million hectares of forest, while ensuring that around 45% of its energy matrix consists of renewable sources by 2030.

Within this framework, changes in agricultural and livestock production systems are particularly relevant, given that land-use change – including deforestation across all Brazilian biomes – accounts for approximately 48% of total greenhouse gas emissions. Additionally, agricultural and livestock activities account for 27% of Brazil's total emissions (Seeg, 2024).

Despite these commitments, recent evidence indicates a deterioration in environmental performance. According to the Institute of Energy and Environment (2022), Brazil's total emissions increased by 21.4% between 2015 and 2021. The Climate Observatory further emphasises that achieving the targets established under the Paris Agreement requires a substantial reduction in deforestation, mitigation of methane emissions, and the adoption of low-carbon technologies in agricultural and livestock production.

Regarding deforestation, the Amazon Biome has shown an upward trend since 2016. Data from Inpe (2024) indicate that deforestation increased at an average annual rate of 6.53% between 2016 and 2023. In parallel, the frequency of wildfires has also intensified. Although fire-related emissions are not yet fully incorporated into the national emissions inventory, the Amazon Biome is becoming increasingly vulnerable to fire events, further exacerbating Brazil's overall emissions profile (Instituto de Energia e Meio Ambiente, 2022).

In recent years, Brazil's environmental conservation policies have not consistently aligned with the commitments established under international agreements. Nevertheless, historical evidence demonstrates the country's capacity to significantly reduce deforestation, particularly following the implementation of the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAm). Established in 2004, the PPCDAm was instrumental in reducing deforestation by approximately 83% between 2004 and 2012. The plan was structured around four key pillars: (i) promotion of sustainable production activities; (ii) strengthening of environmental monitoring and enforcement; (iii) land-use and territorial planning; and (iv) implementation of regulatory and economic instruments aimed at curbing deforestation. This multidimensional approach – particularly the integration of economic instruments – is critical, as deforestation is closely linked to agricultural and livestock expansion. Given the sector's strong integration into global markets, fluctuations in agricultural prices, exchange rates, and sectoral income can exert significant pressure on deforestation dynamics, both at the national level and within the Amazon Biome (Ministério do Meio Ambiente e Mudança do Clima, 2024).

Although the PPCDAm was revoked in 2019, it was reinstated in 2023, preserving the comprehensive structure of the original 2004 plan, including economic and regulatory instruments to mitigate deforestation. Given the economic drivers of deforestation, it is essential to examine how macroeconomic variables shape these dynamics. This issue is particularly relevant in the Amazon Biome, where unregulated land occupation remains a persistent challenge and a major concern for both domestic and international stakeholders, given the region's critical role in climate regulation and biodiversity conservation.

A growing body of literature has examined the determinants of deforestation, including conservation policies, price mechanisms, and public policy design. Studies such as Assunção *et al.* (2015), Carvalho and Domingues (2016), Diniz *et al.* (2009), Ferreira and Coelho (2012) and Mello Júnior *et al.* (2023) highlight the importance of economic variables and external market conditions in shaping deforestation dynamics. In particular, Assunção *et al.* (2015) provide evidence that deforestation responds to agricultural commodity prices, with higher prices increasing incentives for forest clearing. However, their findings also demonstrate that the substantial decline in deforestation observed during the 2000s was primarily driven by command-and-control policies implemented in Brazil, rather than by price dynamics alone, underscoring the effectiveness of environmental enforcement mechanisms. In line with this literature, the present study aims to investigate how macroeconomic variables influence deforestation dynamics, with a particular focus on the Amazon Biome, which remains central to national and international debates on conservation, biodiversity, and sustainability.

Given the importance of understanding the interaction between macroeconomic conditions and deforestation, this study aims to assess whether a long-run relationship exists between selected economic variables – namely, agricultural and livestock prices, the real exchange rate, and agricultural and livestock GDP – and deforestation in the Legal Amazon. Specifically, the study pursues three main objectives: (i) to evaluate the evolution of deforestation in the Legal Amazon between 2000 and 2023; (ii) to analyse the long-run relationship between deforestation and selected macroeconomic variables (prices, exchange rate, and income); and (iii) to examine the dynamic responses of deforestation to shocks in these variables.

This paper is structured as follows. The introduction outlines the research context and objectives. The second section reviews the relevant literature on deforestation. The third section describes the methodological approach and the dataset employed. The fourth section presents the empirical results and the estimation of the time-series model. Finally, the concluding section summarises the main findings and discusses their policy implications, followed by the references.

2 LITERATURE REVIEW

This section reviews selected studies that examine the relationship between macroeconomic variables and deforestation in Brazil and the Amazon Biome. Box 1 summarises some of these contributions.

Box 1 – Selected articles for studying the relationship between macroeconomic variables and deforestation

Author	*Objective*	*Data*	*Methodology*	*Main results*
Silva *et al.* (2023)	Analyse the impact of conservation policies on private lands and their impact on deforestation between 2003 and 2020.	CAR data on properties MapBiomas data on deforestation	Descriptive Analysis of Variables Spatial Analysis	They noted the importance of the CAR and governance policies. The involvement of private properties is needed to amplify the effect of conservation policies. Expand monitoring.
Carvalho (2021)	Analyse the impact of settlements on deforestation in the Legal Amazon from 2002 to 2014.	Deforestation Data (Prodes), Settlements (Incra) and Commodity Prices	Fixed Effects Differences in Differences	The number of settlements must be combined with control policies to be effective against deforestation.
Ferreira Filho, Ribeira, and Horridge (2016)	Analyse the control over deforestation and agricultural expansion. The economic impact of food supply. The importance of changes in land use.	Satellite Data and the Land Use Transition Matrix from 1994 to 2002.	Term BR	Conservation policies can improve the country's position in international trade. However, it must include a more conscious land use policy. Policies to reduce deforestation will not threaten the supply of food demand.

Author	Objective	Data	Methodology	Main results
Lorenço (2021)	Evaluate the relationship between deforestation and socio-economic indicators.	GDP and price data from IBGE and Firjan. Inpe Deforestation	Spearman Correlation	The importance of conservation policies alongside economic indicators and encouraging sustainable crops.
Mello Júnior *et al.* (2023)	Analyse the effects of the PPCDAm on deforestation	Prodes and PAM data	Differences in Policy Evaluation	Supervision, remote monitoring, and expanding conservation policies are the main instruments for controlling deforestation.
Ferreira and Coelho (2012)	Evaluate the impact of agricultural prices on deforestation from 1999 to 2008.	Prices and GDP (IBGE - PAM) Deforestation (Prodes) Economic data (inflation, government spending, rural credit)	Panel Data	Prices and income growth affect deforestation by increasing demand for food, a pressure that can be mitigated through conservation policies.
Diniz *et al.* (2009)	Estimate the Granger Causality of the main variables that determine deforestation.	Municipal data from 1997 to 2006 for economic and social indicators	Granger Causality	Sustainable practices are required since there is evidence that the variables cause deforestation.
Assunção *et al.* (2015)	Evaluate the impact of conservation policies on deforestation in the Amazon. Evaluate the role of agricultural prices in deforestation trends.	Panel for the 380 municipalities of the Legal Amazon using Inpe and PAM	Fixed Effects	An important role for conservation policies, which can be influenced by prices. As a result, there is a need for greater conservation policies.
Carvalho and Domingues (2016)	Analyse deforestation caused by macroeconomic factors	TerraClass and the Agriculture and Livestock Farming Census	CGE analysis	Predicting growth trends in the biome, without registering that there is pressure for more deforestation to occur.

Source: Prepared by the authors based on the consulted studies.

Taken together, this body of literature indicates that deforestation is shaped not only by macroeconomic variables but also by structural characteristics of the productive system, patterns of domestic demand, institutional capacity, and the effectiveness of environmental enforcement. In addition, prior studies have consistently documented the role of price fluctuations in influencing deforestation dynamics. More recent contributions have further advanced this debate by demonstrating that the relationship between economic dynamics and deforestation is neither linear nor confined to conventional macroeconomic aggregates.

Lima *et al.* (2025), for instance, identify a non-linear relationship between deforestation and economic growth in the Brazilian Legal Amazon, suggesting that forest loss may generate only temporary economic gains that tend to diminish as deforestation intensifies. Similarly, Silveira *et al.* (2025) show that the relationship between economic complexity and deforestation is dynamic and non-linear, indicating that changes in the productive structure may initially intensify forest conversion, but may also contribute to its reduction over time – particularly when accompanied by stronger environmental enforcement mechanisms.

From a broader macro-structural perspective, Haddad *et al.* (2024) emphasise that domestic demand, rather than exports alone, plays a central role in driving deforestation in the Brazilian Amazon, thereby extending the debate beyond commodity-driven explanations. In a related vein, Ferreira Filho and Hanusch (2022) demonstrate that productivity gains concentrated in land-intensive activities, particularly agriculture, tend to increase deforestation. In contrast, productivity improvements in less land-intensive sectors may alleviate pressure on forest areas. Collectively, these studies underscore the importance of productive structure, sectoral composition, and structural transformation in shaping deforestation trajectories.

Recent research has also highlighted the critical role of institutions, monitoring systems, and environmental law enforcement in determining forest outcomes. Nunes *et al.* (2024) document significant changes in command-and-control dynamics in the Brazilian Amazon between 2000 and 2020, providing evidence of a weakening in enforcement capacity in recent years. Assunção, Gandour, and Rocha (2023), in turn, demonstrate that satellite-based monitoring systems – such as Deter – combined with environmental inspections, have played a significant role in reducing deforestation. Their findings provide robust evidence that monitoring effectiveness and enforcement capacity are central components of forest governance.

Although the literature on environmental macroeconomics, the political economy of deforestation, institutions, enforcement, and governance is extensive and rapidly evolving, this study does not seek to exhaust these debates. Rather, the selected studies provide an updated and analytically relevant foundation for situating the present investigation within the current state of the art. Building on the contributions summarised in Box 1, this study examines the relationship between macroeconomic variables and deforestation, following the approach of Diniz *et al.* (2009) through the application of Granger causality tests. However, in contrast to that study, we employ a time-series framework to assess the existence of long-run relationships between macroeconomic variables and their dynamic effects on deforestation over time, as detailed in the following methodology section.

3 METHODOLOGY

To achieve the objectives of this study, a time-series econometric approach is employed, incorporating the variables presented in Box 2.

Box 2 – Variables Used in the Time Series Model

Variable	*Description*	*Source*	*Model*
Deforestation	Deforestation in the states of the Legal Amazon in 1000 km²	MapBiomas – Prodes	Def
Agriculture and Livestock Farming Prices	Cepea's IPE considers the prices in FOB dollars (including transportation costs to the ship going to the importing country) of Brazilian agribusiness exports, including fresh and processed agriculture and livestock farming products. In other words, it refers to the prices received by exporters by product category.	Cepea/Esalq/USP	IPE
Real Exchange Rate	The real effective exchange rate is a weighted arithmetic average of the country's bilateral real exchange rates against 23 selected trading partners.	Ipea	Exchange Rate

Variable	Description	Source	Model
Agriculture and Livestock Farming GDP	The agriculture and livestock farming sector refers to GDP calculated from a production accounting perspective and includes agriculture and livestock farming establishments that produce for the market and for their own consumption. This activity covers the following sectors: agriculture, livestock, forestry, fishing, and aquaculture.	IBGE	GDPdef
Action Plan for the Prevention and Control of Deforestation in the Legal Amazon	A binary dummy variable was used, where 0 represents the years without PPCDAm (2000–2003), 1 represents the years of PPCDAm implementation (2004–2018), 0 again for the years when it was discontinued (2019–2022), and 1 for 2023, when the plan was resumed.	*Dummy*	PPCDam

Source: Prepared by the authors based on the consulted sources.

The primary objective of the analysis is to determine whether long-run relationships exist among the selected variables. Accordingly, a time-series framework is adopted. It is important to note that, due to the relatively small sample size associated with the use of annual data, certain variables commonly included in the literature to explain deforestation dynamics – such as rural credit, institutional indicators, and enforcement measures related to environmental policies – are not incorporated into the empirical model. This reflects the specific scope of the present study, which prioritises the role of macroeconomic variables.

For the application of time-series techniques, the statistical properties of the variables must be carefully examined. In particular, the series should be stationary, meaning that their statistical moments – such as mean, variance, and covariance – remain constant over time, and that the roots of the characteristic equation lie outside the unit circle (Lütkepohl, 2004). Box 3 presents the stationarity tests conducted for the variables included in the analysis.

Box 3 – Description of the Unit Root Tests

Test	Description	Null Hypothesis
Dickey-Fuller GLS test	One of the most recent methods is based on the Dickey-Fuller model, where there is a lower probability of making a type II error.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)
Ng-Perron test	This test assumes that any possible trend has already been removed. Furthermore, estimates can be made using Monte Carlo simulations, which offer considerable gains.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)
Phillips-Perron test	It applies a nonparametric correction to the Dickey-Fuller test, yielding a consistent estimate even in the presence of lagged dependent variables and serial correlation.	H0: γ = 0 (it has a unit root) H1: γ < 0 (AR (1) stationary)

Source: Prepared by the authors based on Bueno (2008).

Macroeconomic time series are typically non-stationary in levels; however, they often become stationary after first differencing, implying that they are integrated of order one, I(1). Although differencing ensures stationarity, it also leads to a loss of long-run information embedded in the data. To address this issue, and following Engle and Granger (1987), an error correction framework is employed to recover the long-term equilibrium relationships among the variables.

Based on the stationarity results presented in Box 3, the study proceeds to estimate autoregressive vector models using the dataset described in Box 2. As emphasised by Enders (2015), Lütkepohl and Krätzig (2004), Lütkepohl (2005), and Pfaff (2008), Vector Autoregressive (VAR) models have become a standard tool for analysing macroeconomic relationships, particularly following Sims' (1980) critique of large-scale structural models. Sims (1980) argued that traditional models fail to adequately account for the endogenous nature of economic variables, whereas VAR models treat all variables in the system as jointly endogenous.

Furthermore, Lütkepohl and Krätzig (2004) highlight that VAR-type models are particularly suitable for modelling data-generating processes involving a relatively small set of variables. These models also require careful consideration of the individual properties of each time series, including the presence of deterministic trends or potential structural breaks, which may affect model specification and inference.

Figure 1 illustrates the data-processing procedure adopted in this study following data collection, ensuring the application of appropriate econometric methods to identify long-run relationships and estimate autoregressive dynamics.

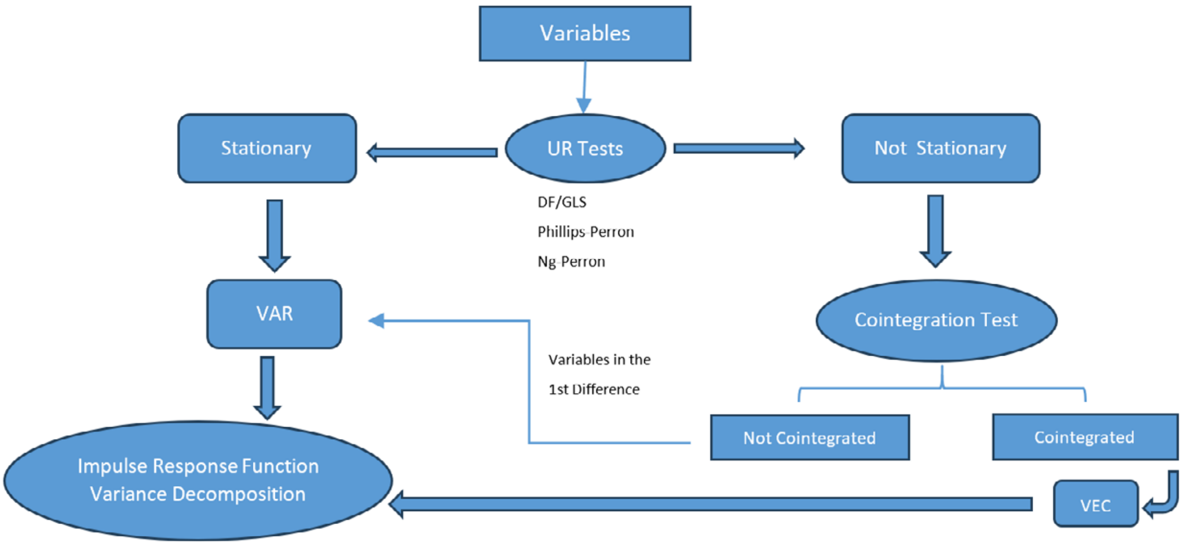


Figure 1 – Steps and Analysis for Building a Time Series Model

Source: Prepared by the authors based on the sources consulted in the methodology.

In addition, the Granger causality test is applied to examine the predictive relationships among the variables. As discussed by Carneiro (1997), this test is based on the principle that future values cannot influence the present or the past; therefore, it evaluates whether lagged values of one variable contain useful information for predicting another variable. A stationary time series is said to Granger-cause another if the inclusion of its lagged values improves the predictive performance of the latter (Carneiro, 1997). For the implementation of the test, non-stationary series are expressed in first differences when necessary. The optimal lag length is determined using the Schwarz Information Criterion (SIC), given its more parsimonious properties in model selection.

Following the presentation of the key elements of the time-series framework, the empirical analysis proceeds to address the research objectives. The EViews software is used to conduct stationarity and Granger causality tests. After identifying which variables in Box 2 exhibit unit roots, the Johansen cointegration test (Trace statistic) is performed using the JMulti software to assess the existence of long-run relationships among the variables. Additionally, JMulti is employed to estimate the most appropriate model specification based on the cointegration properties of the system. Depending on the results of the Johansen tests, either a Vector Autoregressive (VAR) model or a Vector Error Correction Model (VECM) is estimated.

The Schwarz Information Criterion is again used to determine the optimal lag structure of the model. Following model estimation, a set of diagnostic tests is conducted to assess model adequacy, including normality tests – such as Doornik–Hansen, Lütkepohl, and Jarque–Bera – and the Lagrange Multiplier (LM) test for serial correlation.

4 DISCUSSION OF RESULTS

To address the research questions posed in this study, this section begins with a descriptive analysis of the main variables, namely deforestation, agricultural and livestock prices, the real exchange rate, agricultural and livestock GDP, and the basic interest rate (Selic). Following this characterisation, we examine the predictive relationships among these variables using the Granger causality test. Finally, we investigate the long-run relationships among the variables within a time-series framework.

4.1 DESCRIPTIVE ANALYSIS OF VARIABLES

The evolution of annual deforestation in the Amazon biome since 2000 (Figure 2) constitutes the central focus of this study. This trajectory is analysed in conjunction with the evolution of agricultural and livestock GDP, the real exchange rate (INPC), and agricultural prices (IPE).

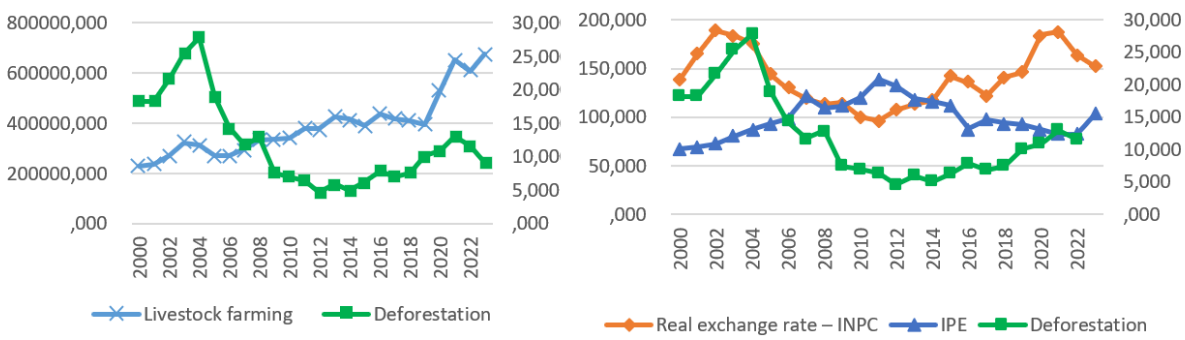


Figure 2 – Evolution of Deforestation in the Amazon Biome (in thousand km²), Agriculture and Livestock Farming GDP (in current BRL at 2023 prices), Real Exchange Rate - INPC, and IPE - Cepea from 2000 to 2023.

Source: Prepared by the authors using data from IBGE, Cepea, and Terra Brasilis.

Note: deforestation data is on the secondary axis.

In general, these variables are often associated with increased agricultural output and, consequently, higher deforestation rates. However, this expected relationship is not clearly supported by the evidence presented in Figure 2. Between 2000 and 2008, deforestation declined significantly, exhibiting a geometric rate of change of approximately −6.16% per year. Over the same period, agricultural and livestock GDP grew at an average annual rate of approximately 3.43%. This pattern persisted between 2008 and 2019, during which agricultural GDP increased at a rate of 2.12% per year, while deforestation continued to decline at an average rate of 0.35% per year.

This decoupling between economic growth and deforestation highlights the effectiveness of the PPCDAm (Action Plan for the Prevention and Control of Deforestation in the Amazon), which coordinated policies aimed at promoting economic activity in the region while simultaneously reducing deforestation rates. The evidence suggests that, during this period, Brazil was able to expand agricultural production without proportionally increasing deforestation.

However, between 2019 and 2022, this pattern reversed. Agricultural and livestock GDP grew at an annual rate of approximately 16.21%, accompanied by an increase in deforestation of approximately 6.10% per year. This shift coincided with the interruption of PPCDAm activities, which were only reinstated in 2023. These results indicate that, for nearly two decades, Brazil successfully implemented policies that allowed for agricultural income growth without exacerbating deforestation. This finding challenges the commonly held assumption that deforestation is a necessary condition for expanding agricultural production.

The relationship between deforestation and variables associated with prices and international competitiveness – captured by the real exchange rate – further reinforces this argument. Between 2000 and 2007, the Brazilian currency (Real) appreciated at an average annual rate of approximately 3.70%, while agricultural prices increased by 8.22% per year. Despite these price increases, deforestation declined at an annual rate of approximately 1.37%. This suggests that higher agricultural prices did not translate into increased deforestation during this period, contradicting the hypothesis that price incentives necessarily lead to forest clearing.

Between 2007 and 2016, the international economic environment remained favourable for Brazilian agricultural exports, although agricultural prices declined at an average rate of 1.53% per year. During this period, the Brazilian currency depreciated by approximately 2.04% annually, enhancing export competitiveness. Despite these favourable conditions for agricultural expansion, deforestation declined sharply at an average rate of 6.75% per year. This finding is consistent with the results of Ferreira Filho, Ribeiro, and Horridge (2015), who demonstrate that Brazil can meet international demand for agricultural products without expanding deforested areas.

In contrast, between 2016 and 2023, deforestation increased at an average annual rate of approximately 6.53%. Over the same period, the exchange rate depreciated by approximately 4.10% per year, increasing the competitiveness of Brazilian products in international markets. Agricultural prices, however, declined slightly at an average rate of 0.16% per year. The combined effect of exchange rate depreciation and relatively lower prices may have stimulated agricultural expansion, thereby increasing pressure on land-use change, particularly through pasture expansion and grain cultivation.

Nevertheless, this expansion strategy raises important concerns. As noted by Abramovay (2019), agricultural productivity in the Amazon region remains relatively low, suggesting that policies should prioritise sustainable intensification rather than the expansion of the agricultural frontier through deforestation.

To further examine the relationships among these variables, the following subsection presents a correlation analysis and the results of the Granger causality tests.

4.2 CORRELATION ANALYSIS AND GRANGER CAUSALITY

Based on the selected dataset, a correlation analysis was conducted, focusing on the relationships between deforestation – the central variable of interest – and the remaining variables (Table 1).

Table 1 – Correlation of the Deforestation Variable with Agriculture and Livestock Farming GDP, Real Exchange Rate, and IPE Variables.

	Agriculture and Livestock Farming GDP	*Real Exchange Rate*	*IPE*
Deforestation	-0.40	0.67	-0.68

Source: Prepared by the authors based on research results.

The results reported in Table 1 indicate a negative correlation between deforestation and both agricultural GDP and agricultural prices (IPE). This finding is consistent with the descriptive evidence presented in Figure 2, where deforestation declined over time despite increases in agricultural income and prices. However, it is important to interpret these results within the context of a policy environment characterised by strong conservation measures, particularly following the implementation of the PPCDAm in 2004.

Regarding the real exchange rate, the results indicate a positive correlation with deforestation. Exchange rate depreciation tends to increase the competitiveness of domestic products in international markets, thereby stimulating exports. In this context, increased external demand for Brazilian agricultural commodities may exert upward pressure on deforestation in the Amazon biome. This pattern may also reflect the expansion of trade with markets that impose relatively less stringent environmental requirements, such as countries in the Middle East and Africa, as well as emerging economies, including China and India.

To further investigate the dynamic relationships among the variables, unit root tests (DF-GLS, Phillips–Perron, and Ng–Perron) were conducted to assess the stationarity of the series. The results, presented in Box 3, indicate that all variables are non-stationary in levels but become stationary after first differencing, suggesting that they are integrated of order one, I(1). Accordingly, the analysis proceeds using first differences where required to ensure stationarity.

Following the stationarity analysis, causal relationships among the variables were examined using a bivariate Granger causality framework. This approach evaluates whether past values of one variable contain useful information for predicting another variable.

Table 2 – Granger Causality Test for the Deforestation, IPE, Real Exchange Rate, and Agriculture and Livestock Farming GDP Variables – with 1 lag* and the variables in the first difference.

Null Hypothesis		*Observations*	*Prob*
Real Exchange Rate does not Cause Granger	Deforestation	22	0.0034
	IPE	22	0.0166
	GDP	22	0.1003

Source: Prepared by the authors based on research data.

**This is consistent with the use of the Schwarz Information Criterion (SIC) to select the optimal lag length.*

Table 2 reports only the statistically significant Granger-causality relationships identified in the analysis.

The results highlight the central role of the real exchange rate in the system, as it Granger-causes the other variables, including deforestation, agricultural prices, and agricultural income. When interpreted alongside the previous findings, these results suggest that the real exchange rate constitutes a key macroeconomic determinant of deforestation dynamics in the Amazon biome.

From an economic perspective, this finding indicates that external market conditions – captured by exchange rate movements – affect both the profitability of agricultural activities and the incentives for production expansion. Exchange rate depreciation, in particular, tends to increase export competitiveness, thereby influencing sectoral prices and income. These mechanisms, in turn, may intensify pressures on land-use expansion and deforestation along the agricultural frontier.

These results are broadly consistent with the literature on the economic drivers of deforestation. Studies such as Assunção *et al.* (2015), Carvalho and Domingues (2016), Diniz *et al.* (2009), and Ferreira Filho, Ribeiro, and Horridge (2015), emphasise the role of macroeconomic conditions and international market incentives in shaping land-use dynamics in Brazil. At the same time, these studies highlight that the effects of such economic pressures can be mitigated through effective conservation policies and the adoption of sustainable production practices. Thus, economic growth and environmental protection are not necessarily mutually exclusive, provided that appropriate institutional and policy frameworks are in place.

It is important to note, however, the methodological limitations of the Granger Causality Test. While the test identifies predictive relationships based on lagged information, it does not establish structural causality in an economic sense.

Building on these findings, the next section examines the existence of long-run equilibrium relationships among the variables using cointegration techniques within a time-series framework.

4.3 LONG-TERM RELATIONSHIP BETWEEN VARIABLES

Given that the series are non-stationary in levels but integrated of the same order and stationary in first differences, it is appropriate to examine the existence of cointegration among them. To assess whether a linear combination of the variables indicates a long-run equilibrium relationship, the Johansen trace test for cointegration was conducted, as shown in Table 3.

Table 3 – Cointegration Test Results for Selected Variables.

r_0	λ_{trace}	*p-value*	*90%*	*95%*	*99%*
0	58,47**	0.0179	50.50	53.94	60.81
1	33,47***	0.0748	32.25	35.07	40.78
2	14,38	0.2699	17.98	20.16	24.69
3	5,11	0.2814	7.60	9.14	12.53

Source: Research results.

*Note: *significance at 1%, **significance at 5%, and ***significance at 10%.*

The results presented in Table 3 indicate the presence of at least two cointegration vectors among the selected variables, suggesting that they are cointegrated. In other words, the variables exhibit a stable long-term relationship. This finding implies that deforestation dynamics respond, over time, to changes in the selected macroeconomic variables. Formally, the existence of cointegration ($0 < r < k$) implies that the Π matrix has reduced rank, and therefore the appropriate specification is a Vector Error Correction Model (VECM). Accordingly, a VECM is estimated with two cointegration vectors[1], including a dummy variable capturing the presence or absence of the PPCDAm, in order to account for institutional changes over time.

To evaluate the contribution of each variable to the dynamics of deforestation in the Amazon biome, a variance decomposition analysis was conducted. This procedure allows for the identification of the proportion of forecast error variance attributable to shocks in each variable over different time horizons. The results are presented in Table 4.

Table 4 – Variance Decomposition of Deforestation in the Amazon Biome.

Horizon	*Def*	*IPE*	*Exchange Rate*	*GDPdef*
1	0.62	0.01	0.57	0.01
2	0.13	0.05	0.82	0.00
3	0.06	0.04	0.68	0.22
4	0.03	0.03	0.45	0.48

Horizon	Def	IPE	Exchange Rate	GDPdef
5	0.02	0.09	0.49	0.40
6	0.01	0.14	0.50	0.34
7	0.02	0.17	0.53	0.29
8	0.03	0.18	0.54	0.25
9	0.04	0.18	0.55	0.23
10	0.05	0.17	0.54	0.23

Source: Prepared by the authors based on the results of the estimated model.

The variance decomposition results indicate a predominant role of the real exchange rate in explaining deforestation dynamics over time, accounting for up to approximately 82% of the variation in deforestation. At longer horizons, price dynamics – captured by IPE (reaching approximately 18%) – and agricultural GDP (explaining up to 48%) also become increasingly relevant. These findings suggest that both price-related incentives and income dynamics contribute to changes in deforestation levels.

Overall, the results indicate that macroeconomic conditions that enhance external competitiveness and sectoral profitability may intensify pressures on deforestation. Consequently, conservation policies should be designed in alignment with macroeconomic dynamics, as the existence of a long-run relationship implies that such variables systematically influence deforestation outcomes over time.

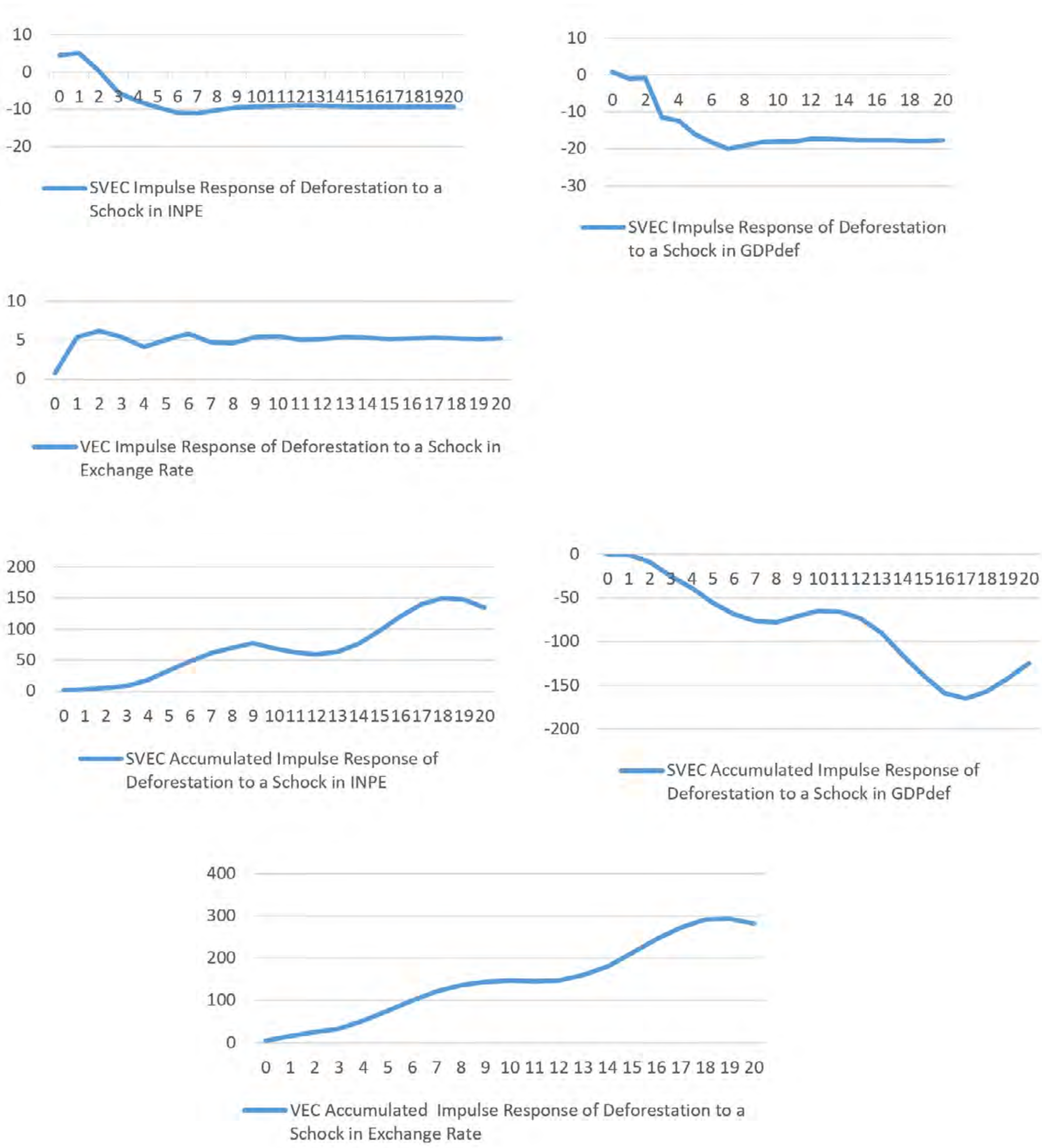
These findings are broadly consistent with the literature summarised in Table 1. For instance, Haddad *et al.* (2024) show that favourable market conditions and price dynamics tend to increase pressure on deforestation rates. Similarly, Silveira *et al.* (2025) argue that economic growth in the region introduces complexity into deforestation dynamics, generating both opportunities for environmental improvement and risks of expansion, depending on institutional conditions.

Across the reviewed studies – and as supported by the results presented here – a consistent conclusion emerges: while economic variables influence deforestation, their effects are strongly mediated by the design and effectiveness of conservation policies. When such policies are weak or poorly enforced, deforestation tends to accelerate. Therefore, it is essential to integrate conservation and sustainability policies with economic development strategies, particularly by creating incentives for sustainable production practices rather than promoting expansion through deforestation for grain cultivation or extensive cattle ranching.

Although the estimated model attempts to capture institutional effects through the inclusion of a binary variable associated with the PPCDAm, other relevant factors – such as rural credit availability, enforcement intensity, and broader institutional changes in environmental governance – could not be incorporated into the empirical specification.

Regarding the dynamic responses of deforestation to macroeconomic shocks, the results – illustrated in Figure 3 – indicate that positive shocks in both prices and the exchange rate generate positive effects on deforestation. This finding reinforces the importance of macroeconomic conditions in shaping the expansion of the agricultural frontier. In particular, exchange rate depreciation increases the profitability of agricultural exports, thereby stimulating investment and the expansion of cultivated areas.

Figure 3 – Accumulated Impulse Response of Deforestation in the Amazon Biome to a Shock in IPE, Real Exchange Rate, and Agriculture and Livestock Farming GDP.



Source: Prepared by the authors based on the results of the estimated model.

This result is consistent with the literature identifying exchange rate movements and commodity prices as key drivers of agricultural expansion in the Amazon, as highlighted by Ferreira Filho and Hanusch (2022), and Haddad *et al.* (2024).

Conversely, the cumulative negative effect of GDP on deforestation suggests a more complex process of structural transformation. This effect may be associated with institutional improvements, technological progress, or enhanced environmental governance accompanying economic growth. As discussed by Lima *et al.* (2025), higher income levels may strengthen institutional capacity for environmental monitoring and enforcement, as well as facilitate the adoption of more efficient production technologies. Similar findings are reported by Assunção, Gandour, and Rocha (2023), who show that monitoring systems such as Deter, combined with command-and-control policies, played a crucial role in reducing deforestation during certain periods, even in the presence of economic incentives favouring agricultural expansion.

These dynamics are also influenced by developments in supply chain governance, including increased monitoring of production processes, destination markets, and private-sector initiatives aimed at enhancing environmental standards. Examples include mechanisms such as the Soy Moratorium and traceability systems in the beef supply chain, which seek to expand market access while promoting compliance with zero-deforestation commitments.

In summary, the evidence suggests that Brazil has previously been able to combine economic growth with reductions in deforestation in the Amazon biome. Achieving this outcome required coordination among multiple actors within both the economic and institutional environment. Reestablishing such coordination is essential to ensure that the agricultural sector continues to generate income and access international markets while, through effective conservation policies, regulatory enforcement, and incentives for sustainable practices, significantly reducing deforestation rates.

5 CONCLUDING REMARKS

This study aimed to assess whether macroeconomic variables, particularly those related to income and international trade, affect deforestation in the Amazon biome. Specifically, the analysis examined the existence of a long-run relationship between deforestation in the Legal Amazon and selected economic variables, namely agricultural prices, the real exchange rate, and agricultural GDP. The results from the Johansen cointegration test indicate that these variables are cointegrated, confirming the presence of a long-term equilibrium relationship.

The descriptive analysis reveals a significant acceleration in deforestation in recent years. However, during the early 2000s through the early 2010s, agricultural income increased substantially while deforestation declined considerably in the Amazon biome. This finding suggests that economic growth in the agricultural sector can occur without necessarily increasing deforestation, particularly in the presence of effective conservation policies.

The variance decomposition results indicate that exchange rate shocks account for a substantial share of the fluctuations in deforestation, while agricultural GDP and prices play a secondary, yet still relevant, role. This suggests that macroeconomic conditions directly affect the economic incentives associated with the expansion of the agricultural frontier. The impulse–response functions further support this interpretation, showing that positive shocks in prices and in the exchange rate generate positive cumulative effects on deforestation. In contrast, the effect of income is more complex, potentially reflecting structural and institutional transformations over the development process.

These findings are consistent with studies such as Lima *et al.* (2025) and Silveira *et al.* (2025), which emphasise the role of structural dynamics and regional economic conditions in shaping environmental outcomes in the Amazon. In this context, the results indicate that macroeconomic variables exert a measurable influence on deforestation, with the real exchange rate emerging as a particularly relevant determinant. This suggests that pressures arising from international market conditions may contribute to the expansion of deforestation and, therefore, should be considered in the design of economic and trade policies.

The results also reinforce the interpretation found in the recent literature that deforestation in the Amazon is closely linked to the profitability of agricultural activities and the region's integration into national and global value chains, as discussed by Ferreira Filho and Hanusch (2022) and Haddad *et al.* (2024). Although the present study captures institutional effects only through the inclusion of a dummy variable, existing evidence shows that command-and-control policies, combined with satellite-based monitoring systems and effective enforcement mechanisms, have played a critical role in reducing deforestation during certain periods. This is highlighted in the work of Assunção, Gandour and Rocha (2023) and Nunes *et al.* (2024).

Overall, the results indicate that deforestation in the Amazon biome is strongly associated with macroeconomic conditions, particularly exchange rate movements, agricultural prices, and income dynamics. Exchange rate fluctuations, by affecting external competitiveness and sectoral profitability, appear to be a central mechanism influencing land-use decisions. At the same time, the empirical evidence suggests that the institutional environment mediates the impact of these economic drivers. Periods characterised by stronger monitoring systems, effective enforcement, and robust conservation policies tend to mitigate environmental pressures arising from favourable market conditions. Therefore, the interaction between macroeconomic incentives and institutional capacity emerges as a key factor in understanding deforestation dynamics in the Amazon.

Despite these contributions, the study presents several limitations. The analysis is based on annual data, which could be extended in future research using higher-frequency datasets, such as monthly observations, and more advanced econometric frameworks capable of handling larger datasets. This would allow the estimation of more complex macroeconomic models – similar to those employed by central banks – and enable the analysis of potential links between monetary policy and deforestation dynamics. In addition, the relatively small sample size limits the scope of the empirical analysis. The model also does not include variables that may be important in explaining deforestation dynamics, such as rural credit availability, enforcement intensity, and broader institutional mechanisms related to environmental governance. The incorporation of these factors represents an important avenue for future research.

NOTE

1 | The estimated VEC model followed the Schwarz Information Criterion (SIC) for lag selection. Normality tests—Doornik–Hansen, Lütkepohl, and Jarque–Bera—were conducted, indicating that the residuals do not deviate from normality. Regarding autocorrelation, the LM test indicates its presence, which may be associated with the small sample size or dynamics not fully captured by the specified lags.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

The authors used ChatGPT (OpenAI) only for language editing and stylistic polishing. All scientific content, analysis, and intellectual input were developed and verified by the authors; we take full responsibility for the accuracy and integrity of the manuscript.

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