METHODOLOGICAL CONTRIBUTIONS TO EXPLAIN THE DETERMINANTS OF DESTRUCTION OF THE AMAZON RAINFOREST

Antônio Cordeiro de Santana¹
Ádina Lima de Santana²
Sérgio Castro Gomes ³
Nilson Luiz Costa⁴
Eder Silva de Oliveira⁵
Ádamo Lima de Santana⁶
Gilmara Maureline Teles da Silva de Oliveira⁷

ABSTRACT

Objective: The objective of this study was to construct econometric models to identify and analyze the variables that define and explain the deforestation cycle in the Amazon.

Theoretical framework: The forest is one of the main sources of carbon sequestration and storage on Earth. Thus, deforestation and forest burning contribute to increasing the impact of the greenhouse effect on climate change, due to CO₂ emissions. The protection of the Amazon forest is prioritized for its contribution to mitigating the effects of climate change.

Results and conclusion: The annual increase in deforested forest area in the Amazon follows a polynomial behavior explained by the exchange relationships between the prices of deforested and occupied areas with crops and pastures and the prices of lands with native forest. It is this exchange relationship that deserves the attention of policymakers for forest preservation through deforestation control.

Research implications: This exchange relationship can cause a turnaround in the deforestation cycle based on the knowledge of the value of standing forests, a fact that would reverse the exchange relationship and require the adoption of sustainable practices in agricultural, livestock, mineral, and forestry production systems.

Originality/value: This research shows that there is an increase in deforested area in the Amazon forest, with only the rate of this deforestation varying, which can be increasing or decreasing.

Keywords: Bioeconomy, Regenerative Agriculture, Reforestation, Biodiversity, Amazon.

¹ Universidade Federal Rural da Amazônia (UFRA), Belém, Pará, Brazil. E-mail: acsufra@gmail.com
Orcid: 0000-0002-4324-9178

² Kansas State University, Manhattan, KS, Estados Unidos. E-mail: adina.santana@gmail.com
Orcid: 0000-0002-7999-0946

³ Universidade da Amazônia (UNAMA), Belém, Pará, Brazil. E-mail: scgomes03@uol.com.br
Orcid: 0000-0002-1731-8766

⁴ Universidade Federal de Santa Maria (UFSM), Palmeira das Missões, Rio Grande do Sul, Brazil. E-mail: nilson.costa@ufsm.br
Orcid: 0000-0002-2560-2214

⁵ Universidade do Estado do Pará (UEPA), Belém, Pará, Brazil. E-mail: ederso@uepa.br
Orcid: 0000-0003-2000-1521

⁶ Corporate R&D Headquarters, Fuji Electric, Tokyo, Japan. E-mail: alwkynew@gmail.com
Orcid: 0000-0003-0745-8519

⁷ Universidade Federal Rural da Amazônia (UFRA), Belém, Pará, Brazil. E-mail: gilmara.teles@ufra.edu.br
Orcid: 0000-0001-6715-5945
CONTRIBUIÇÕES METODOLÓGICAS PARA EXPLICAR OS FATORES DETERMINANTES DA DESTRUIÇÃO DA FLORESTA AMAZÔNICA

RESUMO

Objetivo: Construir modelos econométricos para identificar e analisar as variáveis que definem e explicam o ciclo do desmatamento na Amazônia.

Referencial teórico: A floresta é uma das principais fontes de sequestro e armazenamento de carbono da Terra. Logo o desmatamento e queima de florestas contribuem para aumentar o impacto do efeito estufa nas mudanças climáticas, em função das emissões de CO2.

Resultados e conclusão: O incremento anual da área de floresta desmatada na Amazônia segue um comportamento polinomial explicado pelas relações de troca entre os preços das áreas desmatadas e ocupadas com lavouras e com pastagens e os preços das terras com floresta nativa. É essa relação de troca que merece a atenção dos formuladores de política para a preservação da floresta via controle do desmatamento.

Implicações da pesquisa: Essa relação de troca pode causar uma reviravolta no ciclo do desmatamento a partir do conhecimento do valor da floresta em pé, fato que reverteria a relação de troca e exigiria a adoção de boas práticas sustentáveis nos sistemas de produção agrícola, pecuário, mineral e florestal.

Originalidade/valor: A causa de maior impacto sobre o desmatamento é o desconhecimento do valor dos ativos naturais e do fluxo de serviços que ofertam à economia e aos seres humanos. Sem este conhecimento, o custo de oportunidade do estoque de terras com florestas na Amazônia, que supera o preço sombra das terras com lavouras, pastagens e manejo florestal, fixado por agentes econômicos em nível próximo a zero, equivalente a um fator de produção público em abundância.

Palavras-chave: Bioeconomia, Agricultura regenerativa, Reflorestamento, Biodiversidade, Amazônia.

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1 INTRODUCTION

In the Amazon, economic agents continue to value natural assets based on the market price of the main product that is used as an input in economic activity (Santana and Khan, 1992; Farley, 2008), neglecting the flow of ecosystem services provided by nature and broad benefit and support for the survival of human beings (Costanza et al., 1997; Farley, 2008; Dasgupta, 2008; Santana et al., 2017). As the prices of these services are not quoted on the market, the opportunity cost becomes low and, as a consequence, stimulates the destruction of the ecological functions of natural ecosystems (Farley et al. 2010; Santana, 2018; Santana et al., 2022).

In this context, one of the main challenges for human beings is to decide how much of natural ecosystems can be converted into economic production, food security and social well-being and how much must be conserved to continue providing the flow of ecosystem services essential to life on Earth. (Daly and Farley, 2008; Farley, 2008; Liu et al., 2010). In Brazil, the
new Forest Code (Law no. 12,651, 25/05/2012, Brazil, 2012) established for the Amazon Biome that 80% of the natural ecosystem structure must be preserved to provide ecosystem services essential to life and 20% can be converted into economic production. This percentage to be preserved is not being met by economic agents, since data from the 2017 Agricultural Census (IBGE, 2019) reveal a level of depletion of the natural ecosystem of 39.6% in rural establishments in the state of Pará (Santana, 2022), as well as the continuity of deforestation in reserve areas and forest conservation units. This situation is reproduced in all states of the Brazilian Legal Amazon (Fearnside, 2020; INPE, 2022).

Economic agents continue to determine the price of the natural asset that must be converted into a manufactured asset (Santana, 2020), acting contrary to the power that agents who preserve the stock of natural assets should have to define the activity and form the price of services ecosystems (Farley, 2008; Dasgupta, 2008). It turns out that, without knowing the value of natural assets, agents always act as price takers, whose signal is given by companies and intermediary agents that operate in the market for natural assets land, water and forest, whose adjustment dynamics are influenced by public policies and the internal and global demands for wood, grains, meat, ores, cellulose and biofuels (Santana and Khan, 1992; Costanza et al., 1997; Fearnside et al., 2018; Gibbs et al., 2015; Carvalho et al., 2019).

The value of natural assets, including forested land, is the key to controlling deforestation, understood as the total or partial suppression of vegetation for land use in agricultural production, livestock, mineral and timber extraction, road infrastructure and flooding of the forest by dams used to produce electrical energy, at levels compatible with the physical growth capacity of ecosystems and economic activity (Farley, 2008; Foley et al., 2011; Azevedo JR. and Santana, 2022; Oliveira et al., 2020; Costa, 2022). In Brazil, the methodologies applied to calculate the value of standing forest for the purpose of compensation for vegetation suppression and for forest concession notices (Monteiro et al., 2011; Santana et al., 2011), underestimate the value of wood and the standing forest, as they only focus on the tree trunks and lose the canopy and the flow of ecosystem services. Therefore, we are moving in the opposite direction of the sustainable use of resources and, in turn, the preservation of the Amazon biome.

Deforestation of the natural ecosystems of the Amazon remains widespread and increasingly impactful, the causal effect of which is attributed to the development of various economic activities – livestock, timber, mining, roads, agrarian reform settlements, land grabbing, family farming, hydroelectric plants, concessions forestry, grains (corn and soybeans), palm oil, forestry, etc. (Kitamura and Müller, 1984; Santana and Khan, 1992;
Young, 1998; Angelsen and Kaimowitz, 1999; Incra, 1999; Brasil, 2002; Fearnside, 1992, 2003; IPAM, 2006; Santana et al., 2016; Margulis, 2001; Rivero et al., 2009; Carvalho et al., 2019; Costa, 2022). Thus, according to information from INPE (2022), actions within environmental legislation to combat deforestation and fires evolved throughout the 2000s (Fearnside, 2020; Gibbs et al., 2015; Koch et al., 2019), reaching the minimum increase in deforestation in 2012; From then on, increases in deforestation evolved again and with greater impact.

Many works have been developed to explain this deforestation process (Gollnow and Lakes, 2014; Rajão et al., 2021; Costa, 2022), but it has not yet been possible to show the causal mechanisms and the chain of effects of the vector of variables that directly impact in the increase in deforestation. This variable evolves in cycles of 16 to 20 years, according to data from INPE (2022) and MapBiamas (2022), and the variables that explain the growth of areas occupied with commodities show different behavior (IBGE, 2022a, b, c). Thus, analyzes carried out over the period from 2000 to 2012 (Gollnow and Lakes, 2014; Santana et al., 2014; Gibbs et al., 2015; Rivero et al., 2009; Ferreira and Coelho, 2015) show a negative correlation and those that consider the period from 2012 to 2021 show a positive correlation (Carvalho et al., 2019; Koch et al., 2019; Costa, 2022; Fearnside, 2020). The main cause of this contradiction in the results and consequent limitation of the analyzes is due to the fact that the specified models do not consider the dynamics of the complete cycle of the variable increase in deforestation and the variable resulting from the vector of variables that cause deforestation.

To resolve this methodological problem and mitigate the controversial narratives surrounding the understanding of this phenomenon, it is necessary to identify the route of the chain of relationships of causes and effects of the variables that directly and indirectly impact deforestation. It is at this point that the work, anchored in the integration of knowledge of economics and ecology, intends to build an analytical model to highlight the result of the vector of variables that directly impacts the increase in deforestation at any stage of the cycle. The question to be answered is what is the chain of cause and effect of the variable or vector of socioeconomic variables, which directly influences deforestation? How to estimate the effects of large projects that directly or indirectly influence deforestation over time?

The hypothesis is that from a systemic econometric model capable of connecting the following three stages: estimation of equilibrium prices in commodity markets; estimate of prices for land with forest and without forest; estimating the effects between the exchange rates of land without forests and with forests and the increase in deforestation, it is possible to identify the variables that present positive correlations with the increase in deforestation throughout the
cycle. The vector defined by exchange relations or shadow prices between the price of the deforested area (average of the prices of pasture areas with different levels of productivity, crop areas with different technological levels and areas deforested and occupied with pasture and crops) and the price of land with primary forest (average prices for easily accessible and difficult to access areas) is directly correlated with the increase in deforestation.

The objective of the work was to build econometric models to integrate cause and effect relationships in product markets (relationship between equilibrium prices of products and the area planted with crops and pastures) and land (forest areas reflecting the supply stock of areas to be converted into deforested areas, which represent the demand for agricultural and logging activities), to configure the dynamics of these causal effects between socioeconomic activities and deforestation of the Amazon forest.

2 METHODOLOGICAL FUNDAMENTALS

The study area for specifying the model for analyzing deforestation in the Amazon is the state of Pará, due to the historical trajectory of deforestation associated with the set of socioeconomic activities linked to developmental programs and policies and inertial actions to combat deforestation and implementation of good sustainable practices by agents linked to extractive, family and business production systems. The state of Pará has the greatest representation of the historical process of deforestation in the Amazon and, therefore, served as the basis for the specification of the econometric model to contemplate the direct and indirect causal relationships of economic and sociodemographic activities on the deforestation and burning of the Amazon forest.

The econometric models were specified to describe the reality of the deforestation cycle in the state of Pará, due to the availability of data for the commodity markets of beef cattle, minerals, wood, grains and palm oil to then be validated for the Legal Amazon, including only municipalities in the Amazon biome. The review of knowledge about the historical factors identified as causing deforestation in the study area is presented below.

2.1 DEFORESTATION FACTORS

The historical factors identified and analyzed until the end of the 1990s (Yong, 1998; Angelsen and Kaimowitz, 1999; Incra, 1999; Margulis, 2001; Santana and Khan, 1992; Fearnside, 2006, Rodrigues, 2004), continue to be highlighted as causes of deforestation of
Amazon ecosystems. However, the introduction and expansion of commodities in the Amazon, involving soybean plantations, eucalyptus for cellulose production, oil palm for biofuel manufacturing, logging, extensive beef cattle farming and mineral extraction, along with infrastructure of highways, ports and expansion of urbanization continue to have an impact on deforestation and forest burning (Fearnside et al., 2018; Gollnow and Lakes, 2014; Gibbs et al., 2015; Carvalho et al., 2019; Santana, 2022).

The period from 2000 to 2021, according to statistics from (IBGE, 2022c; MapBiomas, 2022) for the state of Pará, the area cultivated with soybeans increased by 32.07% per year, with cocoa 7.46% per year, palm oil 7.42% per year and pasture 1.89% per year. The area harvested with black pepper, banana, rice, beans, corn and cassava only fluctuated around the historical average. Regarding productivity, there were increases of 1.06% per year in soybeans and 1.36% per year in cocoa. The other crops did not show productivity gains. Real prices, in turn, remained stable during the period, except for the price of cassava root, which grew 5.06% per year.

Commodities, in the same period, evolved through the cultivated area effect, due to the stock of land areas without primary forests (areas occupied by degraded pastures, family farming crops and capoeira areas), which increased the demand for agricultural area. deforested land, whose supply is defined by the stock of areas with private and public forests (Costa, 2022). This information indicates that commodity prices, even though they remain remunerative and stable over time, have not enabled the inclusion of more productive and sustainable technologies and innovations on a broad basis (Santana, 2020). They only guaranteed gains to medium and large producers through the scale of production, made possible by replacing areas with temporary crops, occupying fallow areas from family farming and incorporating areas with degraded pastures. Therefore, the evolution of the area effect more than counterbalanced the price and productivity effects. As a result, incremental environmental liabilities increased over time.

The state of Pará, when considering all the historical factors that cause deforestation and burning of the Amazon forest, according to Kitamura and Müller (1984), Santana and Khan (1992), Young (1998), Incra (1999), Angelsen and Kaimowitz (1999), Fearnside (1992; 2006), Margulis (2001), Santana et al. (2011), Gibbs et al. (2015), Carvalho et al. (2019), Amorim et al. (2020) and Costa (2022), is the area of study of the specification and application of the econometric model to the causes of deforestation and contribute to the design of monitoring and control policies. These factors are: opening of roads (federal and state), implementation of agrarian reform settlement projects, mining projects; hydroelectric plants; sectoral projects.
(wood, livestock, eucalyptus, palm oil and soy); forestry concessions; subsidized interest credit policy and tax incentives fed by government programs to stimulate sustainable growth in the Legal Amazon, in response to national and international demands for commodities.

The opening of roads makes settlements possible and the expansion of roundwood extraction, which reduces the cost of deforestation and the implementation of pastures and temporary and permanent crops (Santana and Khan, 1992; Young, 1998; Margulis, 2001; Homma et al., 2014; Alencar et al., 2016; Amorim et al., 2020). The synergy between these activities gains strength in areas surrounding large mining projects, hydroelectric plants, forest concessions and within agrarian reform settlement areas (Monteiro et al., 2011; Santana, 2012; Alencar et al., 2016; Santana et al., 2019). The expansion of commodities in the Amazon, involving soybean plantations, oil palm linked to the biofuel matrix, eucalyptus for cellulose, paper and coal, the continuity of extensive beef cattle farming and mining, have enabled the growth of agricultural production and forestry, through the area effect (IBGE, 2022c; Santana et al., 2014; Santana, 2022). This practice, in addition to depleting the stocks of areas without primary forest (areas occupied by pastures, crops, fallow forests) increases the demand for deforested area, the supply of which is given by the remaining stock of the 20% of areas with primary forest destined for the activity, economy in the Amazon Biome. On the marginal fringe of the land market, there is the illegal supply of vacant land areas and those occupied without legalized property rights (BRASIL, 2002; IPAM, 2006; Alencar et al., 2016).

In this context, family farmers from agrarian reform settlement projects distributed along federal highways, or on the edges of areas with commodities and concessions for the exploration of wood and minerals, who on a small scale deforest and burn to meet, initially, come into play subsistence agriculture and livestock farming and, later, these areas are incorporated into the production of grains, palm oil, eucalyptus and agroforestry systems (Santana et al., 2011). Deforestation of areas destined for conservation occurs in different ways as a reflection of actions triggered by mining and logging activities, which fuel “land grabbing” activities and land conflicts with indigenous people, extractivists, squatters, due to the limitations of the property right to enable the possession and use of land in accordance with regulatory frameworks (INCRA, 1999; BRASIL, 2002; Rodrigues, 2004; IPAM, 2006; Monteiro et al., 2011; Santana et al. 2023).
2.2 THEORETICAL BASIS OF THE MODEL

The theoretical model proposed to specify the chain of variables that produce impacts on the deforestation of the Amazon forest, from an econometric perspective capable of generating the vector resulting from theoretical contributions on the rational use and preservation of natural ecosystems, contemplates the neoclassical assumptions of economic growth (Pigou, 1935; Solow, 1974, 1979; Stiglitz, 1979), ecological and physical (Georgescu-Roegen, 1975; Schneider and Kay, 1994; Mayumi et al., 1998; MEA, 2003; Raine et al., 2006; FAO, 2007) on real wealth and depreciation of natural and manufactured assets. Thus, real wealth is defined by natural assets and manufactured assets, and both are subject to depreciation and natural and/or induced wear and tear. However, these liabilities cannot be considered homogeneous (Georgescu-Roegen, 1975, 2013; Daly and Farley, 2008), as neoclassical economists argue (Solow, 1974; Stiglitz, 1979).

The depreciation of natural assets through management and/or destruction is not reversed immediately, it can take years and, even so, some ecosystems do not return to their original situation, as they lose ecological and economic value permanently (Boyce, 2001; Farley, 2008; Azevedo Jr. and Santana, 2022). Furthermore, until now, natural assets are only seen as a source of inputs and/or raw materials for economic activities (Farley, 2008; Dasgupta, 2008; Santana et al., 2011). The flow of ecosystem services is neglected by all activities carried out in the Amazon (agriculture, livestock, forestry, mineral extraction, hydroelectric plants and fishing). Even with the recognition of the effects of human activity on natural ecosystems, analyzes that support the exploitation of natural assets without including the opportunity costs or shadow prices of natural assets in cash flows continue to expand (Farley, 2008; Liu et al., 2011; Azevedo JR and Santana, 2022; Santana et al., 2023).

Due to the lack of knowledge of the total economic value of natural assets, economic activity in the Amazon continues to advance through the deforestation of forest areas, which represent the land market supply for agriculture, the price of which is a small fraction of the real value of the natural asset land with forest (Santana, 2018; Costa, 2022). In this way, the demand for deforested area, defined by rural-based economic activities, in interaction with supply, forms the market equilibrium price for land with and without forest (Santana et al., 2014; Costa, 2022).

The prices of deforested areas occupied by crops and livestock are determined by the equilibrium prices of commodities which, in turn, define the dynamics of demand for deforested area, which is achieved through the deforestation of forested land areas (Santana et al., 2014;
Costa, 2022). However, this logic goes against knowledge about the socioeconomic and environmental opportunity cost of natural assets, which are indispensable for providing the means of subsistence and well-being of human beings (Farley, 2008; Dasgupta, 2008; Santana et al., 2022).

Following this thought, studies that monitor the relationship between the performance of economic activities and deforestation, perhaps because they accept as irrefutable the initial models that sought to identify the direct and indirect effects of economic activities on deforestation (Young, 1998; Incra, 1999; Margulis, 2003), do not explain the logic of correlations within and between commodity and land markets. Furthermore, there are modeling flaws in not considering the complete cycle that characterizes deforestation accumulated under the influence of equilibrium prices in the commodity market and large projects supported by public credit policies and tax incentives (Santana et al., 2014; Castro and Castro, 2022). The advancement of economic activities in the form of production and increase in cultivated area reflect the consensus of researchers and a large part of society, whose trend was positive in the period analyzed. On the other hand, the incremental evolution of deforestation exhibits cyclical behavior, indicating an inverse relationship between the advancement of economic activities and deforestation in the period from 2000 to 2021.

That said, a theoretical model is proposed to represent the chains of causes and effects of the variables that determine the formation of equilibrium prices in product and land markets on the deforestation of natural ecosystems in the Amazon. Thus, the consistency of the model with economic and ecological interaction occurs through the direct relationship between the increase in deforested area and the exchange relationship between the prices of deforested land and land with forest.

In Figure 1, the first link in the chain of causes and effects of deforestation is configured by the correlation between the equilibrium prices of the commodity market (cultivated area depending on the price of products and other explanatory variables) and the formation of land prices with and no forests in the land market (link 1, Figure 1). The second link guides the construction of exchange relations based on the ratio between the equilibrium prices of land without forests (pasture, crops and total) and the prices of land with forests (link 2, Figure 1). Link three of the general econometric model specification defines the increase in deforestation as a function of exchange relationships between land market prices (link 3, Figure 1). The functional form of the models must obey the non-linear behavior between the variables.

The economic and ecological foundation of these causal relationships indicates that the functional form is a polynomial of the second degree and, therefore, non-linear. In effect, partial
studies focused on just one phase of the production evolution cycle and increase in deforestation can only help in the partial diagnosis of deforestation and lead to errors in interpretation and guidance of the effects of public policies linked to land use and on the future of the agrarian-based economy and the natural ecosystems of the Amazon.

**Figure 1**
The causes and effects between the variables that impact the deforestation of the Amazon forest in the period from 2000 to 2020, state of Pará.

Source: Own preparation. IAD - Increase in deforested area.

### 2.3 CONSTRUCTION OF THE EMPIRICAL MODEL

The increase in deforestation and, in turn, the evolution of the accumulated deforested area of the Amazon forest, involving rural properties and reserve areas, conservation units and vacant federal and state lands, is a direct function of the exchange relationship between the prices of land with primary forest to no forest (land occupied by crops and pastures) and the price of land without forest, respectively. What matters in the decision to deforest is the amount of ha of forest that can be purchased for one ha of deforested area and occupied with pasture and/or crops.

Based on statistics on Municipal Agricultural Production (IBGE, 2022a), Municipal Livestock (IBGE, 2022b) and Plant Extraction and Forestry (IBGE, 2022c), it is observed that there was no gain in productivity for the main commodities (cocoa, palm oil, soybeans) nor for family farming (beans, corn and cassava). The response to cyclical changes in the prices of these products, in search of profitability and profitability, occurs through the expansion of the cultivated area.
Table 1 illustrates the positive correlation between prices and harvested crop areas and pasture area in the state of Pará. This is the first link in the chain of effects of factors that are associated with deforestation. Thus, the relationship between economic market variables, influenced to a lesser or greater extent by national policies and international commodity trade strategies, impact the prices of forest, pasture and agricultural land.

All correlations are statistically significant at 5%, except for soybeans, which did not show statistical significance (Table 1). Therefore, the prices of land with forest and without forest are formed based on the market equilibrium prices of these products, which are representative of agricultural, livestock and timber activities in the state of Pará (Santana, 2022). The impact of the expansion of these activities on the shadow price of land is influenced directly and indirectly by programs and projects to expand the infrastructure of roads, ports, hydroelectric plants, concession of areas for the exploration of wood and minerals, areas for settlement of reform agrarian and urbanization dynamics that, together, mobilize migration between countryside and city and between regions (Margulis, 2001; Rivero et al., 2009; Monteiro et al., 2011; Walker et al., 2013). These programs and projects, in general, are linked to the demands of international commodity markets, according to the monitoring and recording of causal relationships pointed out by Fearnside (2003, 2006) and other studies focused on the destruction of chestnut plantations (Kitamura and Müller, 1984; Santana and Khan, 1992), in the relationship between logging activity and deforestation (Inra, 1999; Alencar et al., 2016) and others such as Rajão et al. (2020) and Carvalho et al. (2019) who focus on soy, timber and livestock activities as the main drivers of deforestation.

### Table 1

**Correlation between commodity prices and areas of land with primary forest, pasture and agriculture, 2020-2021, state of Pará.**

<table>
<thead>
<tr>
<th>Variables</th>
<th>PACMata</th>
<th>VP</th>
<th>PAPasto</th>
<th>VP</th>
<th>WORD</th>
<th>VP</th>
<th>PASMata</th>
<th>VP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMtora</td>
<td>0.530</td>
<td>0.012</td>
<td>0.422</td>
<td>0.050</td>
<td>0.4344</td>
<td>0.044</td>
<td>0.4375</td>
<td>0.042</td>
</tr>
<tr>
<td>Pboi</td>
<td>0.612</td>
<td>0.003</td>
<td>0.665</td>
<td>0.001</td>
<td>0.6161</td>
<td>0.003</td>
<td>0.6417</td>
<td>0.002</td>
</tr>
<tr>
<td>Pdendê</td>
<td>0.855</td>
<td>0.000</td>
<td>0.859</td>
<td>0.000</td>
<td>0.7358</td>
<td>0.000</td>
<td>0.7870</td>
<td>0.000</td>
</tr>
<tr>
<td>Pcacau</td>
<td>0.690</td>
<td>0.000</td>
<td>0.796</td>
<td>0.000</td>
<td>0.6929</td>
<td>0.000</td>
<td>0.7370</td>
<td>0.000</td>
</tr>
<tr>
<td>Cassava</td>
<td>0.784</td>
<td>0.000</td>
<td>0.752</td>
<td>0.000</td>
<td>0.6129</td>
<td>0.003</td>
<td>0.6674</td>
<td>0.001</td>
</tr>
<tr>
<td>PSoy</td>
<td>0.040</td>
<td>0.287</td>
<td>-0.016</td>
<td>0.393</td>
<td>0.0688</td>
<td>0.375</td>
<td>0.0428</td>
<td>0.387</td>
</tr>
<tr>
<td>IPopulation</td>
<td>-0.903</td>
<td>0.000</td>
<td>-0.891</td>
<td>0.000</td>
<td>-0.786</td>
<td>0.000</td>
<td>-0.832</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Source: Research data. VP < 0.05 Not significant for PSoy.
In this context, Costa (2022) relies on the behavior of the variable stock of land without forests, which evolves countercyclically to deforestation. Thus, the drop in the increase in deforested area coincides with the expansion of agricultural activities and crops in these already deforested areas. This is observed in the positive correlations between commodity prices and deforested areas occupied by crops and pastures (Table 1). Therefore, at the limit of the stock of land without forests, or at the peak of rising commodity prices, deforestation begins again more vigorously to increase the supply of deforested land, advancing the stock of land with public and private forests. In effect, the deforestation process has been fueled by subsidized credit and tax incentives since the mid-19th century (Costa, 2019), increased urbanization and the expansion of international demand for commodities, both dependent on the legal instability of land and environmental regulation policies. The increase in population (IPopulation) has a negative and significant correlation with the prices of deforested land (Table 1).

The expansion of economic activities in deforested areas occurs through the replacement of less competitive activities of family farming and areas of degraded pastures and extensive livestock farming that are unable to maintain themselves with the expansion of palm oil, soybeans, eucalyptus, agroforestry systems and semi-deforested beef cattle farming, intensive and intensive (Santana et al., 2012; Rajão et al., 2020; Carvalho et al., 2021; Santana, 2022). This trajectory of commodity expansion is the basis of the narrative of REDD+ advocates (Danielsen et al., 2013; Wunder et al., 2020; Hajjar et al., 2021), whose main cause of deforestation is family farmers in the settlements, in search of new areas for subsistence production (Santos et al., 2014; Alencar et al., 2016; Skutsch and Turnhout, 2020).

The prices of forested and non-forested areas show a high positive correlation between them and an inverse correlation with the increase in the deforested area, both significant at 1%, indicating that such prices are generated simultaneously (Table 2). Thus, the prices of land areas can be separated into two variables: the price of the area with forest – PACMata and the average prices of areas of deforested land (pasture and crops), called the price of the area without forest – PASMata, which presents the highest correlation (Table 2).

The negative correlation between land prices and the increase in deforested area indicates that a higher price in these prices would be associated with a lower deforestation rate. It turns out that the logic behind the decision to deforest is not like that, given that there are fundamental differences between these areas of land. Forested land is the basic input for economic production, which can only develop with the suppression of the natural ecosystem (Santana et al., 2011). The price of land with forest is based on the presence of trees of high commercial value, water sources and streams, proximity to infrastructure and the condition of
the relief (Santana et al., 2017). Land without forests is valued based on soil fertility, net income from agricultural activities and strategic spatial location (Santana et al., 2014; Santana 2022).

Table 2

<table>
<thead>
<tr>
<th>Variable</th>
<th>PACMata</th>
<th>PACPasto</th>
<th>PACLavoura</th>
<th>PASMata</th>
<th>IADesmatada</th>
<th>Dacumulated</th>
<th>IPopulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PACMata</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PACPasto</td>
<td>0.9568</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WORD</td>
<td>0.9515</td>
<td>0.9276</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PASMata</td>
<td>0.9685</td>
<td>0.9657</td>
<td>0.9928</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IADesmatada</td>
<td>-0.8197</td>
<td>-0.7497</td>
<td>-0.7013</td>
<td>-0.7281</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAcumulated</td>
<td>0.7778</td>
<td>0.8260</td>
<td>0.6823</td>
<td>0.7393</td>
<td>-0.6776</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>IPopulation</td>
<td>-0.9025</td>
<td>-0.8913</td>
<td>-0.7858</td>
<td>-0.8323</td>
<td>0.8067</td>
<td>-0.8910</td>
<td>1</td>
</tr>
</tbody>
</table>

Source: Research data. Vp < 0.01.

Therefore, what guides the decision to deforest is the difference between the price of land deforested and occupied with crops and pasture and the price of land with forests. It is the ratio between the opportunity costs of land that determines the increase in deforestation. As the price of the forested area has a low opportunity cost or shadow price, due to the lack of knowledge of the value of this natural asset as a supplier of inputs for economic activities, especially the timber industry, and ecosystem services for well-being of human beings and the survival of biodiversity, the expansion of local, national and global demand for food and raw materials produced from the use of deforested land, makes the exchange ratio and, in turn, the impact on the degradation and/or destruction of natural ecosystems in the Amazon.

On the other hand, it is observed that the prices of land with and without forests present positive and significant correlations with accumulated deforestation. As a result, accumulated deforestation follows a third-degree polynomial trajectory and the increase in deforestation follows a second-degree polynomial. The results of this model indicate that the causes that determine the formation of prices for land with and without forests do not directly translate into an increase in deforestation but rather an increase in total accumulated deforestation. Therefore, the land use process has always required the incorporation of areas of land without forests in the period analyzed, within the operating logic of the first recorded cycle of 16 to 20 years, according to historical data from four decades of deforestation (Ferraz, 2020; Anualpec, 2021; INPE, 2022; MapBiomas, 2022; IBGE, 2022a,b,c).

Therefore, the texts by Fearnside (2006), Carvalho et al. (2019) and Rajão et al. (2020), taken as an example among many others, instead of explaining this basic issue, it makes the
understanding of the variables that cause direct impacts on the increase in deforestation unclear. The lack of distinction between accumulated deforestation and incremental deforestation, in addition to causing distrust in the arguments presented, encourages other researchers (Martha JR et al., 2012) to present contrary results for the same phenomenon.

Based on the data in Figure 2 and Table 2, there is no evidence of a break in the cyclical trajectory of evolution of the deforested area, nor of stationarity in incremental deforestation. This would require the control of illegal deforestation and the mitigation of legal deforestation in private areas, even without reaching the “exaggerated limit” established in the Forest Code, and in public areas, vacant and/or under concession, and in areas of extractive and indigenous reserves.

**Figure 2**

*Behavior of the total area of deforested land and the increase in the deforested area in the period from 1988 to 2022, Legal Amazon.*

In Figure 2, the behavior of the price series for land with and without forest can be seen evolving positively over time. The prices of land with crops grow until 2014 and then fall, while the price of land with pasture evolves until 2017. These prices show a positive correlation with each other and with the evolution of accumulated deforestation (Table 2). In the opposite direction, there is a relationship between land prices and the increase in deforested area. These relationships are not explicitly presented in the texts cited in this study on land use in the Amazon. Therefore, the relationship between the equilibrium prices of commodities determines the price of areas of land with forests and cultivated with pasture and crops which, in turn, in
the same direction as accumulated deforestation. However, in light of production and cost economics, prices have an inverse relationship with the increase in deforested area, a fact that tends to leave economic agents and readers not versed in mathematics and the behavioral dynamics of complex phenomena out of understanding the problem. As a result, society tends to follow the narrative presented didactically and generalized by various authors without taking into account the knowledge applied to the agrarian economy and natural assets.

Based on the information in Figure 2, the direct effects of economic activities on deforestation can be observed from the relationship between land prices and the total deforested area and the opposite behavior to the increase in the undeforested area. Therefore, the analyzes available in Fearnside (2018), Gibbs et al. (2015), Gollnow et al. (2014), Koch et al. (2019), Walker et al. (2013) and Castro and Castro (2022) do not clearly present this knowledge about the behavior of the series throughout the deforestation cycle, which makes it difficult to understand the results presented, given that the description informs a cause and effect relationship while the graphs show that the series evolve in opposite directions. As a result, studies on the deforested area only focus on the phase of the cycle that is important to establish a relationship with a causal factor.

Here is the key to understanding the problem. Analyzes on the causes of deforestation in the Amazon forest should not be limited to analyzes of satellite images and the potential impacts of large projects implemented in the Amazon, without adequately specifying quantitative and/or qualitative models. It is necessary to combine these methodologies to identify the variables that can define the vector resulting from the chains of causes and effects between and within product markets that impact deforestation. In this way, we can help society understand this dynamic and enhance the functionality of economic agents' decisions in line with the guidelines of land and environmental regulation frameworks.

At this point, a differentiated analysis methodology is presented for everything that has already been published about deforestation in the Amazon, before and during the 21st century. The increase in deforestation in the Amazon has always been directly associated with the exchange relationship between the prices of deforested areas, which represent the demand for economic activities for land without forests, and the prices of land with forests, which define the potential supply of land to be converted. in economic production and social well-being.

In Table 3, the correlation matrix between the variables (increase in deforested area – IADeforested and accumulated deforestation – DAcumulated of the Amazon forest) and the exchange relationships between the prices of land with economic activity (crop – RTLavoura, pasture - RTPasto and total area without forest - RTASmata) and the price of land with native
forest - PTACmata. All correlations are positive and significant at 1% for the increase in deforested area and negative for accumulated deforestation (Table 3 and Figure 3). The correlations between exchange relationships and deforestation are high and with greater value for land with crops, whose market prices for areas occupied with soybeans, palm oil and cocoa are higher than for land with pastures (Figure 3). This is due to the greater economic return of these activities in relation to extensive and low-productivity livestock farming, especially in small establishments, where low-quality pastures predominate (Santana and Santana, 2015; Silva et al., 2017; Santos et al., 2019; Olímpio et al., 2022; Santana, 2022).

**Table 3**

*Correlation between deforestation and the exchange relationship between the prices of land with economic activities and land with forest, state of Pará, 2000 - 2021.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>RTPasto</th>
<th>RLavoura</th>
<th>RTASmata</th>
<th>IAdeforested</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTPasto</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RLavoura</td>
<td>0.7739</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTASmata</td>
<td>0.8156</td>
<td>0.9976</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>IAdeforested</td>
<td>0.6224</td>
<td>0.7839</td>
<td>0.7838</td>
<td>1</td>
</tr>
<tr>
<td>DAcumulated</td>
<td>-0.4755*</td>
<td>-0.8970</td>
<td>-0.8711</td>
<td>-0.6768</td>
</tr>
</tbody>
</table>

Source: research data. Vp < 0.01; *Vp = 0.0267.

In Figure 3, the behavior of the data series of exchange ratios and the increase in deforestation is observed. The evolution of the series indicates a direct and linear association between the increase in deforested area and the exchange rate of land with pastures and a second-degree polynomial relationship with the exchange rate of land with agriculture and the total area without forests. The areas deforested for farming follow a different trajectory than what occurs with deforestation for the formation of pasture. In agriculture, there is a combination of areas of native forests for direct incorporation into food production, fallow areas and the replacement of areas with less competitive crops for more profitable crops. In extensive livestock farming in the Amazon, the replacement of degraded pastures with crops is restricted in relation to the historical process of continuous opening of new areas with forests to replace degraded pasture areas, especially in areas with undulating relief or “folded land areas”. in popular language.
Figure 3
Behavior between the increase in deforestation and the exchange relationship between the prices of land areas with primary forest and land with pastures and agriculture, 2000-2021.

Source: Research data.

The specification of the econometric model to represent the relationships between the variables in Figures 3 can contribute, based on the integration of scientific, technological and innovative knowledge with the new law of thermodynamics, in the construction of good sustainable practices to reconcile the dynamics of productive activities with levels deforestation and restoration of ecosystems capable of enabling economic growth with social inclusion and environmental sustainability (Schneider and Kay, 1994; Mayumi et al., 1998; Farley, 2008; Santana, 2022). This dynamic evolves from the combination of natural ecosystem stocks and local technological and innovative systems with greater economic return, social inclusion and environmental sustainability, associated with global environmental governance (Kazancigil, 2005; Raine et al., 2006; Dasgupta, 2008 ; Cechin and Veiga, 2010; Lorenzetti and Carrion, 2012; Georgescu-Roegem, 2013)

With this, the increase in the deforested area is explained by the exchange relationship defined between the market prices of deforested land occupied with crops and pastures and the prices of land with forest, through a second-degree polynomial as in equation 1. The model is specified for the reality of the state of Pará due to its representative characteristics of the processes of inducing deforestation for the implementation of economic activities and infrastructure and commercialization logistics. Then, the model is validated for the Legal Amazon.

\[
IADESM_t = \beta_0 + \beta_1 RTA_{(Sm/cm)} + t + \beta_2 RTA^2_{(Sm/cm)} + \beta_3 VD + \epsilon_t \tag{1}
\]
Where: IADESMt is the increase in the deforested area on private and public lands in year \( t \) in km², RTA(Sm/Cm)t is the exchange ratio of market prices for land without forest and with forest (\( i = \text{crops and area total deforestation} \)) in year \( t \); RTA(Sm/Cm)it squared in year \( t \); VD is a dummy variable to capture the effect of atypical information in years \( t \); \( \epsilon_t \) is the random error term that captures the effects of variables that were not included in the model, in year \( t \), and, in this case, contemplates the propagation of the inertial effects of large projects and population growth on deforestation over time. The model parameters were estimated by the Robust Least Squares Method, using Eviews 7.

The price of land with forests does not include the ecosystem services of natural assets—soil, water, and forest—in the marketing interaction with biodiversity and human beings. Includes only timber forest species with high commercial value and non-timber products integrated into regional and global value chains, proximity to road and port infrastructure, urban centers, and large mining projects, hydroelectric plants, beef cattle farming, forestry concessions, agrarian reform settlements, oil palm, and soy.

Using this model, from a neutral point, given by the value of the exchange ratio that keeps the increase in the area deforested with crops stationary, it is clear that the exchange ratio tends to influence the increase in the area not deforested at a decreasing rate, until reaching the level of the exchange ratio that generates the maximum increase in deforestation. In the case of livestock, depending on the time for pasture degradation, the dynamics of the relationship is linear and recursive, given that deforestation to form pasture in one year is directly influenced by deforestation carried out in the previous year. The model is represented in equation 2.

\[ IADESM_t = \beta_0 + \beta_1 \text{RTA(Cpasto/Cm)}_t + \beta_2 IADESM_{t-1} + \beta_3 VD_t + \epsilon_t \text{ (two)} \]

Where RTA(Cpasto/Cm) is the exchange ratio of market prices for land with pastures and forests. The model parameters were estimated using the Robust Least Squares Method, using Eviews 7.

3 RESULTS AND DISCUSSION

Initially, the result of causality is presented between the variable exchange ratio, given by the ratio between the prices of land without forests and the price of land with forests, and the increase in the deforested area in the state of Pará and in the Legal Amazon (Table 4). The explanatory variables of the model, using the adjusted R2 and Rw2 statistics, explained between
71.4% and 83.68% and between 56.56% and 96.51% of the variations in the increase in the deforested area, respectively in Pará and Amazônia Legal, in the period 2000 to 2021. The R2n statistic for the models and z for the variable parameters present statistical significance at 1% attesting to the adequacy of the model.

The results indicate that the exchange relationship between the prices of deforested areas and the price of the area with forest, with a value less than or equal to 1.47 and 1.56, respectively for Pará and Legal Amazon (1.0 ha of area deforested would buy 1.52 ha of land with forest), would make the increase in the deforested area equal to zero (Table 4). This means that the opportunity cost of land with forest is between 68.03% in Pará and 64.10% in the Legal Amazon in relation to the prices of land without forest, making deforestation unfeasible. Therefore, in light of the integration of economic and ecological knowledge, the valuation of standing forest areas may reveal a significantly high shadow price for natural ecosystems and condition deforestation to more productive, inclusive and sustainable agricultural and forestry activities (Georgescu-Roegen, 1975; Farley, 2008; Martha JR et al., 2012; Santana, 2020).

From this initial level, the increase in the deforested area evolves at decreasing rates until reaching the maximum level, associated with an exchange ratio equal to 6.55 and 7.33 and a maximum increase in the annual deforested area of 9,225.92 and 29,030, 67 km², respectively for Pará and the Legal Amazon (Table 4, Figure 4). These levels of deforested areas per year are close to the maximum values of 8,870 and 27,772 km², respectively, evidenced in Pará and Amazônia Legal by INPE (2022) in 2004. In effect, it appears that the opportunity cost of land with forest for this maximum level of deforestation is very low, varying between 15.27% in Pará and 13.64% in the Legal Amazon of the market price of land without forest. In the period from 2000 to 2021, the average annual increase in the area deforested to meet the expansion of livestock and agricultural activities was 4,535.82 km²/year in Pará and 12,183.14 km² in the Legal Amazon, which represents 49.16 and 41.97% of the maximum estimated deforestation level (Table 4, Figure 4).

Table 4

Results of the general deforestation model for the state of Pará and Legal Amazon

<table>
<thead>
<tr>
<th>IADesmatada - Pará</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Statistics - z</th>
<th>Value - p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-8,624,67</td>
<td>2,899,727</td>
<td>-2,9743</td>
<td>0,0029</td>
</tr>
<tr>
<td>RTA(Sm/Cm) – Pará</td>
<td>4,686,56</td>
<td>1,237,744</td>
<td>3,7864</td>
<td>0,0002</td>
</tr>
<tr>
<td>RT2A(Sm/Cm) – Pará</td>
<td>-357,85</td>
<td>123,102</td>
<td>-2,9069</td>
<td>0,0037</td>
</tr>
<tr>
<td>VD-PA</td>
<td>2,506,15</td>
<td>1,047,924</td>
<td>2,3915</td>
<td>0,0168</td>
</tr>
<tr>
<td>R-squared</td>
<td>0,7548</td>
<td>Adjusted R-squared</td>
<td>0,7140</td>
<td></td>
</tr>
<tr>
<td>Rw-square</td>
<td>0,8368</td>
<td>Rw-square Adjusted</td>
<td>0,8368</td>
<td></td>
</tr>
<tr>
<td>Rn-squared statistics</td>
<td>72,6568</td>
<td>Prob, (Rn-squared statistic)</td>
<td>0,0000</td>
<td></td>
</tr>
</tbody>
</table>
Based on the results in Table 4, it is estimated that the increase in deforested area increases when the price of land without forests reaches the range between 1.47 and 7.33 times the price of the area with forests (Figure 4). This interval in the increase in deforested area is fueled by the impact of agricultural and logging activities, highlighting the operational inefficiency of environmental and land policies. Therefore, economic agents define the value of the disposition to be received for areas with low-level forest, given that the real opportunity cost of these lands is unknown. In effect, the destruction of natural ecosystems is framed within the basic rule of production and cost economics, in which the marginal increase in the deforested area is equal to zero. Thus, the exchange relationship that generates the technical optimum for deforestation is close to that which defines the economic optimum for the conversion of forest areas into deforested areas, given that it meets the demands of agricultural activities and timber and non-timber extraction (Santana, 2022).
Figure 4

Behavior between the exchange relationships between the prices of areas of land without forests and the price of areas of land with forests in the period 2020/2021, state of Pará and Legal Amazon.

From the maximum level of increase in deforested area, this level starts to fall due to a self-control mechanism triggered by the global demand for food, wood and minerals, which processes the inertial adjustment of their cycles, as observed in the period from 2004 to 2012. At this stage of the cycle, the decrease in the increase in the deforested area was exacerbated by the expansion of technological innovations that made the use of deforested lands viable, even with some degree of degradation due to the inappropriate use of the natural ecosystem, together with the effect of environmental policies of inspection and control of deforestation and fires (Santana et al., 2011; Marth JR., 2012; Gibbs et al., 2015; Carvalho et al., 2019; Koch et al., 2019; Castro e Castro, 2022). Furthermore, there was global pressure in support of controlling the destruction of natural ecosystems which, within the limits of environmental and land regulations, contributed to the increase in the deforested area reaching the lowest level in 2012. In this phase of the decline in deforestation, according to Santana et al. (2017), the global population's willingness to pay for forest preservation has become high enough to neutralize the value of the willingness to receive for forest replacement, without considering the inertial effects of large development projects implemented in the Amazon and the random effects of clandestine deforestation of public forests.
Therefore, the exchange ratio on the increase in the deforested area explained between 71.4% and 83.68% in Pará and 56.56% to 96.51% in the Legal Amazon of the variations in the annual increase in the deforested area of forest Amazon. The other effects produced by the expansion of logging, mining, highways and population growth accounted for 28.6% to 16.32% in Pará and 43.44% to 3.49% in the Legal Amazon of the annual increase in the deforested area. In the period 2000 to 2021, the impact of large non-agricultural projects accounted, on average, for 22.96% of the destruction of natural ecosystems in the state of Pará. This impact, depending on the legislation in force and which ensures the right to exploit natural resources for many years, without guaranteeing property rights and knowledge about the value of the standing forest, tends to keep the flame burning for the continuation of the cyclical trajectory of deforestation in the Amazon.

3.1 AGRICULTURAL AND DEFORESTATION

The exchange relationship between the prices of farmland and forest land explained, through adjusted R2 and Rw2 statistics, 78.36% and 88.9%, respectively, of the increase in the area deforested and occupied by crops in Pará and the Amazon Cool. The significant Rn and z statistics at 1% (Table 5) attest to the adequacy of the model in polynomial form.

The results in Table 5 indicate that the increase in the area deforested and occupied with crops starts from the exchange ratio equal to 1.21 and 1.68, respectively for Pará and the Legal Amazon (Figure 5). From this point onwards, the deforested area evolves at decreasing rates in response to increases in the exchange ratio until reaching the maximum level of increase in the deforested area under the influence of agricultural activity, for an exchange ratio equal to 8.21 and 9.47 equivalent to 9,243.01 and 28,427.67 km2, respectively for the state of Pará and Legal Amazon (Figure 5). The maximum level of annual deforestation observed does not differ from that estimated with the average exchange ratio of deforested land and the opportunity cost of land with forest, as it was higher by only 4.21% and 2.36% of the price of land occupied with forests. crops, respectively, in the state of Pará and the Legal Amazon.
Table 5

Results of the deforestation model to implement crops in the state of Pará and the Legal Amazon.

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Statistics - z</th>
<th>Value - p</th>
</tr>
</thead>
<tbody>
<tr>
<td>IADesmatada - Pará</td>
<td>-5,989,152</td>
<td>2,471,4480</td>
<td>-2,4233</td>
<td>0.0154</td>
</tr>
<tr>
<td>RTA(CLav/Cm) - Pará</td>
<td>3,097,252</td>
<td>891,1637</td>
<td>3,4755</td>
<td>0.0005</td>
</tr>
<tr>
<td>RT2A(CLav/Cm) - Pará</td>
<td>-188,696</td>
<td>73,3140</td>
<td>-2,5738</td>
<td>0.0101</td>
</tr>
<tr>
<td>VD-PA</td>
<td>2,522,61</td>
<td>1,120,8070</td>
<td>2,2507</td>
<td>0.0244</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Statistics - z</th>
<th>Value - p</th>
</tr>
</thead>
<tbody>
<tr>
<td>IADesmatada - A. Legal</td>
<td>0.715337</td>
<td></td>
<td></td>
<td>0.6679</td>
</tr>
<tr>
<td>Rw-square</td>
<td>0.837194</td>
<td></td>
<td></td>
<td>0.8372</td>
</tr>
<tr>
<td>Rn-squared statistics</td>
<td>63,856</td>
<td></td>
<td></td>
<td>0.0000</td>
</tr>
</tbody>
</table>

RTA(Sm/Cm) = 1.21, indicates IADesmatada = 0

RTA(Sm/Cm) = 9.47 indicates IADeforested = 28,427.61 km²

Source: research results.

The exchange ratio equal to 1.21 and 1.68 signals the beginning of the dynamics of family production developed in areas of capoeiras or secondary forests that are fallow to partially recover soil fertility and continue guaranteeing family subsistence (Table 5, Figure 5). Producers in settlement areas and/or vacant areas who adopt the practice of deforestation to form pasture in partnership with ranchers and loggers deforest areas of primary forests. This process is triggered when the prices of land with forests reach the lower limit in areas of settlement and occupied public forests, whose property rights are not yet legalized (INCRA, 1999; BRASIL, 2002; IPAM, 2006; Santana et al., 2011; Silva et al., 2017; Rajão et al., 2020; Amorim et al., 2020). The exchange relationship begins to increase and impact deforestation with the presence of large agricultural projects (soy, palm oil, eucalyptus and cocoa), livestock, roundwood and mineral extraction, ports and population concentration in urban areas (Carvalho et al., 2019; Skutsch and Turnhout, 2020; Hajjar et al., 2021; Santana, 2022; Castro and Castro, 2022). At this stage, the influence of factors not regulated by local product and land markets have a greater potential influence on the increase in deforestation.

The increase in the area deforested and occupied by pasture is explained by the variable exchange relationship between the prices of areas with pasture and forest and the influence of the area deforested in the previous year (Table 6). It is a linear model of dynamic adjustment, which allows the representation of the deforestation adjustment process as the exchange ratio.
Methodological Contributions to Explain the Determinants of Destruction of The Amazon Rainforest

varies, incorporating the effects of large projects, programs and public policies. Thus, the increase in the area deforested to establish pasture in one year impacts the area to be deforested in the following year, according to the adjustment coefficient equal to 0.393 (= 1 – 0.607) and 0.4186 (=1 – 0.5814), respectively for the state of Pará and Legal Amazon.

Figure 5
Behavior between the exchange relationships between the prices of pasture and crop areas in the period 2020/2021, in the state of Pará.

Cattle ranching and wood extraction begin the deforestation process in forest areas that are difficult to access and occur in a widespread manner in almost all municipalities in the Amazon states in private areas, reserve areas and non-regularized public areas. In this case, when the exchange ratio approaches zero, a situation in which the price of the pasture area is equal to or lower than the price of the area with forest, which can occur with highly degraded lands, the increase in deforestation is at a level close to 948.04 and 841.74 km² per year, respectively in Pará and the Legal Amazon (Table 6, Figure 5). From this point on, livestock farming influences the increase in deforestation at constant rates for any positive exchange relationship. This is a characteristic of the activity that, for economic agents, is highly liquid and safe in the sense of offering guarantees for the supply of families' basic needs even if profitability is low or even bioeconomically unfeasible (Santana, 2022). In effect, the public policy of the “green seal” of the state of Pará for the traceability of farms that supply cattle for...
slaughter in the state of Pará, by allowing freedom for part of the farms in the indirect cattle delivery chain to deforest and the exclusion of small herds, it does not contribute to controlling deforestation, in addition to not meeting the ideas propagated by the Brazilian federal government of zero deforestation.

The limitations of the models disseminated in the literature to represent the main causes of deforestation, the framing of a large portion of the forest as a public good, deforestation evolving in a cycle with amplitude between the extreme points of 16 to 20 years and in the face of complex causal factors, produced controversial results for some variables according to the convenience of the moment. These factors made many of the published studies dependent on adequate empirical measurements.

The focus, according to the main narratives and diffuse interests, was concentrated on the search to prove the expansion of commodities (grains, livestock, wood and minerals) as directly responsible for the increase in the deforested area. However, the complexity of the combinatorial arrangement of these commodities with other land use activities makes the explanatory scope of the studies limited, especially because they do not present the complete chain of cause and effect events within and between product and land markets.

Table 6

Results of the deforestation model to implement pasture in the state of Pará and the Legal Amazon.

<table>
<thead>
<tr>
<th>IADesmatada - Pará</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Statistics - z</th>
<th>Value - p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-1611.827</td>
<td>1674.7600</td>
<td>-0.9624</td>
<td>0.3358</td>
</tr>
<tr>
<td>RTA(Pasture/Cm) - Pará</td>
<td>3,097,252</td>
<td>891,1637</td>
<td>3.4755</td>
<td>0.0005</td>
</tr>
<tr>
<td>IADesmtada (-1) - Pará</td>
<td>0,607</td>
<td>0,1220</td>
<td>4.9743</td>
<td>0.0000</td>
</tr>
<tr>
<td>VD-PA</td>
<td>2,522.61</td>
<td>1,120,8070</td>
<td>2.2507</td>
<td>0.0244</td>
</tr>
<tr>
<td>R-squared</td>
<td>0,7148</td>
<td>Adjusted R-squared</td>
<td>0.6645</td>
<td></td>
</tr>
<tr>
<td>Rw-square</td>
<td>0,8453</td>
<td>Rw-square Adjusted</td>
<td>0.8453</td>
<td></td>
</tr>
<tr>
<td>Rn-squared statistics</td>
<td>65,7040</td>
<td>Prob. (Rn-squared statistic)</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>

RTA(Sm/Cm) = 0.00, indicates IADeforested = 948.044 km²

<table>
<thead>
<tr>
<th>IADesmatada - ALegal</th>
<th>Coefficient</th>
<th>Standard error</th>
<th>Statistics - z</th>
<th>Value - p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-7301.769</td>
<td>2422,1230</td>
<td>-3.0146</td>
<td>0.0026</td>
</tr>
<tr>
<td>RTA(Pasture/Cm) – ALegal</td>
<td>3867,862</td>
<td>876,1218</td>
<td>4.4148</td>
<td>0.0000</td>
</tr>
<tr>
<td>IADesmtada (-1). The cool</td>
<td>0.5814</td>
<td>0.0572</td>
<td>10.1658</td>
<td>0.0000</td>
</tr>
<tr>
<td>VD-AL</td>
<td>8143,508</td>
<td>1235,2150</td>
<td>6.5928</td>
<td>0.0000</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.7042</td>
<td>Adjusted R-squared</td>
<td>0.6520</td>
<td></td>
</tr>
<tr>
<td>Rw-square</td>
<td>0.9769</td>
<td>Adjusted Rw-square</td>
<td>0.9769</td>
<td></td>
</tr>
<tr>
<td>Rn-squared statistics</td>
<td>426,391</td>
<td>Prob. (Rn-squared statistic)</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>

RTA(Pasture/Cm) = 0.00, indicates IADeforested = 841.739 km²

Source: research results.
In this study, we contributed to understanding the chaining mechanism of causal events and to offering intelligibility about the models applied in studies on deforestation in the Amazon. By showing the sequence of multiple causalities of the factors that define the equilibrium prices of commodities, their relationship in the formation of prices for land with and without forests and the link between market prices for land and the increase in deforested area, it is presented the dynamics that explain the evolution of the deforestation cycle at the same time that it undoes the narratives that try to explain deforestation based on common sense.

The additional contribution that the results reveal to the control of deforestation is basically anchored in the valuation of natural assets, which increases the opportunity cost of land with forest, the need for land regularization and effective implementation of the forestry code. Therefore, the main barrier to deforestation is knowledge of the value of forested land, which, naturally, imposes a substantial increase in the minimum level of increase in productivity and profitability of land use systems in the Amazon.

4 CONCLUSIONS

The results allow us to conclude that the increase in the deforested area of the Amazon forest is explained by the exchange relationship between the price of land without forest and land with forest. The effect of commodity prices follows a chain path connecting the formation of equilibrium prices in product and land markets before impacting deforestation. The first results from the interaction between commodity prices and the areas of land cultivated with crops and pastures which, in turn, form the equilibrium prices of deforested and forested land. The exchange relationship between the prices of land without forests (demand) and land with forests (supply), therefore, presents a direct and contemporary correlation with the increase in deforestation throughout the cycle. This explains the intentional delimitations of part of the deforestation cycle to substantiate and disseminate narratives in accordance with the partial purpose of justifying the impacts of public policy actions for and against deforestation.

The cause and effect relationships between land prices with and without forests and the increase in deforestation are not linear, as they configure cycles adjusted to second degree polynomial models. Thus, the level of deforestation increases with the increase in the exchange ratio until reaching the maximum increase in deforestation and then the increase starts to decrease even with the increase in the exchange ratio, given that, in general, at the end of the phase of strong deforestation a large deforested area becomes available for occupation by commodities. At this stage, the price of land with forests starts to grow faster than the price of
land without forests, given the decrease in demand pressure for deforested land and the scarcity of supply of land with forests in areas of easy access, configured by action of various local, national and international cyclical and structural factors.

Therefore, studies that attribute a positive causal relationship between commodity prices and the increase in deforestation hide the logic of transmission of causal effects between product markets and factors involved in land use dynamics. In general, studies present the direct causes of deforestation as commodity prices, large mining and agricultural projects, road infrastructure, city expansion, agrarian reform settlements, forest concessions for forest extractivism, urban population, although these factors present inverse correlations to the annual increase in deforestation.

As a result, one comes across many articles whose results present contradictions regarding the same phenomenon. The mistake is in stating that deforestation is falling or increasing in a given period, when in fact the data presented reveal the behavior of the increase in the deforested area at decreasing or increasing rates. Therefore, the deforested area in the Amazon has always grown continuously during the period analyzed.

Based on the results of this study, it can be concluded that the cause of greatest impact on deforestation is the lack of knowledge about the value of natural assets and the flow of services they offer to the economy and human beings. Without this knowledge, the opportunity cost of the stock of land with forests in the Amazon, which far exceeds the shadow price of land with crops, pastures and forestry management, is set by economic agents at a level close to zero, equivalent to a factor of public production in abundance. As a result, pressure on the stock of land with primary forests, due to land without destination in the Amazon (INCRA, 1999; Brasil, 2002; IPAM, 2006), continues until destruction exceeds critical limits for the sustainability of biodiversity and the survival and well-being of human beings. In the Amazon, the 80% of the area to be preserved by law lacks technical and scientific foundations for the adequate size of the biome to meet society's demands.

The value of natural assets creates a barrier with the shadow prices of lands with primary forests in relation to lands without forests and guides the path that economic agents must follow, combining knowledge in science, technology and innovation with the new law of entropy in the implementation of complex production systems and greater productivity, social inclusion and environmental sustainability (Schneider and Kay, 1994; Raine et al., 2006; Baral et al., 2014; Costanza et al., 2017; Santana, 2022). These systems can be made viable, within the scope of family and business ventures, through payment for ecosystem services, access to credit backed by the value of private or common-use natural assets, and other long-term interest financing.
compatible with annual rates increase in the carbon stock stored by natural ecosystems (FAO, 2007; Blignaut et al., 2014; Santana, 2020; Santana et al., 2023). Thus, the stock of forest land to be preserved can be maintained and economic activity in areas of deforested land can be maintained along with the ecosystems that must be restored, enriched and/or converted into economic production.

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Methodological Contributions to Explain the Determinants of Destruction of The Amazon Rainforest


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