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Murilo César Rabelo Soares[1] | Fabrício Molica de Mendonça[2]

Douglas Marcos Ferreira[3]

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[1] Master in Development, Planning and Territory (UFSJ).
Administrative Technician at the Federal University of São João del-Rei. São João del-Rei - MG, Brazil.
E-mail: murilorabelo@ufsj.edu.br

[2] PhD in Production Engineering (UFRJ).
Professor at the Federal University of São João del-Rei.
São João del-Rei - MG, Brazil.
E-mail: fabriciomolica@ufsj.edu.br

[3] PhD in Applied Economics (UFV).
Professor at the Federal University of São João del-Rei.
São João del-Rei - MG, Brazil.
E-mail douglasferreira@ufsj.edu.br

ABSTRACT

This work aimed to analyze the effects of the Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) and other environmental policies implemented in the 2000s on annual deforestation rates, in the period from 2004 to 2022. Quantitative methodology was adopted, with a survey of the historical series of deforestation and application of an econometric model with panel data. Variables such as cattle herd, soybean area, permanent crops, wood production, environmental management expenses, agriculture, agrarian organization and rural credit stock were analyzed in two periods: 2008-2014 and 2015-2022. The results showed that, between 2008 and 2014, deforestation rates decreased due to the integration between monitoring, environmental control, land planning and use of already deforested areas. In the period from 2015 to 2022, PPCDAm suffered negative impacts due to the implementation of policies that weakened its guidelines, compromising the progress achieved. The analysis, based on the fixed effects model (MEF), showed that the main causes of deforestation in this period are associated with the growth of the cattle herd and the expansion of the soybean cultivated area, processes intensified after the revocation of the plan in 2019. It was concluded that the PPCDAm influenced the containment of deforestation and that its interruption compromised the progress made.

Keywords: Deforestation, Legal Amazon, Econometric Analysis, Environmental Policies.

RESUMO

Este trabalho teve como objetivo analisar os efeitos do Plano de Prevenção e Controle do Desmatamento na Amazônia Legal (PPCDAm) e de outras políticas ambientais implementadas na década de 2000 sobre as taxas anuais de desmatamento no período de 2004 a 2022. Adotou-se metodologia quantitativa, com levantamento da série histórica de desmatamento e aplicação de modelo econométrico com dados em painel. Foram analisadas variáveis, como rebanho bovino, área de soja, lavoura permanente, produção de madeira, gastos com gestão ambiental, agricultura, organização agrária e estoque de crédito rural, em dois períodos: 2008-2014 e 2015-2022. Os resultados mostraram que, entre 2008 e 2014, as taxas de desmatamento diminuíram em função da integração entre monitoramento, controle ambiental, ordenamento fundiário e uso de áreas já desmatadas. No período de 2015 a 2022, o PPCDAm sofreu impactos negativos devido à implementação de políticas que enfraqueceram suas diretrizes, comprometendo os avanços alcançados. A análise, baseada no modelo de efeitos fixos (MEF), mostrou que as principais causas do desmatamento nesse período estão associadas ao crescimento do rebanho bovino e à expansão da área cultivada de soja, processos intensificados após a revogação do plano em 2019. Concluiu-se que o PPCDAm influenciou a contenção do desmatamento e que sua interrupção comprometeu os progressos obtidos.

Palavras-chave: Desmatamento, Amazônia Legal, Análise Econométrica, Políticas Ambientais.

INTRODUCTION

The regional development model adopted in the Brazilian Legal Amazon (ALB), created by Law No. 1,806/1953, has always been the subject of discussions (Almeida *et al*., 2022) for intertwining environmental, economic and social issues. On the one hand, there was an incentive from the Government for land occupation and the expansion of agricultural, livestock and mining activities through colonization programs, subsidies and access infrastructure for the use of natural resources. On the other hand, the region's ecological importance requires measures to mitigate environmental impacts, preserve biodiversity and combat climate change. This paradox has created tensions between the forces of economic growth, which result in deforestation and environmental degradation, caused by different causes, and control and preservation initiatives, which seek the ecological integrity of the forest.

The increase in forest exploitation and deforestation recorded in the 1980s and 1990s raised concerns about discussing the Government's role in controlling environmental, preservation biodiversity and combating climate change. However, the measures taken in the 1990s, based on the

adoption of restrictive legislation, such as, for example, Provisional Measure nº 1,511/96[1], without an efficient monitoring apparatus, did not guarantee the reduction of deforestation (Fearnside, 2005). Such legislation, to be effective, must be accompanied by public policies aimed at combating deforestation. Among the policies created in the late 1990s and early 2000s, the Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) stands out, implemented in 2004, with a series of integrated measures and actions distributed over time.

PPCDAm sought to balance economic development with environmental preservation by reducing deforestation rates in the region, conserving biodiversity, mitigating climate change and promoting sustainable development through economic activities that do not depend on deforestation. This Plan focused on environmental governance, inspection, monitoring, territorial planning, promotion of sustainable economic activities, involvement of local and indigenous communities, and the promotion of international cooperation to obtain technical and financial support.

Following the implementation of the PPCDAm, deforestation rates reached their lowest rates between 2012 and 2014, growing again from 2015 onwards, reaching their peak in 2021. This trajectory reflects the challenges faced by the Plan, combining positive and negative initiatives and policies that impacted deforestation. Positive actions include the Real-Time Deforestation Detection System (DETER), created in 2004; the intensification of inspection operations between 2004 and 2008; the implementation of the Rural Environmental Registry (CAR), in 2012; international pressure; and climate agreements. Among the negatives, the following stand out: the revision of the Forest Code, in 2012; the economic and political crises, between 2014 and 2015; and the changes in environmental policy, starting in 2019, which weakened supervision, harming the continuity of environmental policies.

In this sense, a question that emerges is: what are the effects of PPCDAm on the annual deforestation rates in the Legal Amazon and its direct causes in the period from 2004 to 2022, considering the positive and negative policies and initiatives that impacted deforestation?

1 Provisional Measure No. 1,511/1996 amended article 44 of the Forest Code, imposing restrictions on the conversion of forest areas. Although it was not converted into law and lost its effectiveness, its content was later incorporated into Law No. 12,651/2012, the new Forest Code. Despite this, deforestation in the Legal Amazon continued to grow due to illegal economic activities and a lack of supervision (Fearnside, 2005).

Therefore, the present work aimed to analyze the effects of the Plan for Prevention and Control of Deforestation in the Legal Amazon (PPCDAm) and other environmental policies implemented in the 2000s on annual deforestation rates, from 2004 to 2022. Specifically, it was intended to: a) Study the behavior of deforestation rates occurring until the year 2022; b) Analyze the phases of the Plan throughout the period and their effects to mitigate the impacts on the advancement of deforestation, considering positive and negative policies and actions, in order to understand the change in trajectory from 2015 onwards; and c) Investigate, through an econometric model, the main causes of deforestation, considering two intervals of trajectory change: 2008 to 2014 and 2015 to 2021.

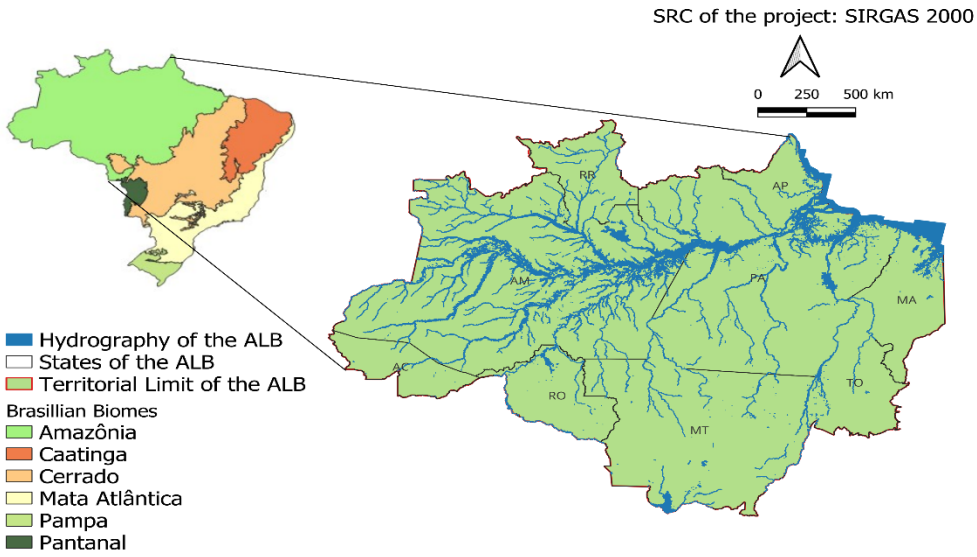
THEORETICAL FOUNDATION

DEFORESTATION IN THE BRAZILIAN LEGAL AMAZON (ALB)

The ALB (Figure 1) was created as a political concept for regional planning and development by Law No. 1,806, of 01/06/1953, amended by Law No. 5,173, of 10/27/1966, and by Complementary Law No. 31, of 10/11/1977. The ALB occupies 59% of the Brazilian territory and covers eight states (Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima and Tocantins) and part of Maranhão (west of the 44ºW meridian), totaling around 5 million km² (Almeida *et al*., 2022). This region includes diverse biomes, with terra firma, floodplain and igapó forests, and protected areas, such as Indigenous Lands and Conservation Units (Manir *et al.*, 2023).

Despite the importance of the Amazon's socio-environmental heritage, its contribution to the stability of climate processes at national, regional and global levels, and the potential of its biodiversity for economic development, there are areas of preserved forests, deforested areas and transition areas, including municipalities that resemble other urban centers in Brazil. Deforestation has already compromised an important portion of the biome, reaching 19.19% of the original forest in four decades (Capobianco, 2021). The causes of this deforestation are complex and not completely understood (Arraes; Mariano; Simonassi, 2012). However, it can be considered as a result of the continuation of traditional patterns of expansion of the agricultural frontier in Brazil, which include the occupation of forested lands without clear legal rights or protection, logging, the introduction of agriculture and livestock farming and population dynamics (Reydon; Fernandes; Telles, 2020).

Figure 1 | Map of AML location in relation to Brazilian biomesyou



Source: based in Assisi *et al.* (2019), based on data from the TerraBrasilis Portal (INPE, 2024).

For Marques (2018), deforestation is caused by the combination of seven accelerating factors that reinforce each other, namely: logging, advancement of the agricultural frontier, fires, mining, hydroelectric plants, urbanization and roads opened in the forest as a result of these factors. The author also highlights the agricultural large estates, which benefit from tax incentives and state financing.

According to Ferreira and Coelho (2015), deforestation is related to the expected income from agricultural activities associated with the prices of *commodities* agricultural costs, agricultural costs and the specific characteristics of each State in the region, such as: distance from the agricultural product market, forest stock area, population, population density, absolute income and *per capita*, climatic characteristics etc.

Authors like Rivero *you at* (2009), Diniz *et al.* (2009), Santos (2010) and Ramírez, Pérez and Cutiño (2022) sought to explain the causes of deforestation in the Amazon through econometric models. The results, in general, showed that the main causes are livestock farming and agricultural production, with emphasis on soybeans. The model by Ferreira and Coelho (2015) pointed out the importance of the variable agricultural prices as one of the causes of deforestation. Fearnside

(2022) states that although the Amazon rainforest is deforested for numerous reasons, cattle ranching is the predominant cause. Medium and large farms are responsible for around 70% of deforestation activities. Therefore, the beef trade is just one of the sources of income that makes deforestation profitable.

Margulis (2003) and Castro (2005) share the view that livestock farming, on medium and large scales, is the activity associated with the majority of deforestation, as it is highly profitable, resulting in more substantial returns compared to conventional livestock farming. In this context, there is a view that livestock farming plays a significant role in the development strategies of the Amazon region, bringing advantages to the Brazilian economy by reducing meat prices in the domestic market and, at the same time, boosting exports, which translates into social gains.

THE DEFORESTATION PREVENTION AND CONTROL PLAN (PPCDAM)

Public policies for the Amazon express divergent and conflicting interests, some based on favoring new support infrastructures for economic development, mainly large-scale agribusiness, and others focused on the interests of local populations and socio-environmental sustainability (Becker, 2005). However, combating deforestation in the Amazon is possible through investments in public policies, private agreements and monitoring systems (Nepstad *et al*., 2014).

At the end of the 1980s and 1990s, after the negative repercussions of the alarming deforestation data in the Amazon in the previous three decades, Brazil approved a set of laws and institutional improvements, including the cancellation of tax incentives for projects in the region and the creation of Ibama to control forest degradation. However, these actions were unable to reverse the situation, which worsened (Capobianco, 2021).

Since 2004, the Amazon has received several initiatives to reduce deforestation, including regional programs, rigorous inspection and land and territorial planning actions (Capobianco, 2021). The following stand out: 1) Sustainable BR-163 Plan (2004), focused on the areas influenced by the paved highway; 2) PPCDAm (2004), with initiatives aligned with PAS guidelines; and 3) Sustainable Amazon Plan (2008), a political-conceptual framework to frame the Amazon in Sustainable Development (Abdala, 2008).

PPCDAm, created in 2004, is considered by the Ministry of the Environment and Climate Change as the main responsible for the 83% reduction in deforestation by 2012 (MMA, 2024). Due to its role in preventing and combating deforestation, several studies have evaluated the effectiveness of the Plan, seeking to understand the public policies implemented and guide future environmental conservation actions and sustainable use of natural resources.

Capobianco (2021) highlights that the reduction in deforestation, starting in 2004, occurred mainly due to the increased perception of risk of non-compliance with environmental legislation, driven by the presence of the Federal Government in the region through public policies, especially the PPCDAm. Mello and Artaxo (2017) analyzed the implementation of PPCDAm, finding relevant results, but they advocate constant improvements to promote sustainable activities. Bizzo and Farias (2017) showed that the plan had a greater impact in the early years, influencing environmental regularization policies and local governance, but its effectiveness decreased over time.

For Candido *et al*. (2023), Between 2004 and 2012, deforestation in the Amazon fell due to the implementation of PPCDAm. However, after this period, the Plan was gradually weakened, with the main negative points being: 1) postponements of the regulation of the Environmental Crimes Law (nº 9,605/1998) through decrees issued annually by the Presidency from December 2008 until the approval of the New Forest Code in 2012, which affected inspection actions; 2) Creation of the Terra Legal Program, in June 2009 (Law No. 11,952), which opposed the creation of Conservation Units (UCs), allowing the expansion, in 2016, of the size limit of properties subject to regularization from 1,500 to 2,500 hectares and the authorization of titling of areas occupied until 2008 (instead of until 2004), encouraging land grabbing; 3) the amendment to the 2012 Forest Code; and 4) the revocation of the PPCDAm, in 2019, and the dismantling of environmental bodies under the Bolsonaro Government.

METHODOLOGY

The work was carried out within the quantitative approach, which seeks to quantify data and use scientific evidence such as tests, models and validation systematizations (Martins; Theóphilo, 2009). In this specific study, we sought to measure changes in deforestation rates over time and their main causes, correlating with the various environmental policies implemented.

The secondary data used in the research and made available on the TerraBrasilis Portal by the National Institute for Space Research (INPE, 2024) were processed in three stages. In the first stage, the behavior of deforestation rates in the period from 1988 to 2022 was surveyed. In the second, the different phases of the PPCDAm were analyzed, starting from its implementation in 2004, considering positive and negative policies and actions. In the third, the regression data was analyzed, using panel data referring to the 773 municipalities in the Legal Amazon.

The choice for panel data is justified by the greater wealth of information, greater variability and efficiency in the use of data, in addition to the reduction of collinearity as highlighted by Gujarati and Dawn (2011). Due to the availability of secondary data, the panel covered two periods: 2008 to 2014 and 2015 to 2021, as they represent different behaviors in the deforestation trajectory.

The variables used were the Increase in deforestation (des), as the dependent variable, and the explanatory variables: Soybean harvested area (acs); Area harvested from permanent crops (acp); Number of cattle herds (bov); Rural credit stock (ecr); Environmental expenses (gao); and Timber extraction (mad). Mining, mining, population, road infrastructure, technological factors and agricultural prices, among others, were not part of the model due to a lack of municipal data.

The logarithmic transformation was applied to the database in order to analyze the coefficients in terms of elasticity. A value of 100 units was added to each variable before applying the logarithmic transformation.

After testing the three panel models, namely: *polled data*, fixed effects and random effects, the test of *Hausman* indicated that the fixed effects model was the most appropriate for data analysis. According to Gujarati and Dawn (2011, p. 594), this model is known as a one-way fixed effects model (*one-way*), as it allows intercepts to vary between individuals but remain constant over time. This model will be applied separately for each period: 2008 to 2014 and 2015 to 2021 (Equations 1 and 2).

Period 1 - 2008 to 2014 (Equation 1)
desit = β0 + β1bovit + β2acsit + β3acpit + β4ecruit + β5gaoit + β6madait + uit
i = 1,2,3 ..., 773
t = 2008, 2009, 2010..., 2014
Period 2 - 2015 to 2021 (Equation 2)
desit = β0 + β1bovit + β2acsit + β3acpit + β4ecruit + β5gaoit + β6madait + uit
i = 1,2,3 ..., 773
t = 2015, 2016, 2017, ..., 2021.

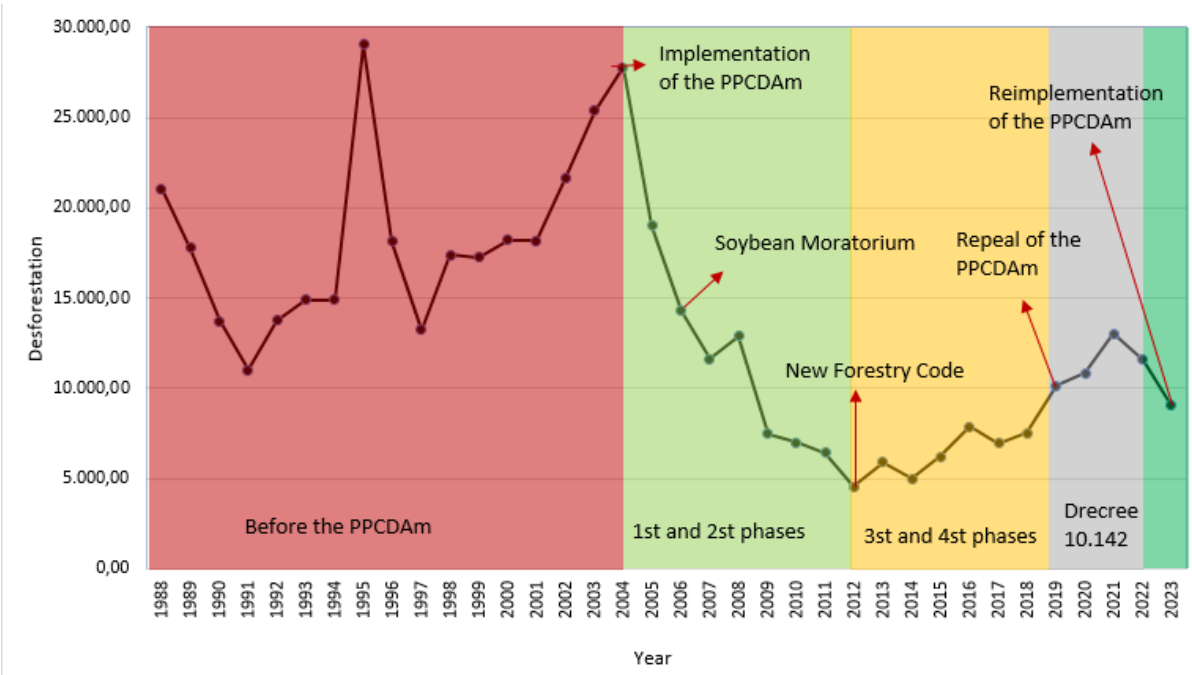
ANALYSIS AND DISCUSSION OF RESULTS

BEHAVIOR OF DEFORESTATION RATES BETWEEN 1988 AND 2022

Annual deforestation rates in the ALB, since 1988, show variations with a growth curve in the 1990s and early 2000s, followed by alternating periods of decline and increase until 2022 (Figure 2). Deforestation reached its highest peak in 1995, with 29,059 km² of forest deforested, followed by another, in 2004, with 27,772 km² (INPE, 2024).

From 2004 onwards, deforestation showed sequential drops, culminating in 2012 with the lowest deforestation rate ever recorded, reaching 4,571 km². After 2012, deforestation increased again, reaching more than 13,000 km² in 2021.

Figure 2 | Annual deforestation rate in the Legal Amazon between 1988 and 2023, PPCDAm chronology



Source: own elaboration based on data from the TerraBrasilis Portal (Assis *et al.*, 2024).

The falls were caused after the implementation of a set of measures aimed at reducing deforestation, with the implementation of several regional programs, inspection and control measures and land and territorial planning actions. Among the programs, PPCDAm stands out. From 2014 onwards, political-operational changes caused the fragility of the Plan and the growth of deforestation (Capobianco, 2021).

PPCDAm can be divided into five distinct phases, each with characteristics, specific objectives and challenges faced. Analyzing deforestation in each of these phases allows us to understand the impact of this policy in its different phases in the region.

DEFORESTATION IN THE DIFFERENT PHASES OF PPCDAM

PPCDAm went through five phases. The first (2004-2008) was marked by the immediate reduction in deforestation rates. The second (2009-2011) consolidated control actions and initiated structuring measures. The third (2012-2015) integrated control measures with sustainable development initiatives. The fourth (2016-2019) consolidated conservation policies and closed the PPCDAm. And the fifth (2023-2027), still in its initial phase, after the repeal of Decree No. 10,142/2019 and the consequent increase in deforestation, reimplanted the Plan, seeking to face new challenges and intensify conservation.

PPCDAM 1ST PHASE (2004-2008) AND 2ND PHASE (2009-2011)

With the launch of PPCDAm in 2004, the annual deforestation rate reduced, reaching 11,651 km² in 2007, a 58% drop compared to 2004, representing the largest individual contribution of a country to mitigating climate change (Capobianco, 2021). This reduction resulted from a synergy of factors, including PPCDAm (Mello; Artaxo, 2017).

West and Fearnside (2021) highlight the creation of protected areas and the implementation of the Deter System, in which monitoring and control expanded state capacity in the region, capturing around 21% of the budget (R$83 million) in phase 1, 37% (R$454 million) in phase 2 and

30% (R$425 million) in phase 3. Messiah *et al.* (2021) associate the almost 32% drop in deforestation between 2004 and 2005 to the forestry crisis. *commodities*, which reduced the demand for beef and soybeans, resulting in a reduction in the planted area and cattle numbers in the ALB States. Assunção, Gandour and Rocha (2015) estimate that conservation policies, implemented from 2004 onwards, prevented approximately 73,000 km² of deforestation between 2005 and 2009.

During this period, in addition to PPCDAm, other initiatives stood out: a) the Soy Moratorium in 2006, an agreement established by the signatory companies not to acquire soy from farms with crops in deforestation carried out after July 22, 2008 in the Amazon biome, aiming to eliminate deforestation from the soy production chain (Portal Moratória da Soja, 2024); and b) the Sustainable Amazon Plan (PAS), which proposed a set of guidelines to guide the sustainable development of the Amazon, valuing sociocultural and ecological diversities and reducing regional inequalities (Brazil, 2008). The Plan was launched in May 2008 and involved the participation of the Governments of the nine States of the Amazon Region and segments of civil society through public consultations that mobilized 6,000 people in the region.

From 2008 onwards, another period of falling deforestation in the ALB began. Two initiatives contributed to reducing rates: the soybean moratorium, an environmental pact initiated in 2006, and the Conduct Adjustment Term (TAC) for meat, signed in 2009 by the Federal Public Ministry (MPF), which caused slaughterhouses to stop purchasing meat from deforested areas (Macedo *et al.*, 2012).

In the view of the Ministry of the Environment (MMA), the implementation of PPCDAm contributed to the reduction of the annual deforestation rate between 2004 and 2011, benefiting regional development by improving compliance with the Brazilian commitment made in Copenhagen, in December 2009, to reduce its greenhouse gas emissions. During the execution of phases 1 and 2, the program created 25 million hectares of Conservation Units (CUs) and approved 10 million hectares of Indigenous Lands (TIs), strengthening the territorial structure for sustainable development. mainly in the 1st phase, with the contribution of all spheres of government in expanding protected areas (Brazil, 2013).

In the second phase (2009-2011), the Monitoring and Control axis was responsible for the drop in deforestation rates due to the efficiency of the DETER system and the agility of integrated actions to monitor deforestation and combat organized crime, carried out by IBAMA, the Federal and Federal Highway Police and the National Public Security Force and supported by the Brazilian Army (Brazil, 2023). In 2012, deforestation reduced by 83% compared to the rate measured in 2004 due to the strengthening of Ibama and ICMBio (Brasil, 2023).

Throughout the Lula Governments, there was transformation in the Brazilian economy resulting from the so-called "*boom* the *commodities*", with growth in the production and export of soy, corn and beef, which are production chains associated with deforestation in the Amazon (Nepstad *et al.*, 2014). The growth in exports – important for the balance of payments – increased the political power of the sector, which became unified. This process of inducing cooperation between the various actors was based on "agribusiness", which, in some way, acted on changing the Forest Code (Candido *et al.*, 2023).

The strengthening and political organization of agribusiness brought three main setbacks to the sustainable development of the region: 1) the successive postponements of the regulation of the Environmental Crimes Law (nº 9,605/1998) through presidential decrees from December 2008 until the approval of the New Forest Code in 2012, which affected inspection actions; 2) the creation of the Terra Legal Program (Law No. 11,952/2009), which opposed the creation of UCs, expanded in 2016, under the Temer Government, the limit of regularizable properties from 1,500 to 2,500 hectares and authorized the titling of areas occupied until 2008, encouraging land grabbing; and 3) the amendment of the 2012 Forest Code in the Dilma Government, which had the support of the Presidency (Candido *et al.* 2023).

PPCDAm 3rd phase (2012-2015) and 4th Phase (2016-2020)

In the third phase (2012-2015), the Plan lost its centrality in the government agenda. In 2013, coordination of the GPTI was transferred from the Civil House to the MMA. With this change, agendas that required interministerial coordination – such as infrastructure, rural credit and the creation of conservation units – lost priority. This fact, combined with the approval of the new Forest Code, which made deforestation rules more flexible, caused rates to rise again, reaching 6,200 km² in 2015, negatively impacting the sustainable development of the region.

The 4th phase of PPCDAm (2016-2020) was launched in 2016. Between 2016 and 2019, deforestation in the ALB was 8,034 km². Comparing this data with the previous phases, it is noted that the previous results were better in relation to the goal of the National Policy on Climate Change (PNMC). While the change in presidential profile from Lula to Temer and the rise of opponents weakened the PPCDAm, Bolsonaro's election began to undermine it, deconstructing state capabilities (Candido *et al.*, 2023).

This 4th phase brought new elements, such as a more refined system for managing indicators and results and clearer planning. However, the Plan was not fully implemented and did not achieve its objectives. While previous phases were marked by the creation of UCs, in this phase, many of these areas were reduced or had their level of protection lowered. In 2019, Management decided to discontinue PPCDAm. Decree No. 10,142/2019 revoked the Decree of July 3, 2003, which established the Permanent Interministerial Working Group (GPTI) and created the Executive Committee for Control of Illegal Deforestation and Recovery of Native Vegetation. The following year, Decree No. 10,239/2020 transferred the role of interministerial articulator to the National Council for the Legal Amazon, chaired by the Vice-Presidency of the Republic (Brazil, 2023).

In the period from 2018 to 2019, deforestation increased, going from 7,500 km² in 2018 to 10,000 km² in 2019 and reaching 13,000 km² in 2021, moving the country further away from the goals established in international agreements. Annual deforestation from 2019 to 2021 was 56.6% higher than between 2016 and 2018 in the Amazon biome (Alencar *et al.*, 2020). This occurred because PPCDAm ended in 2019 and the Government reduced the budget of environmental agencies and changed the procedures for assigning responsibilities to offenders (Rajão *et al.*, 2020).

This dismantling process manifested itself in different aspects: non-compliance with standards, scrapping of implementation structures, intimidation of public servants, unavailability of resources, sabotage of data production and dissemination, denial of data and proven facts, and promotion of pseudoscience and false academic controversies. This influenced the increase in deforestation on private and public lands, especially in less restrictive protection areas (APAs) and without destination (Rajão *et al.*, 2020).

For Coelho-Junior *et al.* (2022), the effects of these dismantling actions led to a decrease in infraction notices in the Amazon Region and the National Plan for the Control of Illegal Deforestation and Recovery of Native Vegetation 2020-2023, presented as a zero-tolerance policy for illegal deforestation, was criticized as insufficient and unclear by national authorities. The impunity of environmental offenders, the worsening of forest fires, the clearing of the way for large infrastructure projects and the weakening of environmental and control agencies have driven deforestation, further harming the sustainable development of the region.

PPCDAM 5TH PHASE (2023-2030)

This phase faces the challenges of deforestation and environmental degradation with an integrated approach structured around four strategic axes. Axis I, Sustainable Productive Activities, promotes practices that reconcile development and preservation, such as sustainable forest management and recovery of degraded areas, in addition to strengthening cooperation with ALB States. Axis II, Environmental Monitoring and Control, focuses on accountability for environmental crimes, improving monitoring and control of deforestation and fires, and improving the Rural Environmental Registry. Axis III, Land and Territorial Planning, aims to protect public lands, strengthen the management of protected areas and align large projects with the goals of reducing deforestation. Finally, Axis IV, Normative and Economic Instruments, focuses on the creation of legal and financial mechanisms to control deforestation, regulate land use and promote sustainable economic alternatives (Brazil, 2023).

Due to lack of data, this phase is not part of the scope of this work. However, there are records that the reimplantation of PPCDAm caused a drop-in deforestation from 11,500 km² to 9,000 m² from 2022 to 2023, reflecting its positive impact (INPE, 2024).

CAUSES OF DEFORESTATION IN THE LEGAL AMAZON

The literature has shown that deforestation is a complex and multifaceted phenomenon, which can be influenced by a wide range of economic, political and social factors that change over certain periods. Therefore, the variables used to explain the increase in deforestation were divided into two periods. The period from 2008 to 2014 represents a general trend of reduction in deforestation rates, while the period

between 2015 and 2021 represents a change in the trajectory towards increasing deforestation.

Table 1 presents the results of the regression obtained using the fixed effects model (MEF), in the period from 2008 to 2014, to explain the direct causes of deforestation. A low p-value, that is, less than 0.05 (< 0.05) indicates that the null hypothesis can be rejected, with the variable being statistically significant at the 5% significance level.

Table 1 | Direct causes of deforestation through regression obtained by the fixed effects model (MEF) in the period from 2008 to 2014

Variable	Coefficient	Standard Error	p-value
Soybean harvested area (Acs)	0.0050	0.0216	0.816
Area harvested from permanent crops (Acp)	0.0303	0.0482	0.530
Cattle herd (Bov)	-0.2462	0.0672	0.000
Environmental expenses (Gao)	-0.0087	0.0073	0.233
Rural credit stock (Ecr)	-0.0667	0.0195	0.001
Logging (Mad)	0.0503	0.0260	0.054
R-sq: overall	0.0779		
F	14.95		

Source: Research data.

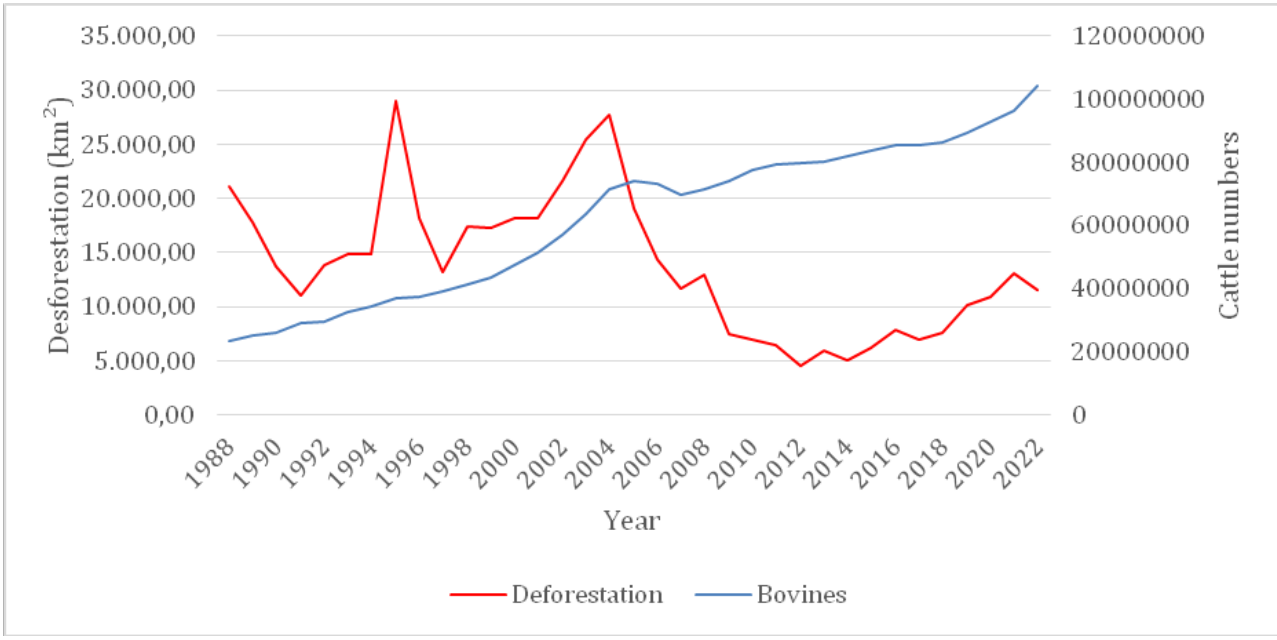
In this first period, the variables Cattle herd strength (Bov) and Rural credit stock (Ecr) had a significant impact on deforestation, as they presented p-values of 0.000 and 0.001, respectively. As for the regression coefficients, the negative signs found show a robust negative relationship.

The estimated coefficient for the Bov variable (-0.2462) was statistically significant and indicates that a 1% increase in the cattle herd was associated with a 0.24% decrease in deforestation. This relationship may be more related to the general drop in deforestation during the period studied than to a true inverse causality, since the reduction in deforestation may have coincided with the increase in cattle numbers (Figure 3), without this increase being the direct cause of the reduction in deforestation.

In relation to the Ecr variable, the estimated coefficient was also statistically significant (-0.0667) and demonstrates that a 1% increase in the stock of rural credit was associated with a 0.06% reduction in deforestation. This suggests that access to rural credit has followed criteria that encourage more sustainable or alternative land use practices that help reduce deforestation.

With regard to the Mad variable, the coefficient of 0.0503 with a p-value of 0.054 demonstrates that, because the p-value is close to the significance level of 0.05, the impact of wood extraction in the period is marginally significant. Logging is in line with the observations of Marques (2018). The data used in the model refers only to legal timber extraction. However, it is known that the majority of wood production in the Amazon is of illegal origin, representing one of the limitations of the model.

Figure 3 | Annual deforestation rate in the Legal Amazon and cattle numbers, 1988 to 2022



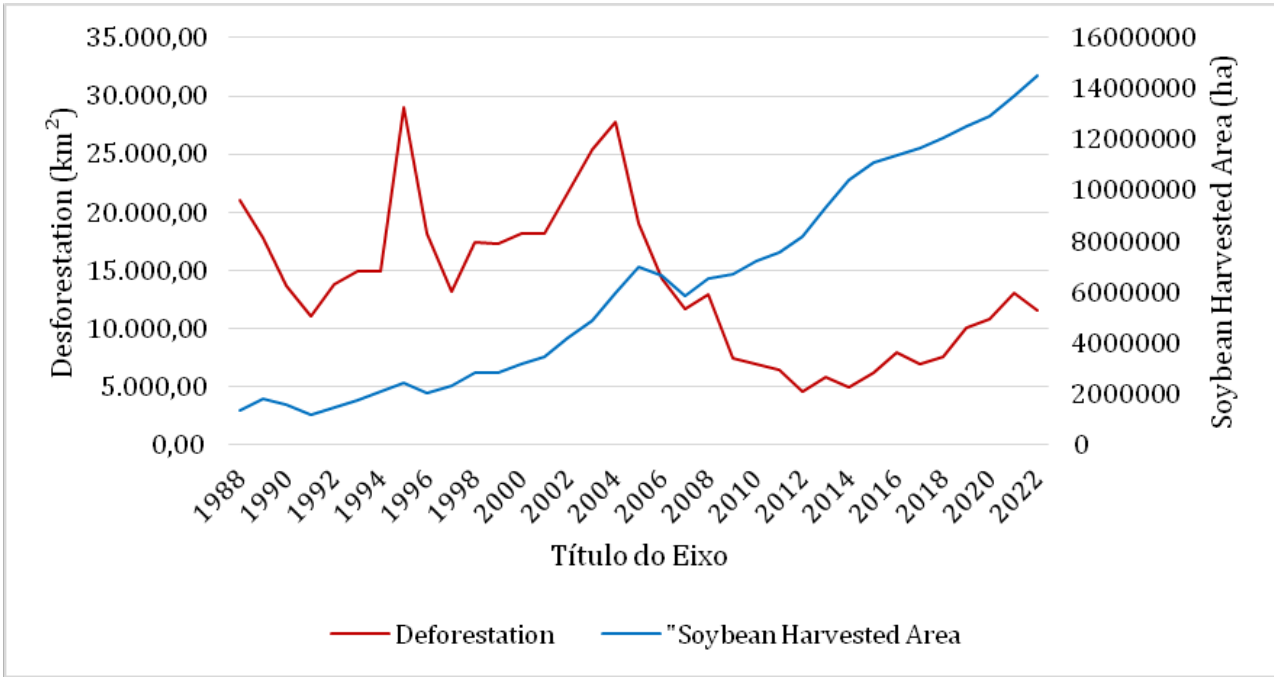
Source: TerraBrasilis Portal / IPEA Data (2024)

The estimated coefficients for the variables Acs, Acp, and Gao were not statistically significant at 5%. The result found suggests that the Area harvested from soybeans (Acs), the Area harvested from permanent crops (Acp) and Expenditure on Environmental Management, Agriculture and Agrarian Organization (Gao) did not have a significant impact on deforestation during the period. In the case of soy, the result may be related to the Soy Moratorium, limiting the expansion of soy in the Amazon and reducing the impact on deforestation, as demonstrated by Macedo *et al.* (2012). In the period from 2008 to 2014, variations in the soybean harvested area (Acs) could not explain the variations in deforestation (Figure 4).

The F value was 14.95 with a probability of 0.0000. This test rejects the null hypothesis that all fixed effects are zero, indicating that the fixed effects are significantly different from zero and should be included in the model.

The effects of some less visible independent variables are in line with the characteristics of the period analyzed, in which there is a general trend of reduction in deforestation, especially with the lowest rate recorded in 2012. The period included relevant political and economic changes, aimed at reducing pressure on the forest, such as the Soy Moratorium in 2006, the implementation of the Sustainable Amazon Plan, in 2008, and the 2nd phase of PPCDAm, in 2009. This may have influenced the results, as the variation in deforestation may have been very small during this period, limiting the model's ability to capture significant variations.

Figure 4 | Deforestation rate in the Legal Amazon and soy harvested area, 1988, 2022



Source: TerraBrasilis Portal / IPEA Data (2024).

Table 2 presents the results of the regression obtained using the fixed effects model (MEF), in the second period analyzed, between 2015 and 2022.

Table 2 | Direct causes of deforestation through regression obtained by the fixed effects model (MEF) in the period from 2015 to 2021

Variable	Coefficient	Standard Error	p-value
Soybean harvested area (Acs)	0.0513	0.0219	0.019
Area harvested from permanent crops (Acp)	0.0400	0.0452	0.377
Cattle herd population (Bov)	0.3473	0.0669	0.000
Environmental expenses (Gao)	0.0131	0.0069	0.058
Rural credit stock (Ecr)	-0.0322	0.0129	0.013
Logging (Mad)	0.0339	0.0257	0.187
R-sq: overall	0.8956		
F	26.49		

Source: research data.

This period was characterized by the effects of actions that contributed negatively to reducing deforestation, such as the review of the Forest Code in 2012, the economic and political crises between 2014 and 2015, and changes in environmental policy from 2019 onwards, as pointed out by Candido *et al.* (2023). During this period, the variables Cattle herd headcount (Bov) and Rural credit stock (Ecr) and Soybean harvested area (Acs) had a statistically significant impact on deforestation.

The Cattle Herd Number (Bov) presented a coefficient of 0.3473, indicating that a 1% increase in the cattle herd was associated with a 0.34% increase in deforestation, differentiating from the previous period in which the two variables presented an inverse relationship. The positive and substantial effect suggests a strong association between the growth of the cattle herd and the increase in deforestation, which can also be seen in Figure 3.

The estimated coefficient of the Ecr variable (-0.0322) shows that a 1% increase in the stock of rural credit was associated with a 0.03% reduction in deforestation. This suggests that access to rural credit continued to comply with criteria that encourage more sustainable land use practices or that help reduce deforestation.

In relation to the Acs variable, the estimated coefficient (0.0513) demonstrates that a 1% increase in the soybean harvested area was associated with a 0.05% increase in the increase in deforestation. Unlike the previous period, between 2008 and 2014, soy began to impact deforestation. This relationship can be visualized through Figure 4.

With regard to cattle and soybeans, the results are in line with the findings by Arraes, Mariano and Simonassi (2012), Marques (2018) and Reydon, Fernandes and Telles (2020). Cattle breeding was the predominant cause during this period, corroborating Rivero *et al.* (2009), Diniz *et al.* (2009), Santos (2010), Fearnside (2022) and Ramírez, Pérez and Cutiño (2022).

The other variables included in the model, namely: areas harvested from permanent crops, environmental expenses and legal timber extraction, were not statistically significant in the period in question, suggesting that there was no impact of these variables on deforestation in the period. As the p-value of the Gao variable was close to the significance level of 0.05, it can be suggested that there was a marginally significant positive relationship between spending on environmental management, agriculture and agrarian organization.

In the second period analyzed, the general R2 was 0.8956, indicating that approximately 89.56% of the total variance in deforestation is explained by fixed effects. The F value of 26.49 confirms that the fixed effects are significant and that the model has a moderate overall explanatory capacity (26.54% of the total variation). Thus, the high fraction of variance explained by fixed effects (89.56%) suggests that the heterogeneity of municipalities is fundamental to understanding variation in deforestation.

CONCLUSION

PPCDAm proved to be an effective policy in its first two phases. Between 2004 and 2012, it achieved its main objective of containing the advance of deforestation in the ALB, due to the integration of monitoring policies, environmental control, land planning and the strengthening of sustainable productive activities, which created an environment of greater supervision, discouraging illegal practices. Even with the increase in agricultural production, deforestation was contained, intensifying agricultural practices in areas already deforested.

In the period from 2013 to 2018, despite economic pressures and the expansion of soybeans and other permanent crops, the PPCDAm continued to moderate deforestation, supported by instruments such as the Rural Environmental Registry (CAR) and policies that encouraged productivity in areas already deforested. However, the revocation of the Plan in 2019, combined with

the weakening of environmental policies and the relaxation of laws, led to a significant increase in deforestation, which reached its highest peak in a decade in 2021. This highlights the importance of a continuous and integrated environmental policy to protect Amazon forests and face the challenges posed by economic expansion in the region.

The regression results, with the fixed effects model (MEF), indicated that the cattle herd and the soybean cultivation area were the main causes of deforestation between 2015 and 2021. However, it is possible to expand these activities without intensifying deforestation, reinforcing the econometric analysis on the direct causes of deforestation and the impacts of public policies. This demonstrates that regional development in the ALB depends on the integration between economic growth and environmental protection, preventing productive expansion from translating into greater forest degradation.

As limitations of the study, the lack of data did not allow analyzing the 5th stage of the PPCDAm. Furthermore, due to the unavailability of municipal data, other variables that could explain deforestation in the period were not included in the model, such as mining, mining, road infrastructure, technological factors and agricultural prices, among others. These limitations can serve as suggestions for further research.

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