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COMPARATIVE ANALYSIS OF DEFORESTATION AND ITS DETERMINANTS IN BRAZILIAN BIOMES

Análise comparativa do desmatamento e seus determinantes nos biomas brasileiros

Análisis comparativo de la deforestación y sus determinantes en los biomas brasileños

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ABSTRACT

Understanding the factors that influence deforestation across the national biomes is essential for developing more effective environmental policies. In this context, this study provides an overview of deforestation and its main determinants in Brazilian biomes between 2008 and 2020. Specifically, it examines variables such as planted area, livestock herd size, forest extraction, forestry, gross value added from production, and climatic characteristics. Through statistical analysis, fluctuations in deforestation levels were identified in the Amazon and Cerrado biomes, both of which displayed highly alarming conditions. In addition, the Caatinga biome was characterized by high temperatures and low rainfall levels, while the Amazon biome registered concerning values for both temperature and precipitation. As for the Atlantic Forest, it exhibited the highest population density and the greatest aggregate production, both in agriculture and overall output.

Keywords: Brazilian Amazon; Sustainable development; Climate change.

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RESUMO

Entender os problemas que afetam o desmatamento nos biomas do país é essencial para a construção de políticas ambientais mais eficazes. Nesse contexto, esta pesquisa busca apresentar um panorama do desmatamento e dos seus principais determinantes nos biomas brasileiros no período de 2008 a 2020. De forma específica, é delineado o comportamento das variáveis área plantada, rebanho, extração vegetal, silvicultura, valor bruto adicionado pela produção e características climáticas. Por meio da abordagem estatística, foi constatada a presença de flutuações nos níveis de desmatamento para os biomas Amazônia e Cerrado, que apresentaram condições muito alarmantes. Além disso, verificaram-se, no bioma Caatinga, altos valores de temperatura e baixos índices de pluviosidade, enquanto o bioma Amazônia alcançou valores preocupantes de temperatura e precipitação. No que concerne à Mata Atlântica, obteve-se a maior concentração de pessoas por área e a maior produção agregada, tanto na produção agropecuária quanto no cômputo geral.

Palavras-chave: Amazônia brasileira; Desenvolvimento sustentável; Mudanças climáticas.

RESUMEN

Entender los problemas que afectan la deforestación en los biomas del país es esencial para la construcción de políticas ambientales más eficaces. En este contexto, esta investigación busca presentar un panorama de la deforestación y de sus principales determinantes en los biomas brasileños en el período de 2008 a 2020. De forma específica, se describe el comportamiento de las variables área plantada, ganado, extracción vegetal, silvicultura, valor bruto agregado por la producción y características climáticas. A través del enfoque estadístico, se constató la presencia de fluctuaciones en los niveles de deforestación en los biomas Amazonía y Cerrado, los cuales presentaron condiciones muy alarmantes. Además, se observaron en el bioma Caatinga altos valores de temperatura y bajos índices de pluviosidad, mientras que el bioma Amazonía alcanzó valores preocupantes de temperatura y precipitación. En lo que respecta a la Mata Atlántica, se obtuvo la mayor concentración de personas por área y la mayor producción agregada, tanto en la producción agropecuaria como en el cómputo general.

Palabras clave: Amazonía brasileña; Desarrollo sostenible; Cambio climático.

1 INTRODUCTION

Deforestation is one of the most critical global issues related to land use, compromising the balance of the planet in multiple aspects, including the economy, ecosystems, and society as a whole. According to the report by the Food and Agriculture Organization of the United Nations (FAO, 2022), although the rate of forest loss decreased by approximately 30% between 2000 and 2010–2018, tropical forests remain under threat. The report indicated that the greatest deforestation during this period occurred in South America, with approximately 68 million hectares cleared.

In Brazil, deforestation is a multifaceted issue shaped by socioeconomic, political, and environmental factors. The primary drivers of deforestation in the country are the expansion of agricultural areas, contributing to nearly 50% of global deforestation, and cattle grazing, responsible for approximately 38.5% of deforestation (FAO, 2022). However, the adverse effects are not restricted to the environmental aspect alone, as they also include socioeconomic consequences, such as limiting possibilities for sustainable economic development based on local assets. In this context, the predatory exploitation of natural resources compromises not only the ability to alleviate poverty but also the potential for regional economic development (Rossoni; Moraes, 2020).

Since the 1990s, there has been growing concern in the specialized literature about the main determinants of forest loss, with an emphasis on the socioeconomic aspects that indirectly influence economic agents through various transmission channels. Other factors frequently addressed in research are linked to economic development, the macroeconomic context, institutions, and demographic dynamics (Damette; Delacote, 2012; Alves, 2021). According to Oliveira *et al.* (2011), deforestation of tropical forests in Brazil plays a central role in climate change, because hotspots of forest loss make the country a major global emitter of carbon dioxide (CO2). The drivers of deforestation are also influenced by factors related to land use, such as the extraction of natural resources, the expansion of land for agriculture and pasture, and the development of infrastructure. These land-use changes directly affect ecosystems and vegetation cover (Geist; Lambin, 2001; Campoli; Stival, 2023). According to the *World Wildlife Fund* (WWF, 2020), commercial agriculture and forestry are among the main factors driving degradation, further exacerbated by increased land speculation, which has become an increasingly significant contributor to the problem.

According to data from the National Institute for Space Research (INPE), the percentage of deforested area in each Brazilian biome corresponds to 17% in the Amazon, 52% in the Cerrado, 69% in the Atlantic Forest, 30% in the Caatinga, 44% in the Pampa, and 16% in the Pantanal (IBGE, 2024a). Based on this scenario, this study aims to present an overview of deforestation in Brazilian biomes, as well as to demonstrate the evolution of environmental and socioeconomic indicators from 2008 to 2020. Specifically, it analyzes the behavior of the following variables: planted area, livestock, plant extraction, forestry, gross value added by production, and climatic characteristics.

Following this introduction, the article is structured into four additional sections. The next section presents a historical overview of deforestation and the concept of sustainable development, followed by reflections on the determinants of deforestation. Section 3 describes the methodological procedures of the research, including the database, the study area, and the method of analysis. Subsequently, in Section 4, the main results found are discussed. Lastly, Section 5 addresses the final considerations of the study.

2 THEORETICAL FRAMEWORK

This section is divided into two subsections: the first provides an overview of sustainable development, relating this theme to deforestation, and the second addresses the main empirical evidence relevant to the research context.

2.1 Deforestation from the perspective of sustainable development

To contextualize the theme of this research, we begin with Raynaut (2006). According to the author, for a long time—and especially with the advent of the Industrial Revolution—the exploitation of natural resources was guided by the conviction that these resources were inexhaustible, combined with an unshakable faith in the progress of science and technology. However, the available resources proved to be insufficient to meet the demands of the productive apparatus. Raynaut (2006) also argues that, starting in the 1950s, it became increasingly evident that an economic model based solely on growth had serious limitations.

In the 1980s, the Brundtland Report introduced the concept of sustainable development as a standard capable of meeting present needs without compromising the satisfaction of future needs, as noted by Moreira (2000). Brüseke (1994) considers that this development standard, in addition to meeting basic needs with future solidarity, should also involve popular participation, the creation of a social system that guarantees employment and social security, as well as the preservation of natural resources and the environment.

In the case of Brazil, Abramovay (2010) points out that, in 2009, the signing of the Copenhagen Protocol represented an important milestone for the country, changing its position on development. This event established Brazil as a relevant player in the fight against climate change, since, until then, Brazilian diplomacy had been reluctant to commit to emission reduction targets. The author also highlights that the main source of emissions in the country comes from deforestation in the Amazon and Cerrado biomes, emphasizing that the Brazilian Cerrado is treated as an agricultural frontier, without receiving the necessary concern for its preservation.

More recently, Brazil joined the so-called 2030 Agenda, in which countries committed to achieving 17 goals set by the United Nations (UN) by the year 2030. These goals include actions to combat global climate change, preserve terrestrial life, and mitigate deforestation.

The control of these actions is, therefore, essential for such commitments to be fulfilled (UN, 2024).

According to Altieri and Masera (2009), 56.9% of the tropical forests of the world are located in Latin America, a region that has suffered from frequent deforestation caused by agricultural production, construction, and commercial extraction. It is estimated that an average of 5.7 million hectares of forest area are lost each year, with Brazil being responsible for the highest rates of deforestation, along with Colombia and Mexico. These levels of deforestation have negatively affected local ecosystems, contributing to climate change, global warming, and biodiversity loss (Altieri; Masera, 2009).

Fearnside (2022) reports that deforestation rates in the Amazon have been increasing rapidly over the past decade, largely due to livestock farming in the region, which accounts for approximately 70% of deforestation activities, through selective logging, the proliferation of fires, forest fragmentation, and edge formation. These factors result in biodiversity loss, significant changes in precipitation patterns, and global warming. Although the study by Fearnside (2022) focuses on the Amazon biome, other studies, such as that by Silva *et al.* (2018), indicate a similar reality in the Caatinga biome.

2.2 The determinants of deforestation

Globally, the determinants of deforestation have been widely discussed in empirical economic literature. In this context, Indarto and Mutaqin (2016) investigated the patterns of conditional heterogeneity of deforestation by applying a quantile analysis developed by Koenker (2005), in addition to fixed-effects panel quantile regressions. The authors argue that the factors driving deforestation are more pronounced in countries that deforest the most, with economic growth, timber extraction, and the price of this natural resource standing out in particular. Furthermore, the distribution patterns of deforestation can be affected differently by macroeconomic shocks.

In turn, Oliveira *et al*. (2011) sought to identify a causal link between environmental degradation and economic growth, using the CKA hypothesis in the Legal Amazon region during the period from 2001 to 2006, with deforestation as the main indicator. The authors estimated a panel data model with spatial dependence, considering variables deemed important in the literature, such as cattle herd size, agricultural crops, plant extraction, forestry, population density, pre-existing forest area, and rural credit. The results indicated that the relationship between environmental degradation and economic growth is expressed in the form of an inverted "N," that is, deforestation initially decreases at lower levels of gross domestic product (GDP) per capita, increases with rising GDP per capita, and then decreases again at higher levels of GDP per capita.

Faria and Almeida (2016) investigated how international trade impacted the dynamics of deforestation in the Brazilian Amazon at the municipal level, providing a balanced overview of the period from 2000 to 2010. Specifically, the analysis of the authors focuses on the expansion of agricultural and livestock activities, but also includes other factors, such as GDP per capita, conservation areas, and property rights. The results indicate that, as trade openness in the Amazon increases, deforestation also rises. It was also found that soybean production and beef cattle farming drive deforestation in the region. In addition, an increase in GDP per capita tends to increase deforestation, while the presence of conservation areas has a negative effect on deforestation.

Delazeri (2016) confirms that the territory of the Legal Amazon is characterized by environmental problems resulting from the exploitation of natural resources. Given the importance of the Amazon for the maintenance of ecological services, the author sought to identify the main causes of deforestation in the municipalities within this region between 2008 and 2012. Through the application of a fixed effects panel, it was found that livestock farming is the primary factor contributing to increased deforestation in the municipalities analyzed. In contrast, the expansion of soybean cultivation was not statistically significant in explaining deforestation.

It has been found that precipitation in the Amazon tends to decrease when forest loss exceeds a certain threshold, although no specific value for this limit has been established. From this perspective, Leite-Filho *et al*. (2021) examined the relationship between historical deforestation and precipitation at different geographical scales in the Southern Brazilian Amazon (SBA). The authors report that forest losses of up to 55-60% in 28 km grid cells increase precipitation, but beyond that point, further deforestation leads to a decrease. Moreover, reducing deforestation can prevent agricultural losses in the SBA of up to US$1 billion annually.

Alves (2021) investigated the determinants of deforestation in municipalities in the state of Pará between 2006 and 2016. Methodologically, quantile regressions for panel data were applied to examine potencial divergences between groups of municipalities in relation to their deforestation patterns. The results indicated that deforestation levels are influenced by several key factors, including GDP per capita, population growth, and the expansion of cattle herds and temporary and permanent cropland areas. Other factors relevant to mitigating these environmental impacts include improvements in socioeconomic indicators (employment, health, income, and education) and environmental indicators (area of remaining forests).

3 METHODOLOGY

This section describes the database, presenting the sources of each variable used throughout the analysis period. Subsequently, the empirical strategy adopted to obtain the research results is presented.

3.1 Database

The database, which contains information on the municipalities that make up each biome, comes from various sources and covers the period from 2008 to 2020. This time frame is justified by the beginning of data collection on deforestation in the Amazon biome. The main variable corresponds to deforestation, measured by INPE in square kilometers. The variables used as determinants were selected based on specialized literature.

Most of the variables were obtained from the Brazilian Institute of Geography and Statistics (IBGE) for each municipality (Table 01). Among these, we highlight GDP per capita and the planted area of temporary crops, which are derived from the Municipal Agricultural Production (PAM) survey. Data on plant extraction and forestry are sourced from the Plant Extraction and Forestry Production (PEVS) survey. This survey provides statistics on the quantity and value of the main products obtained from the exploitation of native forest resources (referred to as plant extraction), as well as on the quantity and value of the main forestry products, that is, products derived from the exploitation of planted forest areas.

Information on the number of livestock per square kilometer comes from the Municipal Livestock Survey (PPM), which provides statistics on livestock numbers, shorn sheep, animal products, and aquaculture production. Population density is defined as the ratio of the population to the area of the municipality, expressed as the number of people per square kilometer. It is worth noting that the variables, in monetary terms, were deflated to December 2020, based on the General Price Index—Internal Availability (IGP-DI) from the Getúlio Vargas Foundation (FGV).

Table 01 – Description of variables

Variables	Description	Measure	Source
Deforestation	Increase in deforestation by municipality	km²	INPE (2024)
GDP *per capita*	GDP *per capita* for municipalities	Reais *per capita*	IBGE (2024a)
Planted area	Planted area of temporary and permanent crops by municipality	km²	IBGE (2024a)
Extraction	Quantity produced through plant extraction by municipality	Tons	IBGE (2024a)
Herd	Cattle herd size	Head per km²	IBGE (2024a)
Forestry	Total forestry production	Tons	IBGE (2024a)
Population	Number of residents	Individuals	IBGE (2024a)
GVA	Gross value added in agricultural activity	Reais	IBGE (2024a)
Precipitation	Total precipitation observed	Millimeters	NOAA (2024)
Temperature	Average temperature observed	Degrees Celsius	NOAA (2024)

Source: Prepared by the authors (2025).

Finally, the Value Added from Agriculture (VAA), provided by IBGE for each municipality, was also considered. Data on precipitation and temperature were obtained from *the National Oceanic and Atmospheric Administration* (NOAA), a U.S. scientific agency that monitors oceanic and atmospheric conditions. This institution plays an important role in weather forecasting, the management of marine and coastal resources, climate monitoring, and scientific research in related areas.

3.2 Study area

The study area comprises the six Brazilian biomes: Amazon, Caatinga, Cerrado, Atlantic Forest, Pampa, and Pantanal (Figure 01). The Amazon biome covers an area of 4,196,943 km², corresponding to 49.29% of the national territory. It is considered the largest tropical forest in the world, hosting a significant number of flora and fauna species, as well as concentrating 20% of global freshwater supply and large mineral reserves. The Amazon is predominantly located in the North region, occupying the entire states of Acre, Amapá, Amazonas, Pará, and Roraima, as well as large portions of Rondônia (98.8%), Mato Grosso (54%), Maranhão (34%), and Tocantins (9%) (IBGE, 2024b).

The Cerrado biome, in turn, covers an area of approximately 2,036,448 km², corresponding to 23.92% of Brazil's territory. This biome is recognized as the most biodiverse savanna in the world and an important water reservoir for South America. The Cerrado is mainly located in the Central-West region, encompassing the entire Federal District, almost the entire states of Goiás (97%), Maranhão (65%), Mato Grosso do Sul (61%), Minas Gerais (57%), and Tocantins (91%), as well as parts of six other states (IBGE, 2024b).

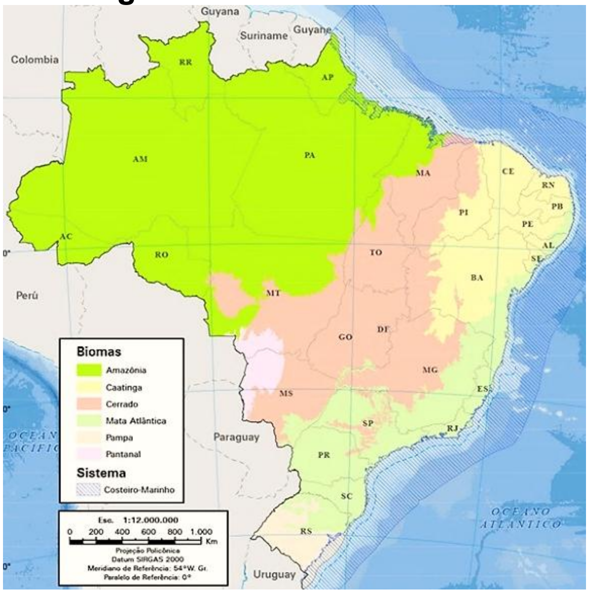
The Atlantic Forest biome covers an area of 1,110,182 km², corresponding to 13.04% of the national territory. This biome is considered one of the areas with the richest fauna and flora in the world. However, because it is located in the coastal region, which is home to more than 50% of the Brazilian population, it is considered the most threatened biome in the country. Currently, only about 27% of its original forest cover remains, and its preserved area is often located in places that are difficult to access. The Atlantic Forest occupies the entire states of Espírito Santo, Rio de Janeiro, and Santa Catarina, covers 98% of Paraná, and extends into portions of 11 other states (IBGE, 2024b).

The Caatinga is a biome unique to Brazil and predominant in the Northeastern region, extending across the entire state of Ceará, covering the entirety of Paraíba (92%), Rio Grande do Norte (95%), and Pernambuco (83%), more than half of Piauí (63%) and Bahia (54%), almost half of Alagoas (48%) and Sergipe (49%), as well as small fractions of Minas Gerais (2%) and Maranhão (1%). Its typical vegetation is dry and thorny, due to limited rainfall for most of the year. Although the Caatinga encompasses rich biodiversity, with species found only in this biome, its typical vegetation has changed considerably, often being replaced by pastures and agricultural areas. However, this biome still covers an area of 844,453 km², corresponding to approximately 9.92% of Brazilian territory (IBGE, 2024b).

The Pampa biome covers an area of approximately 176,496 km², corresponding to 2.07% of Brazilian territory. It is restricted to the state of Rio Grande do Sul, where it occupies 63% of the territory. The region is characterized by a rainy climate and negative temperatures in winter, which has led to much of its vegetation cover being converted to agricultural activities, especially rice cultivation.

Finally, the Pantanal biome covers an area of 150,355 km², representing only 1.76% of Brazil's territory (IBGE, 2024b). It is recognized as the largest continuous floodplain in the world and remains the most preserved biome in the country. Its main economic activities are cattle ranching and tourism.

Figure 01 – Brazilian biomes



Source: IBGE (2019).

3.3 Method of analysis

In terms of the approach adopted, this research is quantitative in nature. As explained by Fonseca (2002), unlike qualitative research, the results of this type of approach can be quantified, with samples usually considered representative of the target population. Therefore, quantitative research focuses on objectivity and is motivated by positivism, emphasizing that reality can only be understood through the analysis of raw data obtained with the aid of standardized and neutral instruments. Thus, mathematical language is employed to specify the causes of a given occurrence and the relationships among variables.

The technical procedures adopted were based on the statistical method. According to Gil (2008), the conclusions of this method cannot be considered absolutely true, but they are highly likely to reflect the real value. This procedure has been widely accepted among researchers in the quantitative field because it offers a reasonable degree of accuracy. Through statistical tests, it is possible to establish, in numerical terms, the probability of accuracy and the margin of error of an obtained value.

4 RESULTS AND DISCUSSION

The research results are presented in two subsections. The first subsection analyzes the evolution of environmental factors, with an emphasis on statistics related to deforestation. The second subsection highlights statistics on socioeconomic factors associated with deforestation.

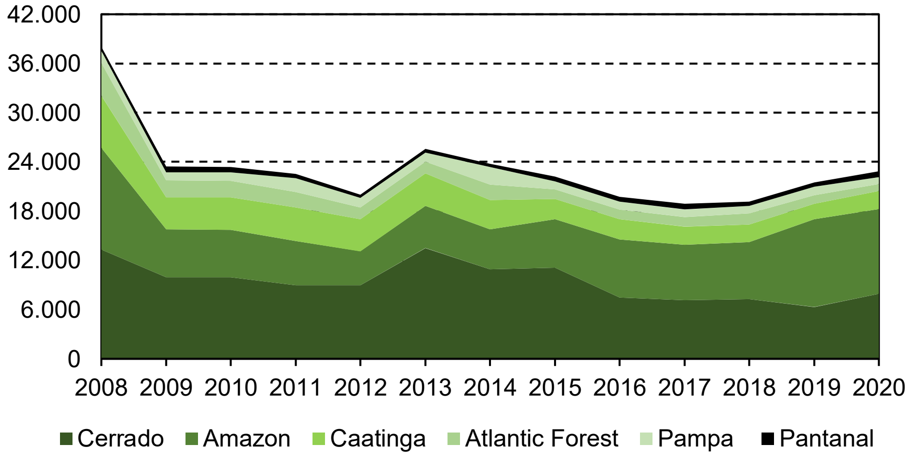
4.1 Descriptive analysis of environmental factors

Figure 02 shows the evolution of annual deforestation per square kilometer in Brazilian biomes between 2008 and 2020. When the analysis is filtered by biome, it can be observed that deforestation in the Amazon fluctuates: it begins with a high value of 12,412 km², then declines significantly until 2012. From 2013 onward, however, there is a clear upward trend, reaching 10,703 km² in 2019 and 10,355 km² in 2020, i.e., almost the same levels as in 2008, which is considered the highest in the entire time series analyzed.

As Delazeri (2016) notes, agricultural and livestock production increasingly contribute to the advance of deforestation in new areas. In addition to socioeconomic changes, the expansion of the agricultural frontier into the Amazon rainforest causes biodiversity loss, climate stress, and a decline in the provision of ecological services.

As Lovejoy and Nobre (2018) warn, if Brazil does not stop deforestation in the Amazon and the loss of vegetation cover exceeds 20% of the original forest, there will be an imbalance in rainfall regulation, as well as environmental damage on a global scale. From this perspective, Leite-Filho *et al.* (2021) argue that extensive forest loss could reduce precipitation rates, significantly affecting agricultural production.

Figure 02 – Brazil: Evolution of deforestation increase (km²) by biome between 2008 and 2020



Source: Prepared by the authors (2025) based on data from INPE (2024).

In the Caatinga, deforestation remained virtually constant between 2009 and 2012, decreasing from 3,942 km² to 2,432 km². From 2013 onward, there was a sharp decline, reaching 1,868 km² in 2019, followed by a slow increase until 2020, although still below initial levels. Deforestation in the Cerrado peaked in 2008, with 13,300 km² of deforested area. After this period, it declined and stabilized, with a gradual reduction until 2012. Subsequently, there was a significant increase, totaling 13,481 km² in 2013. Another downward trend occurred in 2019, followed by a slight increase in the deforested area to 7,905 km² in 2020.

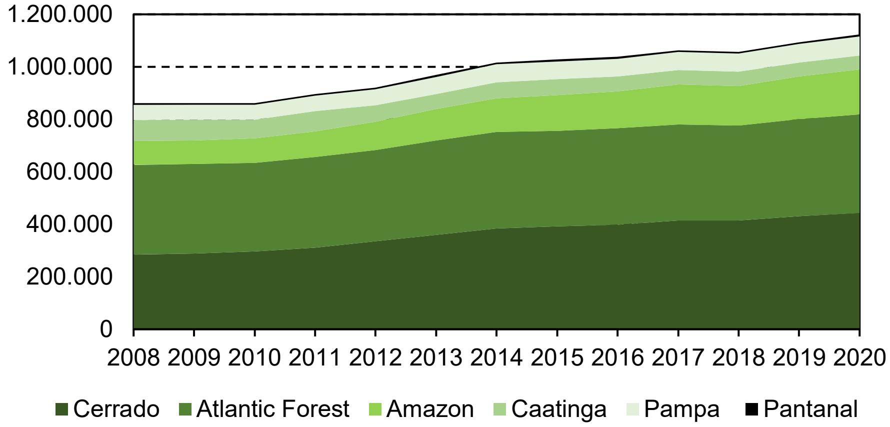
With regard to the Atlantic Forest, there was a continuous decline throughout the period analyzed, from 6,351 km² deforested in 2008 to 790 km² in 2020. It should be emphasized that this biome experienced the greatest reduction in deforestation compared to other Brazilian biomes. In the Pampas, despite some fluctuations during the study period, the general trend was a decline in deforestation, from 1,449 km² in 2008 to 888 km² in 2020.

Finally, deforestation in the Pantanal reached an area of 518 km² in 2008, with fluctuations throughout the period. The minimum value, 369 km², was reached in 2014. By the end of the series, there was a 30.7% in levels of deforestation, reaching 677 km² in 2020. This biome was the only one to show an increase compared to the initial period analyzed. In general, the rise in deforestation in the Amazon and Cerrado is exceptionally worrying, given the critical role these biomes play in global climate regulation and biodiversity preservation.

Regarding the determinants of deforestation, Figure 03 shows the distribution of planted area, in square kilometers, across the different Brazilian biomes between 2008 and 2020. It can be observed that, in 2008, the Atlantic Forest had the largest planted area (34,204,092 km²) compared to the other biomes; however, by 2020, the Cerrado recorded the highest value for this indicator. In relative terms, the variation in planted area over time was equivalent to 55.9%. The Cerrado is one of the most favorable biomes for agriculture due to its soil and climate characteristics. Therefore, this increase in planted area may reflect the expansion of agribusiness, particularly in grain production and livestock farming.

Another important piece of data is the reduction in the planted area in the Caatinga, with a decrease of 32.8%. This decrease might be explained by climatic difficulties, which cause prolonged droughts, making agriculture less viable. Additionally, conservation policies may have limited the agricultural expansion in this biome. On the other hand, this reduction may have positive effects, such as the recovery of degraded areas and the preservation of ecosystems. It is essential to balance agricultural development with environmental preservation to ensure long-term sustainability.

Figure: 03 – Brazil: Distribution of planted area (in km²) of biomes between 2008 and 2020



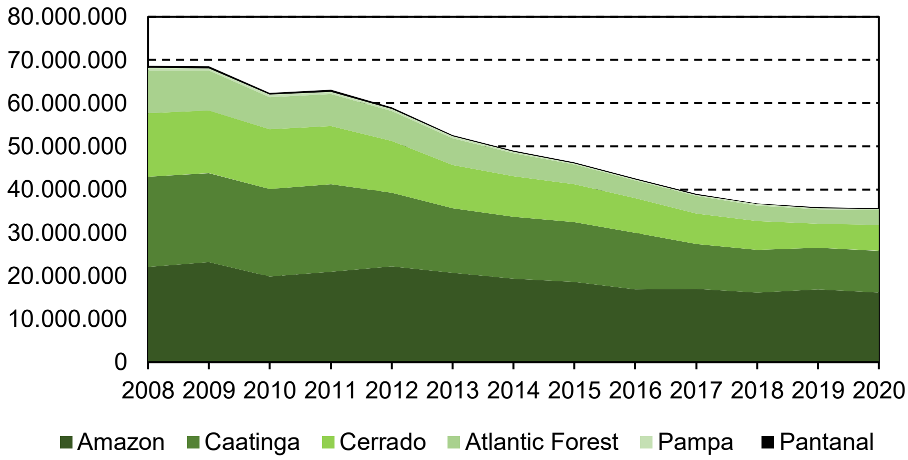
Source: Prepared by the authors (2025) based on data from IBGE (2024a).

Figure 04 shows the amount of plant extraction between 2008 and 2020, highlighting a significant decline in this activity across all biomes. Plant extraction is an activity more prevalent in the Amazon biome, which is explained by its territorial area, covering approximately 60% of the national territory. In addition to being the largest biome in Brazil, the region is also home to one of the greatest biodiversities in the world, offering a wide range of plant resources.

The constant prevalence of this activity in the Amazon can be attributed to a combination of natural, economic, and social factors, as the wealth of natural resources in this region makes it particularly favorable for extraction. Conversely, the decline in plant extraction across all biomes can be explained by several factors, including stronger enforcement against illegal deforestation and the implementation of environmental policies, with an emphasis on sustainability.

Figure 05 compares the distribution of livestock numbers, measured in heads per km², across the different biomes between 2008 and 2020. There was an increase in livestock density from 2008 to 2020 in virtually all biomes, only the Pantanal showing a slight negative variation of around 2.12%. Once again, the Atlantic Forest has the largest amount, increasing from 3,988,820 heads per km² in 2008 to 4,594,512 heads per km² in 2020. The increase in this indicator is attributed to the expansion of livestock farming, which, in turns, is associated to deforestation and the conversion of natural lands into pastures.

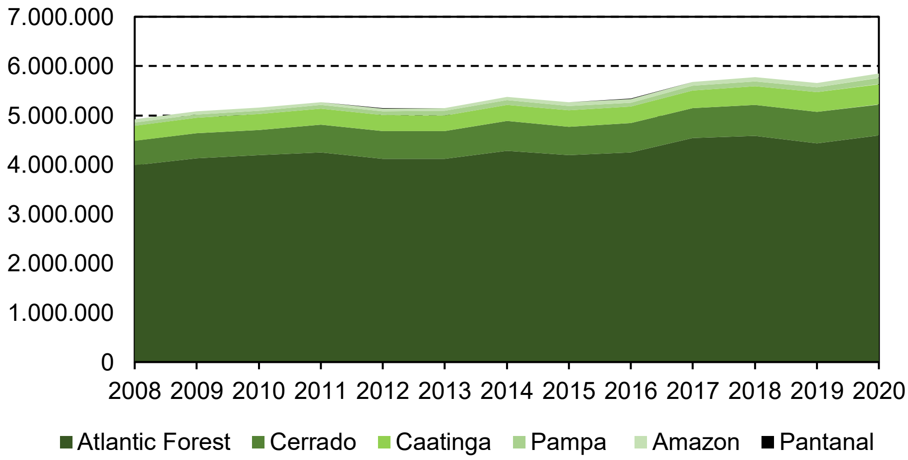
Figure 04 – Brazil: Distribution of the quantity produced in plant extraction (in tons) from biomes between 2008 and 2020



Source: Prepared by the authors (2025) based on data from IBGE (2024a).

From this perspective, Soares (2019), in a study on the determinants of deforestation in the state of Pará, based on municipal data for the period from 2011 to 2016, found that increases in livestock density, along with changes in GDP *per capita*, contributed positively to the rise in deforestation in the state.

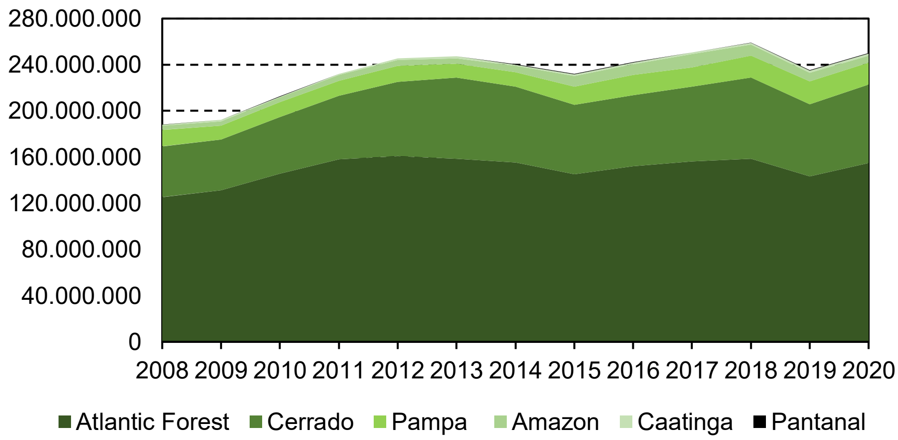
Figure 05 – Brazil: Distribution of livestock (heads per km²) by biome between 2008 and 2020



Source: Prepared by the authors (2025) based on data from IBGE (2024a).

Figure 06 below illustrates the distribution of forestry, which includes forest cultivation activities, across Brazilian biomes between 2008 and 2020. There was a significant increase in this activity in all biomes, with the Atlantic Forest biome once again standing out. However, although the Pantanal has the lowest values in absolute terms, this biome recorded the largest percentage change during the period, with a growth of 648.57% between 2008 and 2020, followed by the Amazon biome, which grew by 74.84%.

Figure 06 – Brazil: Distribution of forestry (in tons) by biome between 2008 and 2020



Source: Prepared by the authors (2025) based on data from IBGE (2024a).

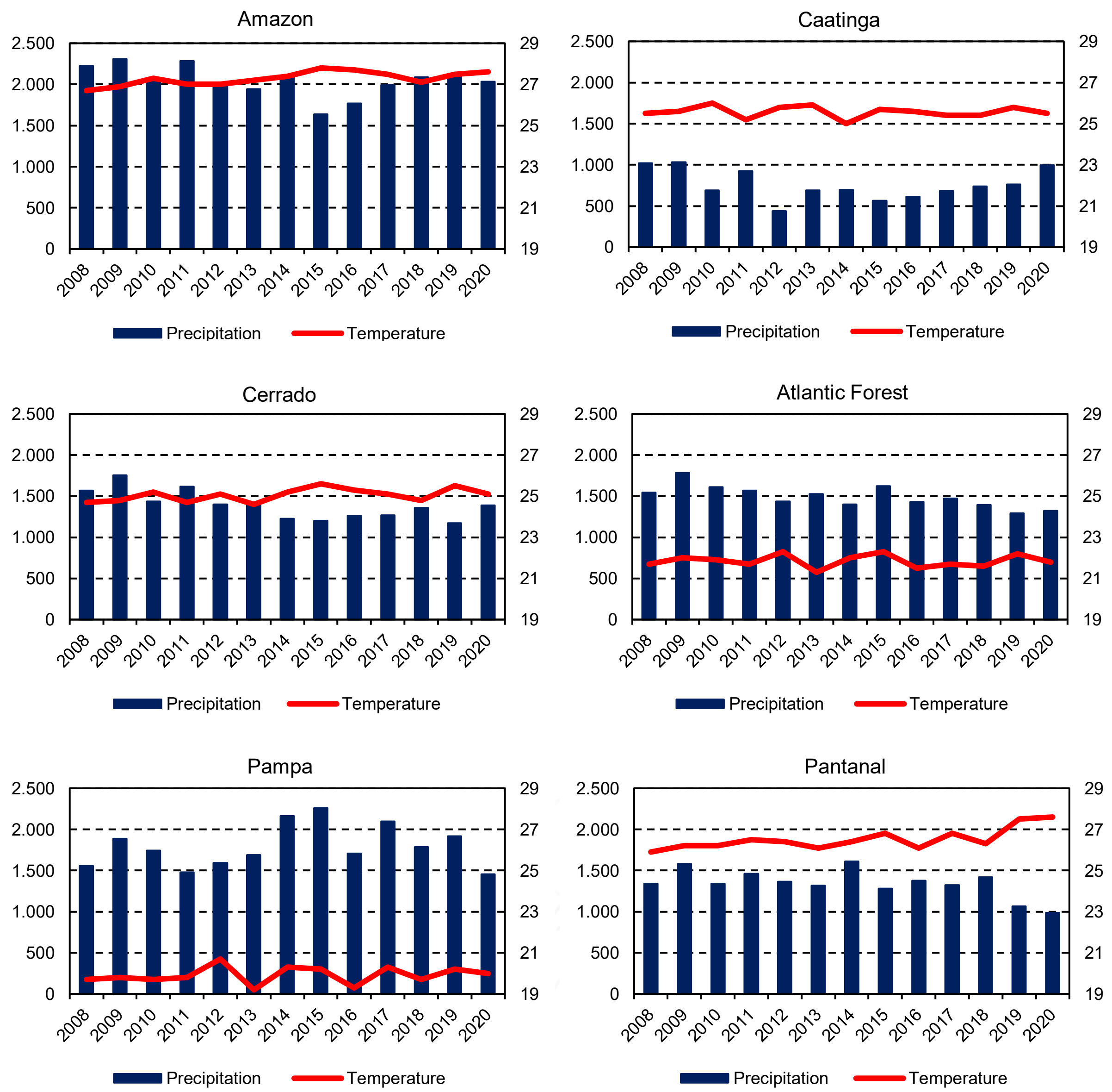
The increase in forestry may relate to the growing demand for forest products, such as paper and wood, as well as to a greater recognition of the economic value of planted forests. In addition, this expansion may be associated with sustainability and reforestation initiatives aimed at the recovery of degraded lands and the mitigation of climate change through increased forest cover. Overall, the data indicate a growth trend in forestry in Brazil, with substantial implications for the economy, the environment, and land use management policies.

Figure 07, in turn, shows the precipitation and average temperature of the municipalities corresponding to each biome between 2008 and 2020. On average, the Amazon biome is the wettest, exhibiting the highest values in the time series, often exceeding 1,500 mm per year and reaching up to 2,500 mm. The Caatinga, by contrast, presents the lowest average precipitation, often below 1,000 mm, which is a typical characteristic of this biome. In the Pampa, there is a variability of values, which may indicate an irregular rainfall pattern. In any case, there is a negative variation in average precipitation for all biomes in the analyzed time interval.

Notably, the Amazon has the highest average temperatures, generally eanging between 27° and 29°C, followed by the Caatinga and the Pantanal, with temperatures between 25° and 27°C, and a slight increase in the Pantanal since 2018. In contrast, the

Pampa biome stands out for its lower temperatures, averaging between 19° and 21°C and remaining relatively stable throughout the analyzed period. These variations are related to the geographical location and climate of each biome. Such analyses are crucial for understanding climate change and its impacts in different regions of Brazil, particularly regarding environmental management and adaptation strategies for each biome.

Figure 07 – Brazil: Precipitation and average annual temperature of biomes between 2008 and 2020



Source: Prepared by the authors (2025) based on data from NOAA (2024).

Although climate change induced by greenhouse gases, impacts resulting from extensive land use, such as deforestation, have been less investigated. As is well known, the conversion of forests into pastures and croplands affects the moisture cycle and energy balance, potentially altering regional precipitation patterns. Thus, regional climate can influence these changes as much as, or even more than, global warming itself (Leite-Filho *et al.*, 2021).

To conclude, regarding environmental issues, even though deforestation levels remain stable, the alarming increases observed in the Amazon and Cerrado biomes are noteworthy. Among the environmental determinants, the growth of planted areas and livestock is undeniable, driven by the unrestrained expansion of agricultural frontiers. These high levels of deforestation have contributed to significant climate changes, resulting in concerning rainfall patterns in the Pampa and Amazon regions.

4.2 Descriptive analysis of socioeconomic factors

Figure 08 shows the evolution of population growth in Brazilian biomes between 2008 and 2020. Each biome has distinct environmental and socioeconomic characteristics, and population changes over time reflect both natural growth and the effects of development policies and lamd-use changes, often linked to deforestation. Notably, the Atlantic Forest region has the highest population concentration, as it is the most urbanized biome in Brazil. In relative terms, the greatest variability occurred in the Amazon, Cerrado, and Pantanal, with 21.2%, 13.6%, and 14.9%, respectively (IBGE, 2024a).

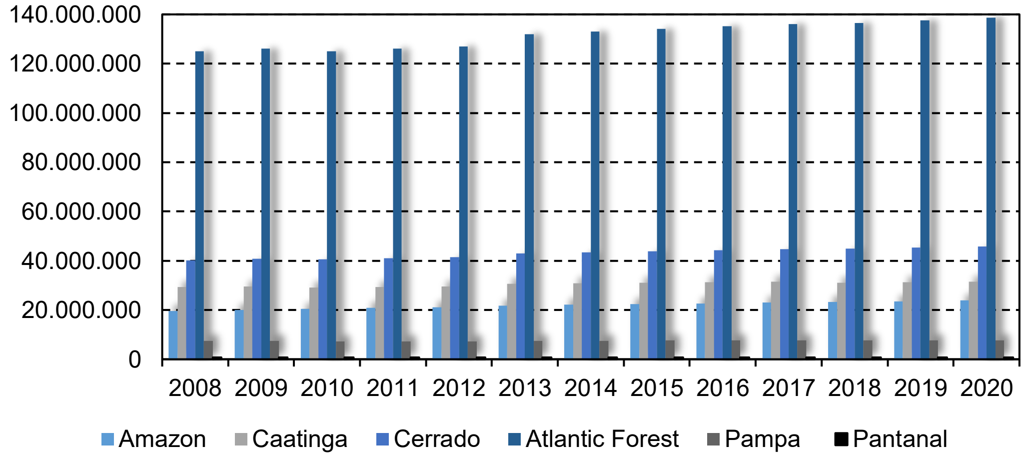
Based on this evidence, population growth in the Amazon may be correlated with economic development in the region, driven by policies focused on agriculture, livestock, and natural resource extraction. However, this increase may be accompanied by intense forestry pressures, leading to increased deforestation in response to the opening of new areas for cultivation and pasture.

The Caatinga biome, characterized by its semi-arid climate, showed more modest population growth, with a relative increase of 7.3% between 2008 and 2020. Given the ecological fragility of this biome, population growth can have severe consequences, such as desertification and soil degradation. From another perspective, population growth in the Cerrado may be related to the transformation of the biome into an important agro-industrial hub, which contributes to the loss of native vegetation cover.

In the Pampa, the population increased by only 3.4% during the entire period analyzed, i.e., it was the biome that showed the smallest variation in relative terms. Even with lower population growth and an economy based on agriculture and livestock, these activities exert pressure on the natural environment, though to a more limited extent compared to other biomes. The Pantanal, despite being one of the least populated biomes, has faced significant environmental challenges, such as deforestation and fires, which are often exacerbated by population growth and economic activities, including tourism and livestock farming.

In short, high population growth tends to be associated with high rates of deforestation. Demographic pressure, which is essential for the evolution of land occupation and use processes, is related to factors of attraction, such as settlement and infrastructure projects, mining, and the expansion of the agricultural frontier (Reydon; Fernandes; Telles, 2020; Alves, 2021).

Figure 08 – Brazil: Distribution of population by biome between 2008 and 2020



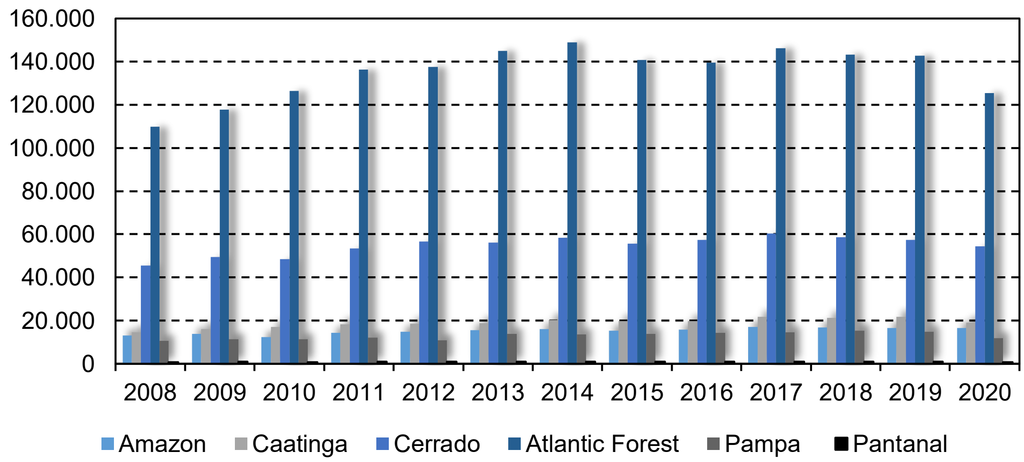
Source: Prepared by the authors (2025) based on data from IBGE (2024a).

Figure 09 below shows the evolution of GDP *per capita* in municipalities within each Brazilian biome during the period under study, which is useful for identifying how wealth was distributed among the different biomes from 2008 to 2020. As can be seen, there is a clear economic disparity in this indicator, although there has been positive variation in all biomes.

The Atlantic Forest biome had the highest GDP *per capita* in all years, which can be partially explained by its larger number of municipalities and other contributing factors. This biome includes densely urbanized and populated areas, such as São Paulo, Rio de Janeiro, and Belo Horizonte. Such urbanization favors industrial development, which, in turn, positively affects GDP *per capita*. In addition, the area surrounding this biome has a large working population with high levels of education, which contributes to a more dynamic labor market. Together, these factors create a conducive environment to economic growth, sustained by high added value.

In addition, it is worth noting that the greatest variation in GDP *per capita* over time, in percentage terms, was observed in the Caatinga biome, with an increase of 29.7%. The economy of the Caatinga region, which predominantly covers the Northeast, is less diversified and industrialized. Moreover, climate challenges affect agriculture and, consequently, limit economic development. Therefore, this variation can be explained by greater investments in agricultural technology, rural development projects, and improvements in water resource management, given that the biome is located in a semi-arid, less urbanized region.

Figure 09 – Brazil: Evolution of GDP *per capita* (in reais) by biome between 2008 and 2020



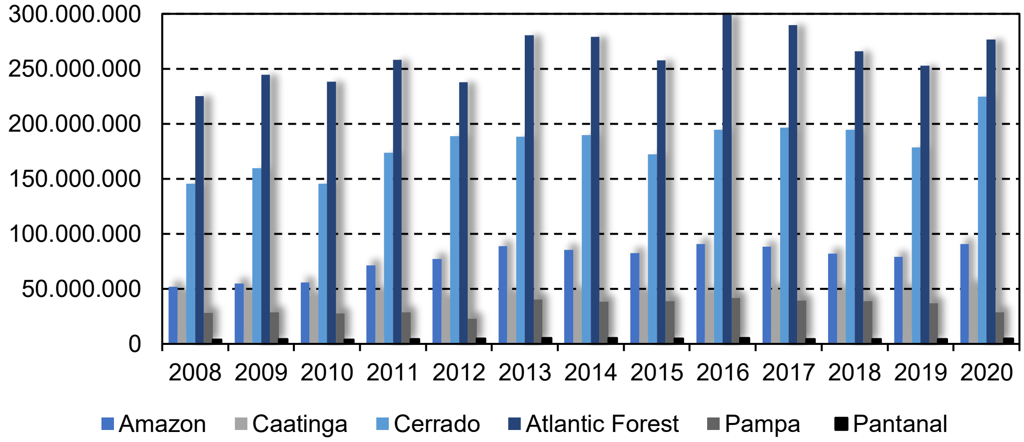
Source: Prepared by the authors (2025) based on IBGE data (2024a).

According to Faria and Almeida (2016), economic growth, as measured by the evolution of GDP *per capita,* suggests an upward trend in various economic activities, including those that contribute to deforestation, such as soybean production and cattle raising. Consequently, the growth cycle, associated with greater income availability, generates an inducing effect, attracting new investments, which in turn leads to higher levels of deforestation (Alves, 2021).

Figure 10 shows the evolution of the value added by agriculture and livestock (in reais) throughout the period investigated. The values represent the total generated by municipalities engaged in agriculture and livestock for each biome. The results reveal that the Amazon recorded a consistent increase, from approximately 52 million in 2008 to 90 million in 2020. This rise can be partly explained by the expansion of the agricultural frontier, which, although it generates economic benefits, also raises concerns about deforestation and biodiversity loss.

The Caatinga also experienced an increase in added value. Although the biome has arid climatic conditions, it supports agriculture and livestock adapted to the environment, including the cultivation of xerophytic plants and goat farming. In the Cerrado, agricultural production has traditionally expanded, driven by the development of grain crops, particularly soybeans and corn, in addition to livestock growth. As a result, value added increased by 54.4% between 2008 and 2020.

Figure 10 – Brazil: Evolution of value added in agricultural activity (VAA) by biome between 2008 and 2020



Source: Prepared by the authors (2025) based on data from IBGE (2024a).

The Atlantic Forest showed a sharp and steady increase, probably due to its high level of urbanization. In contrast, the value added in the Pampa remained moderate, reflecting the particularities of the region, which is known for its slash-and-burn agriculture. Finally, the Pantanal recorded the smallest variation in the time interval considered, as agricultural activities in this biome are limited by its unique topography and ecology, with an emphasis on extensive livestock farming.

In summary, the evolution of GVA in Brazilian biomes reflects a scenario of economic growth, but it is important that this growth be accompanied by practices that minimize adverse environmental effects. Specifically, proper soil and water management, the preservation of natural areas, and investments in sustainable agricultural technologies are essential to promote both productive and sustainable agriculture.

5 FINAL CONSIDERATIONS

This study aimed to broaden the debate in the literature on deforestation by presenting an overview of all Brazilian biomes from 2008 to 2020, as well as analyzing the evolution of environmental and socioeconomic indicators, seeking to understand how each biome responds to these indicators.

A fluctuation in deforestation levels was observed in the Amazon and Cerrado biomes, revealing an alarming situation. This reinforces the need for public policies that promote the mitigation of these effects, given that these biomes are essential for global climate regulation. It is worth noting that, in Brazil, the Cerrado biome is still predominantly perceived as an agricultural frontier, rather than an area to be preserved. This perception is confirmed when analyzing the values of planted area and livestock, in which the biome stands out as the most conducive to agricultural production. However, it is important to remember that this production comes at the cost of high levels of deforestation.

With regard to climate variables, the Caatinga exhibited high temperatures and low rainfall, reflecting the fact that most of its municipalities are located in the semi-arid region. The conclusion is that this region lacks adequate policies to cope with the prolonged periods of drought characteristic of the area. The Amazon biome, in turn, recorded worrying values for temperature and precipitation, suggesting that the high levels of deforestation in this region are contributing to these variations and driving severe climate change.

In socioeconomic terms, it was observed that most of the population is concentrated in the Atlantic Forest region, a biome that includes municipalities along the Brazilian coast, where urbanization is higher. This biome also exhibited greater aggregate production in agriculture and livestock, as well as in the overall economic output. However, it is worth emphasizing that, to achieve effective sustainable development, it is essential to consider how this region has been impacted by deforestation levels.

Undoubtedly, it is important to implement measures that promote awareness of biome preservation and the adoption of sustainable practices. Moreover, it is essential to invest in scientific research aimed at developing sustainable technologies, as well as management and conservation practices tailored to each biome. Finally, it is crucial to strengthen and rigorously enforce existing environmental laws, in addition to proposing new legislation that addresses the specific particularities and needs of each Brazilian biome.

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