

## DEFORESTATION AND LAND USE CONFLICT IN THE ATLANTIC FOREST (BAHIAN HYLEA): A SPATIOTEMPORAL ANALYSIS

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### ABSTRACT

Deforestation in the Atlantic Forest of Bahia is associated with socioeconomic and environmental drivers. The remaining forest cover remains below the threshold required to ensure long-term conservation. Climate change and persistent social inequalities intensify these pressures. This study analyzes public data from 189 municipalities in the state of Bahia, integrating environmental and socioeconomic variables. Statistical analyses were conducted in RStudio, applying normality and correlation tests to identify patterns and relationships among variables. Spearman's rank correlation coefficient was used to evaluate temporal trends and associations among variables. The results demonstrate a strong association between deforestation and the expansion of cattle ranching and pasture areas. This relationship weakens over time, as the correlation between livestock, pasture, and deforestation decreases from 0.52 to 0.26 in 2023, indicating shifts in land use dynamics. Urban dynamics and agricultural expansion also influence deforestation patterns, which increased from 0.87% in 2004 to 0.91% in 2023, consistent with demographic census data, with correlation coefficients of 0.24 and 0.22.

**Keywords:** Forest conservation. Environmental impact. Agricultural census. Biodiversity. Land cover change.

### DESMATAMENTO E CONFLITO DE USO DA TERRA NA MATA ATLÂNTICA (HILÉIA BAIANA): UMA ANÁLISE ESPAÇO TEMPORAL

### RESUMO

O desmatamento na Mata Atlântica da Bahia associa-se a fatores socioeconômicos e ambientais. A cobertura florestal remanescente permanece abaixo do limiar considerado necessário para garantir sua conservação a longo prazo. Além disso, as mudanças climáticas e as persistentes desigualdades sociais intensificam as pressões ambientais.

Para compreender essas dinâmicas, esta pesquisa analisou dados públicos de 189 municípios do estado da Bahia, que incluíram variáveis ambientais e socioeconômicas. As análises estatísticas ocorreram no RStudio, com aplicação de testes de normalidade e de correlação para identificar padrões e relações entre as variáveis. O coeficiente de correlação de Spearman avaliou as tendências temporais e as associações entre as variáveis. Os resultados indicaram forte associação entre o desmatamento e a expansão da pecuária e das áreas de pastagem. Entretanto, essa relação enfraqueceu ao longo do tempo, pois a correlação entre pecuária, pastagem e desmatamento reduziu-se de 0,52 para 0,26 em 2023, indicando mudanças no uso da terra. A dinâmica urbana e a expansão agrícola também influenciaram os padrões de desmatamento, que passaram de 0,87% em 2004 para 0,91% em 2023, em consonância com os dados dos censos demográficos, cujos coeficientes foram de 0,24 e 0,22.

**Palavras-chave:** Conservação florestal. Impacto ambiental. Censo agrícola. Biodiversidade. Mudança na cobertura do solo.

## INTRODUCTION

The Atlantic Forest has a history of deforestation directly linked to the arrival of Europeans in Brazil (since the 16th century) and the subsequent predatory economic cycles (Guedes Pinto and Voivodic, 2021). In the central portion of the Atlantic Forest, specifically the southern region of the state of Bahia (Hiléia Baiana), 500 years of colonization and successive economic cycles (Brazilwood, sugarcane, cassava flour, timber, and cocoa) have substantially reduced and degraded the native vegetation. However, these forests still serve as refuges for the regional biota inhabiting the few remaining forest patches and the complex mosaic of land covers and land uses that characterize the dominant human-modified landscape (Faria et al., 2021).

Brazil is one of the four tropical countries with the largest deforested areas (Ayad et al., 2024). Although these countries share extensive tropical forest ecosystems, the historical and socioeconomic drivers of deforestation differ considerably among them. In Brazil, forest loss has historically been associated with the expansion of cattle ranching, large-scale agriculture, especially soybean production, and infrastructure development, particularly in the Amazon and Atlantic Forest regions. In Indonesia, deforestation has been strongly linked to the expansion of oil palm cultivation and industrial logging since the late twentieth century.

In the Democratic Republic of the Congo, forest loss is more closely related to subsistence agriculture, fuelwood and charcoal production, and rapid population growth, reflecting different development pressures. In Bolivia, deforestation has increased in recent decades mainly due to agricultural expansion, cattle ranching, and the use of fire for land clearing. These contrasting trajectories demonstrate that, although tropical deforestation is a global environmental concern, its underlying historical processes, economic drivers, and governance challenges vary significantly across countries.

Deforestation driven by the expansion of pastures and agriculture, infrastructure development, urbanization, and political and financial incentives for land occupation are the main drivers of land cover and land use changes in Brazilian biomes, affecting biodiversity, water resources, carbon emissions, and regional and local climate conditions (Parras et al., 2024). The biomes under the greatest pressure are the Amazon (419 Mha, 49% of the country) and the Cerrado (203 Mha, 23% of the country) (Rausch et al., 2019). However, the Atlantic Forest (111 Mha, or 13% of the country) is the Brazilian biome that has undergone extensive land-use change since the colonial period of the 16th century (Souza et al., 2020).

The Atlantic Forest biome is home to 70% of the Brazilian population and contributes to 80% of the national economy, encompassing major urban centers and industries and supporting most of the country's food production (Marques and Grelle, 2021), which depends on its critically threatened ecosystem services. It is also connected to global markets through the trade of commodities such as sugar, coffee, orange juice, and orange pulp (Guedes Pinto, 2021). In addition, annual water assessments indicate reductions in water availability of 83%, 73%, and 67% for the periods 2011–2040, 2041–2070, and 2071–2099, respectively; and reductions of 59%, 53%, and 65% under other modeled scenarios (Alvarenga et al., 2018). These findings suggest that climate change may affect the water balance in various ways, including changes in evapotranspiration, soil moisture, human health, ecosystem stability, natural disasters, and the availability of water, food, and energy.

Halting deforestation and promoting ecosystem restoration are essential for mitigating climate change and achieving the target of limiting global temperature rise to 1.5°C, as established in the Paris Agreement (Seddon et al., 2021). Poverty and the severe loss of natural vegetation, as observed in the Atlantic Forest domain, interact negatively with climate change. Societies facing scarcity of natural resources are the least resilient to climate impacts, and low-income populations are the most vulnerable (Srivastav et al., 2021). Therefore, given the combination of declining natural resources and low standards of human well-being, it is unsurprising that parts of the Brazilian Northeast and the metropolitan regions of Rio de Janeiro, São Paulo, and Belo Horizonte are identified as socio-climatic hotspots (Guedes et al., 2023), while the Atlantic Forest is classified as one of the three biodiversity hotspots most vulnerable to climate change (Wilson et al., 2021).

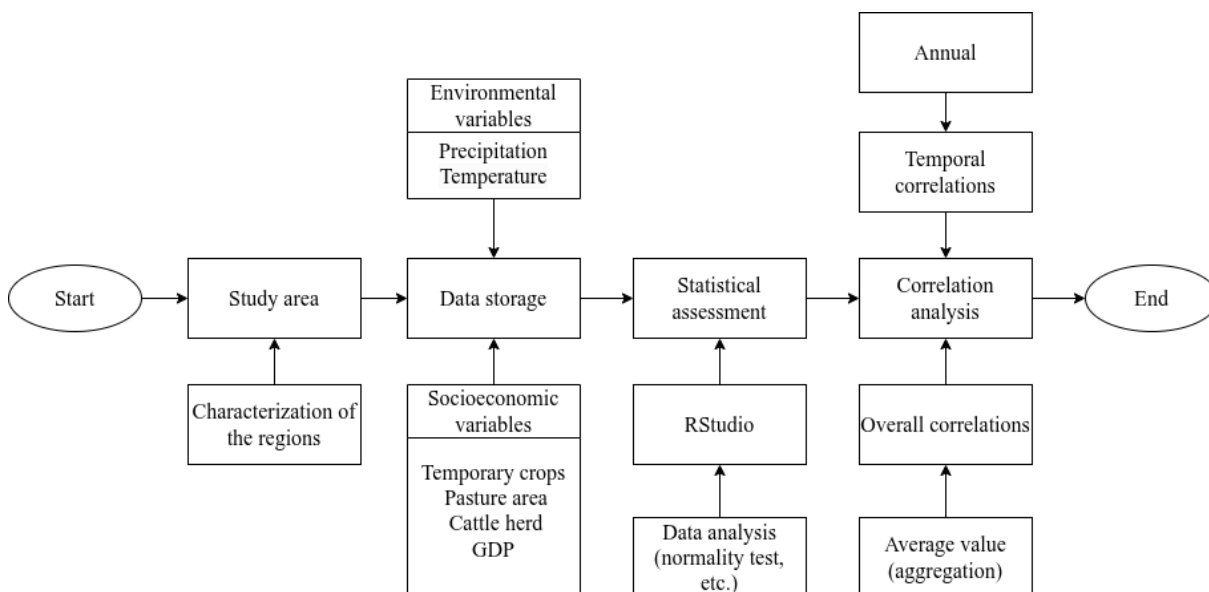
Socio-environmental and climate vulnerability has been widely discussed within the framework of the 2030 Agenda, which serves as a guiding reference for mitigating these impacts. The Sustainable Development Goals (SDGs), established under the global pact adopted in 2015 and reaffirmed in 2022, constitute the core of the 2030 Agenda, which comprises 17 goals and 169 targets. Among them, Goal 15, “Life on Land”, stands out for promoting the conservation, restoration, and sustainable use of natural resources. More broadly, the SDGs seek to restructure consumption patterns and guide the transformation of production systems based on principles of social responsibility and environmental stewardship, thereby contributing to the mitigation of anticipated environmental changes (Kasinathan, 2022).

Given this context, this study aims to evaluate deforestation in the Atlantic Forest biome and its correlation with socio-environmental and economic factors in the study area through a spatiotemporal assessment. The research seeks to contribute to the identification of economically viable strategies and practices for sustainable agricultural activities that help mitigate environmental impacts, particularly regarding water resource management and climate change.

## METHODOLOGY

For this study, an approach was adopted that began with the definition of the study area and the characterization of the regions involved. Next, socioeconomic and environmental variables were collected from publicly available databases. The data were then statistically analyzed using RStudio, version 2024.09.0+375. The analysis concluded with a two-stage correlation assessment: overall correlation and temporal correlation, complemented by an evaluation of land cover and land use (Figure 1).

Figure 1 - Methodology flowchart, 2025.

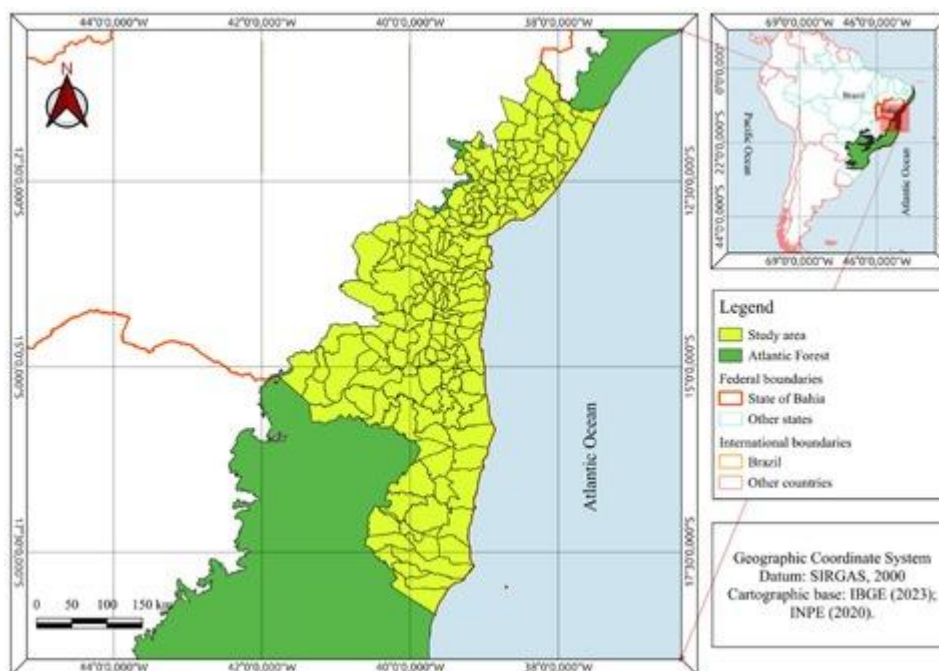


Source: The authors (2025).

### Study area

The study area comprises 189 municipalities in the state of Bahia, grouped into 12 regions (Figure 2): Lower South, Discovery Coast, Extreme South, South Coast, North Coast and Agreste of Bahia, Middle Rio de Contas Region, Middle Southwest of Bahia, Salvador Metropolitan Region, Portal do Sertão, Recôncavo of Bahia, and Vale do Jiquiriçá. Together, these regions cover approximately 125,569 km<sup>2</sup> (IBGE, 2023).

Figure 2 - Illustration of the location of the Atlantic Forest in the state of Bahia, 2025.



Source: The authors (2025).

In the Extreme South region, the Descobrimento, Monte Pascoal, and Pau-Brasil National Parks stand out, collectively protecting approximately 50,000 hectares of native forest. In the South Coast region, areas such as Ilhéus and Itacaré contain significant Atlantic Forest remnants, including the Serra do Conduru State Park. This region concentrates high levels of biodiversity and endemism and plays a critical role in the conservation of endangered species (RBMA, 2024).

In the North Coast and Agreste of Bahia, urbanization and agricultural expansion affect forest remnants; however, the remaining Atlantic Forest fragments continue to play essential roles in biodiversity conservation and ecosystem service provision. The Lower South region contains remnants that are critical for the conservation of local flora and fauna, particularly in areas such as the Pre-Coastal Plateau. The presence of traditional communities and agroforestry systems, such as cabruca cocoa cultivation, contributes to the preservation of native vegetation and supports the regional economy.

In the Middle Rio de Contas Region, which includes municipalities such as Jequié and Ipiaú and borders the Lower South, Vale do Jiquiriçá, and South Coast regions, Atlantic Forest fragments support biodiversity conservation and protect water resources that supply local populations.

In the Recôncavo of Bahia, encompassing areas surrounding All Saints' Bay, the Atlantic Forest persists in fragmented landscapes that contribute to environmental stability and the quality of life of local communities. Urban and industrial pressures in these areas intensify the need for conservation and restoration policies aimed at preserving ecosystems and ensuring the sustainable use of natural resources.

### Dataset

The socioeconomic and environmental variables associated with deforestation were analyzed for the period 2004–2023, based on annual records from 189 municipalities in Bahia. The dataset included deforested area, pasture area, temporary crop area, cattle herd size, Gross Domestic Product (GDP), precipitation, and average temperature.

The areas of deforestation, pasture, and temporary crops were expressed in km<sup>2</sup>, while precipitation was recorded in mm, temperature in degrees Celsius (°C), cattle herd size as number of head, and GDP in Brazilian reais (R\$).

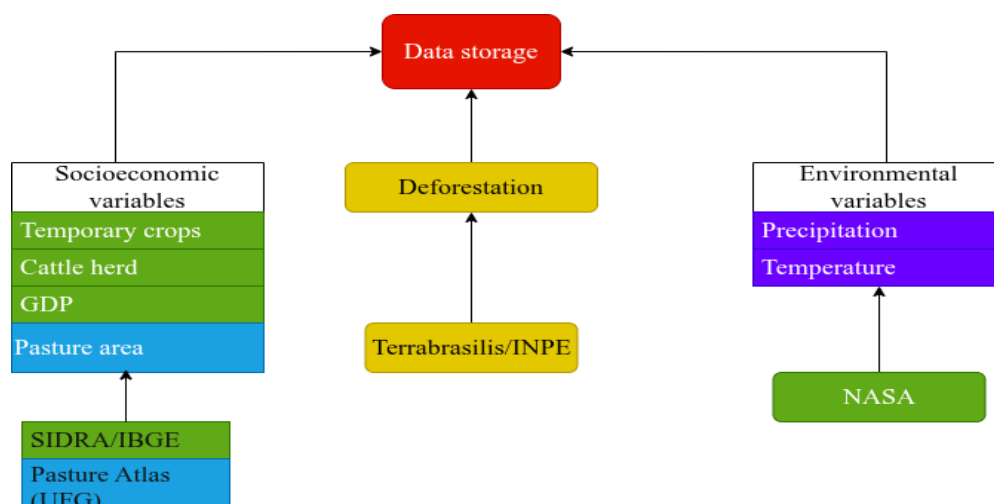
The database was structured with annual information by municipality and includes data on temporary crops (pineapple, cotton, garlic, peanuts, rice, oats, sweet potato, potato, sugarcane, onion, barley, peas, beans, tobacco, sunflower, castor bean, cassava, watermelon, melon, corn, soybean, sorghum, tomato, and wheat), in addition to cattle herd size and GDP, obtained from the platform of the Brazilian Institute of Geography and Statistics (IBGE) through the SIDRA system. Pasture area data were obtained from the Atlas of Pastures of Brazil, developed by the Image Processing and Geoprocessing Laboratory of the Federal University of Goiás.

Absolute values were used to assess the relationship between the magnitude of deforestation and the socioeconomic and environmental variables associated with municipal production dynamics. Although larger municipalities may present higher absolute values, this approach allows the identification of patterns of anthropogenic pressure and agricultural expansion over time.

Climate data were obtained from the NASA Prediction of Worldwide Energy Resources (NASA POWER) database, which provides time series derived from the assimilation of satellite observations and global atmospheric models, with an approximate spatial resolution of 0.5° × 0.5° (~50 km). These data present reliable accuracy for variables such as temperature, with mean errors estimated between 1 and 2 °C, and are widely applied in regional climate analyses (NASA POWER, 2026). This study uses representative municipal-scale averages without applying additional downscaling procedures.

Deforestation data were collected from the TerraBrasilis platform of the National Institute for Space Research (INPE), made available through the Satellite Deforestation Monitoring Project (Figure 3). In addition, forestry data (2014–2023, in km<sup>2</sup>) and census population data for the years 2010 and 2022 were also obtained from the SIDRA/IBGE platform. It should be noted that these data were treated differently according to their temporal availability. Forestry information was correlated with deforestation data for the same time interval (2014–2023), allowing a joint analysis of the variables over the period. Population data, in turn, were analyzed separately and correlated with the deforestation values corresponding to those years (2010 and 2022). Therefore, no interpolation was performed for the intermediate years in order to avoid introducing artificial estimates into the time series.

Figure 3 - Data acquisition flowchart, 2025



Source: The authors (2025).

### **Statistical Evaluation**

To avoid ambiguity regarding the nature of the correlation analyses, it is important to clarify that this study distinguishes between spatial and temporal approaches. First, a general spatial correlation analysis was performed using values aggregated over the entire study period (2004–2023). At this stage, mean values of deforestation and the socioeconomic and environmental variables were calculated for each municipality, and Spearman's correlation coefficient was applied to these aggregated values. This procedure aimed to identify overall spatial patterns of association among municipalities, rather than temporal dynamics, allowing the assessment of how areas with higher deforestation are spatially associated with specific land-use, economic, and environmental characteristics.

Second, a year-by-year correlation analysis was conducted to evaluate temporal variations in the relationship between deforestation and the explanatory variables. Correlations were calculated annually, considering all municipalities simultaneously for each specific year. This method does not represent a classical time-series correlation with temporal lags, but rather a temporal comparison of spatial correlations, enabling the identification of changes in the strength and direction of associations over time. Finally, a spatiotemporal analysis of land cover and land use was carried out based on MapBiomas data for selected years (2004, 2014, and 2023). This analysis was descriptive and comparative in nature, focusing on spatial patterns and temporal changes in land-use classes, and was not directly integrated into the statistical correlation procedures.

In RStudio, the data were organized into a dataframe, excluding regional divisions so that the results would reflect deforestation across the entire study area. Data processing followed the approach proposed by Bizarrias, Silva, and Penha (2023), who emphasize the importance of preliminary steps before conducting statistical analyses. These steps included the analysis of missing values, identification of outliers, and assessment of variable normality.

For variables with missing values, imputation was performed using the median, replacing missing observations with the median of the respective variable within each time series. This method was adopted because of its robustness against extreme values, which are frequently observed in environmental and socioeconomic datasets, preserving the central tendency without introducing significant distortions into the data distribution.

To reduce the influence of extreme values and differences in scale, the logarithmic transformation  $\log(x + 1)$  was applied. This transformation is widely used in environmental and economic analyses to attenuate asymmetrical distributions and stabilize variance, thereby making the data more suitable for subsequent statistical analyses.

Next, outlier values were identified in the analyzed variables. Detection was performed through graphical analysis using boxplots and by applying the interquartile range (IQR) method, which is widely employed in exploratory data analysis.

However, considering that the study involves socioeconomic and environmental variables associated with municipalities presenting different levels of development, it was decided not to automatically remove values identified as outliers. In studies addressing deforestation and territorial dynamics, extreme values may represent actual characteristics of the analyzed system, such as municipalities with high agricultural production or regional economic centers.

Discrepant values were individually evaluated regarding their territorial representativeness and retained whenever they reflected actual conditions. For example, high GDP values in specific municipalities were interpreted as the result of concentrated economic activity rather than measurement error. These values were therefore preserved in the analysis to avoid distorting spatial patterns relevant to understanding deforestation dynamics.

To assess data normality, the Shapiro–Wilk test and visual analyses using histograms and Q–Q plots were employed. According to Nascimento (2024), the Shapiro–Wilk test demonstrates high sensitivity in detecting deviations from normality, maintaining good performance even with small sample sizes.

**Correlation Analysis between Deforestation and Socioeconomic and Environmental Variables** In addition to the correlation calculations, a visual analysis of annual fluctuations and overall relationships among the variables was conducted. Correlation graphs were generated using packages

such as ggplot2 and corrplot, visually representing the relationship between deforestation and the variables under study.

A spatiotemporal analysis was also performed based on spatial and statistical data on land cover and land use from Collection 9 of the MapBiomas project for the years 2004, 2014, and 2023. The data were organized into spreadsheets and expressed as percentages of land cover and land-use classes, allowing a comparative analysis across the different periods. Data processing and analysis were carried out in RStudio (R Core Team, 2024), combining quantitative and visual approaches to support the interpretation of territorial dynamics over time.

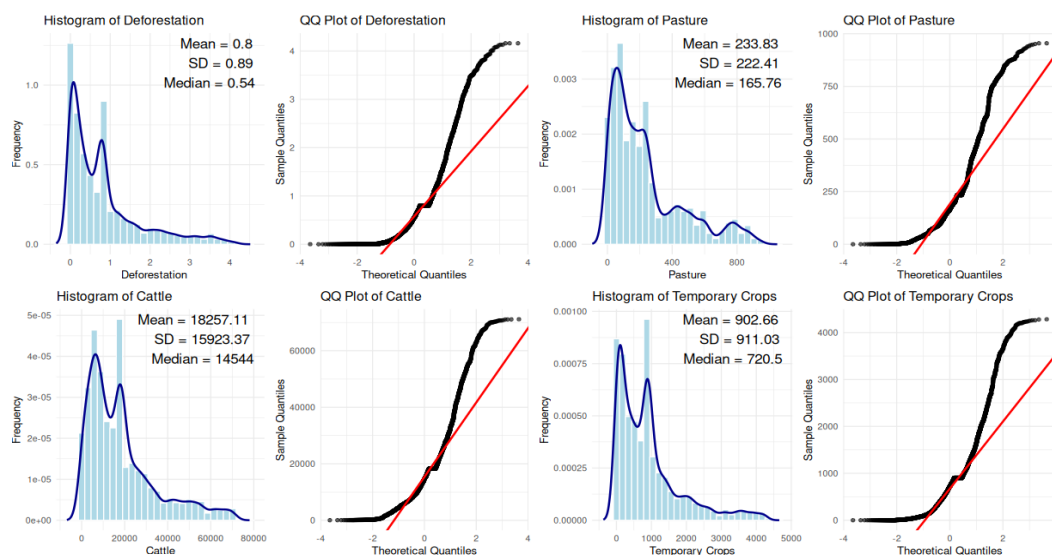
The land cover and land-use classes analyzed included areas of native vegetation, such as Forest Formation and Savanna Formation, as well as anthropogenic areas, such as Pasture, Forest Plantation, Mosaic of Uses, and Urban Infrastructure. Percentage variations between years were calculated for each class, enabling the evaluation of expansions or reductions in each category over time. This approach revealed patterns of native vegetation loss and increases in land uses associated with economic activities such as agriculture, livestock, and forestry.

This analysis contributed to a deeper understanding of land-use and land-cover dynamics in the Atlantic Forest region of Bahia, highlighting the impacts of deforestation and the intensification of productive activities on forest remnants.

## RESULTS AND DISCUSSION

The results of the Shapiro–Wilk test showed p-values lower than 0.05 and W statistics greater than 0.80 for all variables, indicating rejection of the null hypothesis of normality. This result was corroborated by visual inspection of histograms and Q–Q plots, which revealed the presence of asymmetry in the distributions (Figure 4).

Figure 4 - Histogram and Q-Q plot of socioeconomic variables, 2025



Source: the authors (2025).

In this context, Spearman's rank correlation coefficient was employed in both stages of the analysis due to its robustness to non-normal distributions and reduced sensitivity to extreme values. It is a non-parametric measure that assesses the strength and direction of associations between variables based on their ranks rather than their absolute values, making it particularly suitable for asymmetric datasets or datasets with heterogeneous distributions.

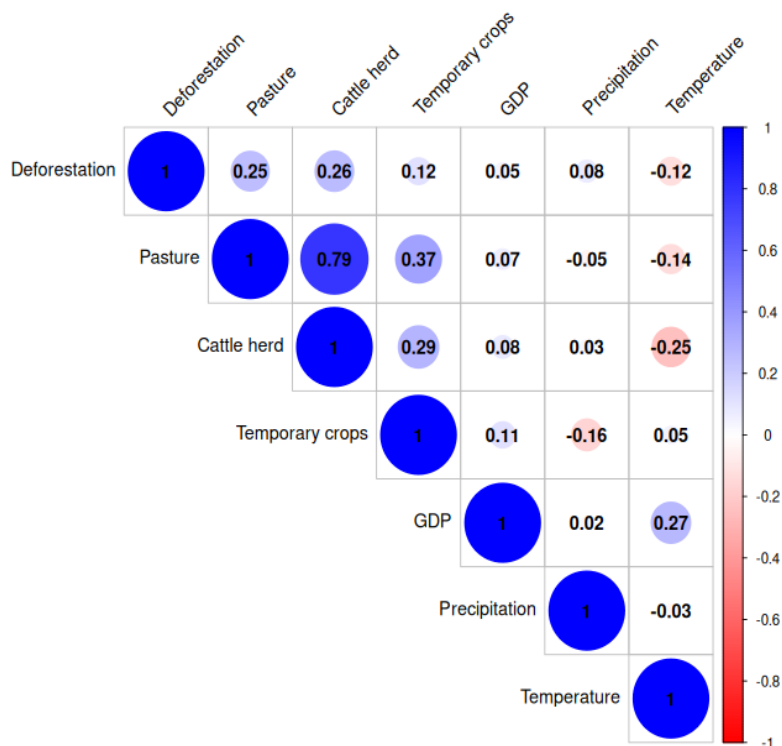
The analysis of missing data identified precipitation as the variable with the highest proportion of gaps, reflecting the difficulty of obtaining complete historical time series for this parameter. Studies addressing atmospheric phenomena and climatic processes require consistent and reliable time series

(Ruezzene et al., 2020). This study focuses on correlation analyses involving deforestation and associated variables. Therefore, the choice of imputation method directly affects the continuity and reliability of subsequent statistical inferences (Austin et al., 2021).

Moreover, according to Tatis, Corrente, and Fumes-Ghantous (2022), in distributions with strong asymmetry, values that exceed the upper or lower limits of a boxplot are often classified as outliers because they are distant from the center of the distribution. However, these values do not always represent actual statistical anomalies and should therefore be carefully reviewed before being removed or corrected. An example of this was identified in the GDP data, which presented the largest number of distant values. Nevertheless, a detailed review confirmed that these values were consistent with the dataset and therefore they were retained in the analysis.

In the spatial correlation analysis, low-magnitude correlation coefficients were identified; however, their statistical significance ( $p < 0.05$ ) should be emphasized. These results indicate weak yet consistent relationships, suggesting that deforestation in the Atlantic Forest of Bahia is a multifactorial process in which no single variable alone dominantly explains the phenomenon. Therefore, the identified associations should not be interpreted as strong causal relationships, but rather as general trends that, when analyzed together with the temporal and spatial approaches, contribute to a more comprehensive understanding of deforestation dynamics (Figure 5).

Figure 5 - Correlation between deforestation and socioeconomic and environmental variables in the Atlantic Forest biome in Bahia, 2025



Source: The authors (2025).

Although the correlation coefficients presented in Figure 5 are of low magnitude, they can be considered statistically significant due to the sample size and the use of Spearman's correlation coefficient, which is appropriate for non-normally distributed data. These values indicate weak but consistent associations, suggesting that deforestation in the Atlantic Forest of Bahia is a multifactorial process in which no single variable alone explains the phenomenon. Therefore, the results should not be interpreted as strong causal relationships, but rather as general trends that, when combined with

the temporal and spatial analyses, contribute to a more comprehensive understanding of deforestation dynamics.

One of the alternatives for public policies aimed at containing deforestation is the implementation of incentives for sustainable cattle ranching. Modern cattle-farming techniques have made it possible to increase productivity without expanding pasture areas. Among these strategies are feedlot systems, rotational grazing, and genetic improvement of herds (Baruselli et al., 2024). According to Telles et al. (2024), the evolution of Brazilian livestock production demonstrates that these advances are associated with adjustments in stocking density (i.e., the number of cattle per hectare), the gradual replacement of natural pastures with cultivated pastures, and the restoration of previously degraded areas.

Degraded pastures represent one of the main challenges for Brazilian agriculture, compromising productivity and contributing to pressure on natural areas. However, their recovery can transform these areas into opportunities to increase agricultural efficiency and encourage forest regeneration. According to Freitas (2022), the adoption of practices aimed at sustainable rural development, especially through Crop–Livestock–Forest Integration (CLFI), has proven effective in reducing the environmental impacts associated with the production sector.

Barros et al. (2023) emphasize that Brazil's agricultural sector operates below its potential, with productivity reaching only 32% to 34% of its maximum capacity. Thus, the use of more advanced agricultural and productive techniques would allow the allocation of more than 18 million hectares for restoration in the Atlantic Forest biome alone, exemplifying a viable strategy for the region analyzed in this study. Furthermore, maintaining a balance between ecosystem preservation and the generation of goods and services essential to social development is fundamental for long-term sustainability. However, this balance must consider the particularities of each regional landscape, adapting strategies to local environmental and productive conditions (Silva et al., 2025).

In this context, specific techniques such as intercropping can be especially effective in promoting more resilient and environmentally integrated production systems. According to Raveloaritiana et al. (2024), the positive effects of intercropping on agricultural yields and the conservation of natural resources can be enhanced when the expansion of this practice on a large scale is accompanied by policies that encourage new intercropping models, especially those that take advantage of the machinery already available on farms.

The Atlantic Forest in Bahia has been extensively studied, highlighting the substantial impact of deforestation on this biome. Although no consensus identifies Bahia as the state with the highest absolute deforestation, research consistently emphasizes the region's vulnerability. Guimarães et al. (2023) analyze this condition by evaluating the risks associated with the expansion of the economic frontier, particularly the implementation of projects such as Porto Sul, which intensify pressure on the remaining Atlantic Forest areas in southern Bahia.

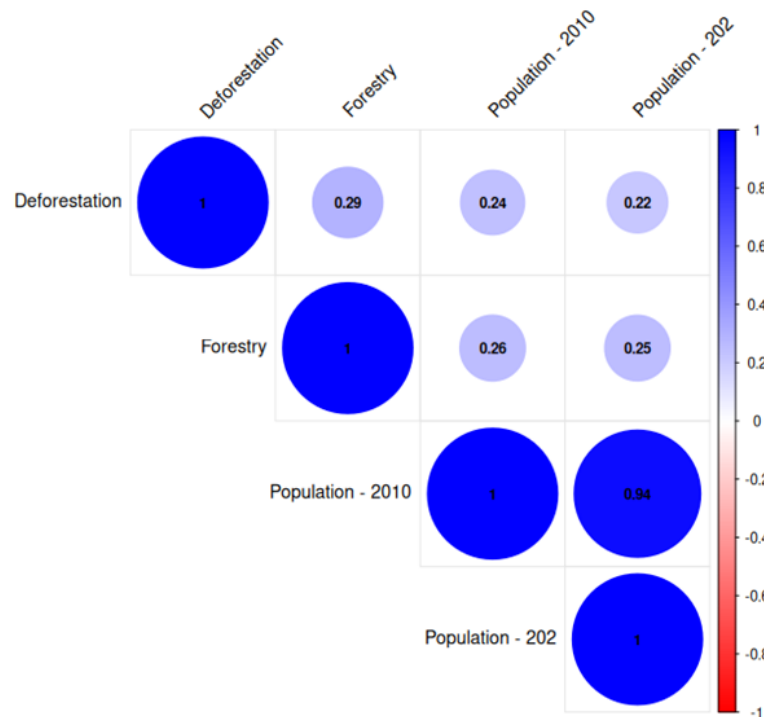
Another relevant point is the positive correlation between deforestation and temporary crop areas (0.12), indicating that fast-growing crops have occupied deforested areas to a lesser extent, although with a need for soil management and treatment. These temporary crops include a wide variety of species such as pineapple, cotton, garlic, peanuts, rice, oats, sweet potatoes, sugarcane, onions, beans, cassava, corn, soybeans, and tomatoes, among others. They are characterized by short production cycles, allowing land rotation and encompassing vegetables, grains, flowering plants, medicinal plants, and root crops.

In addition, there is a negative correlation between temperature and deforestation (-0.12), indicating that the advance of deforestation does not necessarily imply an increase in temperature in the Atlantic Forest biome in the state of Bahia. On the other hand, precipitation showed a positive correlation (0.08), suggesting that, in certain parts of the analyzed area, this variable may be influenced by the loss of vegetation cover. As highlighted by Silva et al. (2025), the Metropolitan Region of Salvador showed a strong correlation between deforestation and precipitation. However, it is important to emphasize that, for any robust inference regarding climate change, it would be necessary to analyze a historical series of at least 30 years, as established by Santos et al. (2022).

Forestry activity showed a positive correlation with deforestation, with a value of 0.29 (Figure 6). Much of this correlation is associated with the Extreme South and Discovery Coast regions, where a pulp-production industrial hub is located, with Suzano in the municipality of Mucuri and Veracel in the municipality of Eunápolis, while eucalyptus plantations extend throughout the region. According to

Oliveira et al. (2021), in 1996 eucalyptus cultivation, which had recently been introduced into the municipality of Eunápolis, occupied an area of 52.38 km<sup>2</sup>, whereas by 2018 this activity already covered 220.55 km<sup>2</sup>. The municipality of Mucuri, in turn, had 581.58 km<sup>2</sup> devoted to forestry activity in 2022 (IBGE, 2023).

Figure 6 - Evaluation of the correlation between forestry activity and the population census of 2010 and 2022 with deforestation, 2025



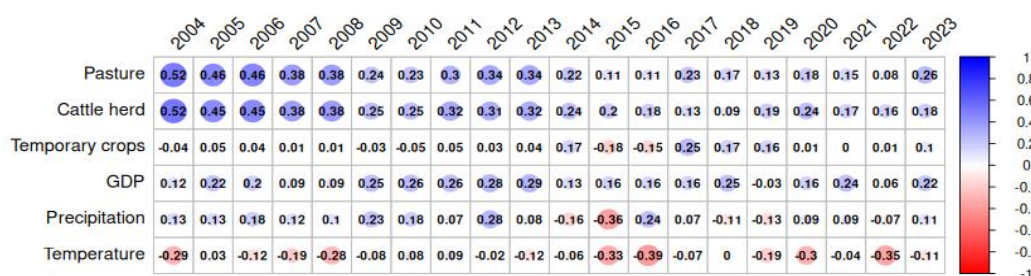
Source: The authors (2025).

The population census showed a positive correlation with deforestation in both 2010 and 2022, although a slight reduction was observed, from 0.24 to 0.22. Population growth is directly linked to increased deforestation, since population expansion increases the demand for housing, infrastructure, and natural resources. Urban and agricultural expansion into natural areas causes environmental degradation, driven by the demand for timber, pastures, and agricultural crops. In addition, regions with high population density exert greater pressure on fragile ecosystems, contributing to biodiversity loss and climate change. This correlation reinforces the urgency of sustainable policies capable of balancing human development and environmental preservation.

### Year-by-Year Correlation Analysis

The year-by-year analysis reveals a steady decline in the correlation between deforestation, pasture area, and cattle herd size over time. The correlation between pasture area and deforestation decreased from 0.52 in 2004 to 0.26 in 2023, while the correlation with cattle herd size declined from 0.52 to 0.18 during the same period (Figure 7). This reduction may be associated with the adoption of Integrated Crop–Livestock–Forestry (ICLF) systems, which promote more efficient use of already cleared land, thereby reducing the need for further agricultural expansion. Among the benefits of this system are improvements in soil fertility and the enrichment of organic matter with essential nutrients such as nitrogen, phosphorus, and sulfur (Denardin et al., 2025).

Figure 7 - Correlation analysis between socio-economic and environmental variables and deforestation, 2025.



Source: the authors (2025).

The integration of productive systems, such as ICLF, aims to optimize land use, increase productivity, and diversify agricultural output, ultimately generating higher-quality food. This approach also reduces the demand for new deforestation, fostering sustainability in agricultural practices through the efficient management of natural resources. Key benefits include soil conservation, biodiversity protection, and the preservation of water resources and landscapes, all of which contribute to greater environmental and productive stability (Freitas et al., 2022).

In addition, changes in land cover and land use within Bahia's Atlantic Forest were assessed for the years 2004, 2014, and 2023. Spatial analysis indicates a continuing process of fragmentation and reduction of native forest cover, represented by dark green areas on the maps. From 2004 to 2014, there was a marked loss of continuous forest cover, particularly in the north-central and coastal zones of the state, suggesting intensified deforestation. Between 2014 and 2023, although forest cover continued to decline, the rate of loss slowed, suggesting a reduction in the pace of direct forest conversion into other land-use categories. (Figure 8).

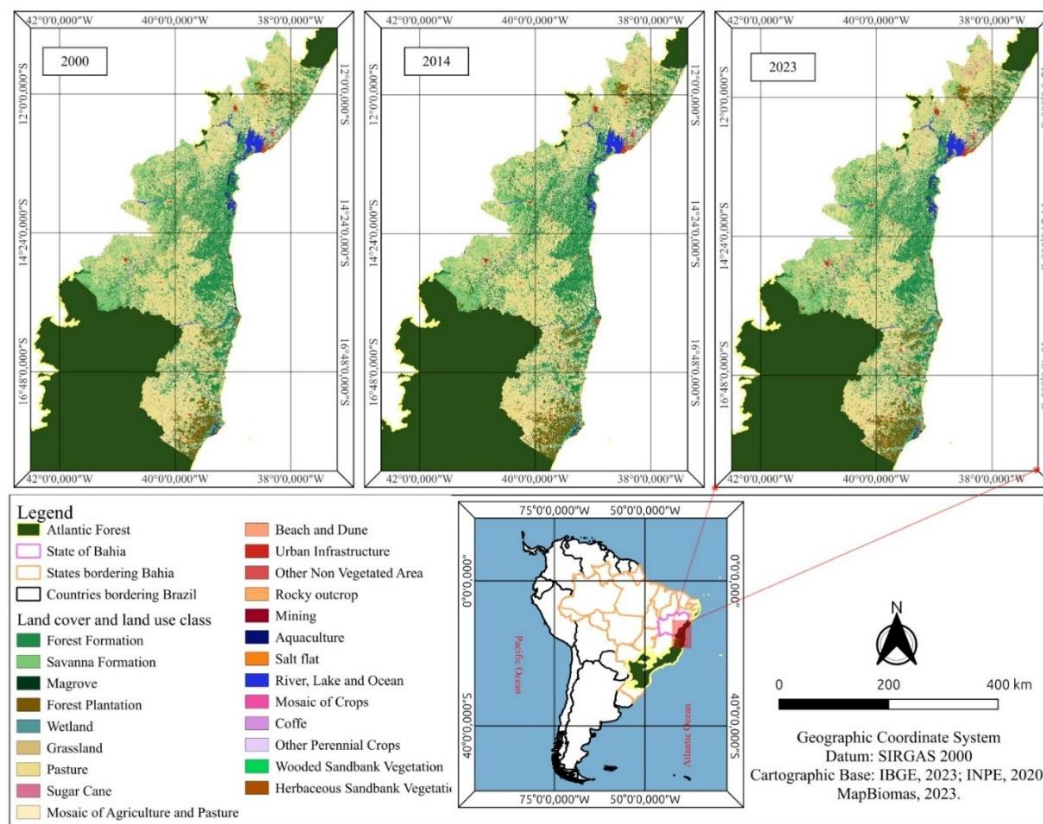
The replacement of native vegetation by other land uses, such as pasture, agriculture, and planted forests, emerges as one of the most significant transformations. Although pasture areas (depicted in light yellow) have declined over the years and remained relatively stable, they still reflect the historical impact of extensive cattle ranching on deforestation (Telles et al., 2024). Concurrently, there has been an increase in the extent of planted forests, which have gradually occupied larger portions of land previously covered by native vegetation (Silveira et al., 2022).

Brazil maintains the largest cattle herd in the world, exceeding 238 million head. Bahia ranks seventh nationally, with 13.3 million head (IBGE, 2024), of which 89% are raised exclusively on pasture (Berça et al., 2021). Agricultural expansion has intensified, particularly for temporary and perennial crops such as coffee and sugarcane in southern and southwestern Bahia, regions historically associated with commercial agriculture (Guimarães et al., 2023). This dynamic reflects the advance of agribusiness and the resulting economic pressure on ecologically valuable areas, especially in transition zones between forest cover and consolidated agricultural lands (Lucas et al., 2023).

Another noteworthy trend is the growth of areas classified as "mosaic of uses," which describe complex landscapes composed of small fragments of native vegetation interspersed with pasturelands, crops, and other land uses. This spatial pattern reflects forest fragmentation processes that, although preserving partial vegetation cover, undermine the ecological integrity of ecosystems and hinder biodiversity conservation and the maintenance of ecosystem services. Urban areas have also expanded, albeit less dramatically, particularly along the coastline, adding further pressure on the remaining forest fragments.

Temporal analysis further highlights the persistence of areas subject to intensive use, such as mining and aquaculture, concentrated in specific regions. This points to the diversification of anthropogenic pressures on the biome. Despite signs of a recent slowdown in deforestation, the findings reinforce the urgent need to implement conservation and forest restoration strategies, particularly in areas critical to ecological connectivity. Strengthening environmental policies, enforcing land-use regulations, and promoting agroecology and sustainable agroforestry systems are key actions that could help mitigate the observed impacts and support the long-term conservation of Bahia's Atlantic Forest (Studer et al., 2023).

Figure 8 - Land cover and land use in the Atlantic Forest region of Bahia, 2025



Source: the authors (2025).

The quantitative assessment of land cover between 2004, 2014, and 2023 supports the change patterns already identified in the spatial analysis. The “Forest Formation” class, which represents the more preserved remnants of the Atlantic Forest, remained relatively stable, changing only slightly from 26% in 2004 to 25.96% in both 2014 and 2023. However, this apparent stability may conceal internal degradation processes or replacement by secondary vegetation. In contrast, the “Savanna Formation” class experienced a consistent decrease, from 10.88% in 2004 to 10.73% in 2014 and 10.78% in 2023, indicating pressure on transitional ecosystems between the Atlantic Forest and the Cerrado. (Table 1).

Table 1 - Land Cover and Land Use in the Atlantic Forest Region of the State of Bahia, 2025

Class	Area in % (2004)	Area in % (2014)	Area in % (2023)
Forest Formation	26.00	25.96	25.97
Savanna Formation	10.88	10.73	10.78
Mangrove	0.54	0.56	0.55
Forest Plantation	3.12	4.53	5.28
Wetland	1.42	1.45	1.32
Grassland (Pastizal, Formación Herbácea)	0.00	0.00	0.00

Pasture	43.31	42.10	40.59
Mosaic of Agriculture and Pasture	11.72	11.49	11.74
Beach and Dune	0.06	0.06	0.10
Urban Infrastructure	0.71	0.88	1.04
Other Non-Vegetated Area	0.03	0.02	0.07
Rocky outcrop	0.05	0.05	0.05
Mining	0.00	0.01	0.02
Aquaculture	0.01	0.01	0.01
Salt flat	0.05	0.04	0.03
River, Lake and Ocean	1.75	1.57	1.68
Mosaic of Crops	0.02	0.08	0.23
Coffee	0.12	0.23	0.28
Other Perennial Crops	0.00	0.00	0.01
Wooded Sandbank Vegetation	0.14	0.14	0.14
Herbaceous Sandbank Vegetation	0.12	0.12	0.12
Sugar Cane	-	0.00	0.03

Source: the authors (2025).

The presence of agricultural mosaics and temporary crops remained relevant throughout the study period. The Agricultural Mosaic class showed relative stability, varying only slightly from 11.72% in 2004 to 11.74% in 2023, indicating the persistence of this land-use pattern in the region. In contrast, an increase in specialized crops, such as coffee, was observed, with the cultivated area rising from 0.12% to 0.23% over the same period, evidencing an intensification of this type of cultivation. Sugarcane, although still representing a small fraction of the landscape, increased from 0.0001% in 2014 to 0.0258% in 2023 (values in the table were rounded), which may indicate an initial process of expansion of this crop in the study area.

Urban and infrastructure areas also showed growth during the analyzed period, increasing from 0.87% in 2004 to 0.91% in 2023. This trend reflects urban expansion within the Atlantic Forest, especially near the coast and urban centers. Other land-cover types, such as mangrove forests and wetlands, remained relatively stable, which may indicate some degree of legal protection or greater difficulty in converting these areas to other uses.

It is also important to highlight the expansion of planted forests and commercial agriculture over former natural areas, as evidenced by the increase in the "Planted Forest" class and crops such as coffee. This pattern indicates the replacement of native vegetation by more intensive economic land uses, which may result in biodiversity loss and habitat fragmentation, even though the total percentage values for Forest Formation appear relatively stable. This type of expansion continues to occur,

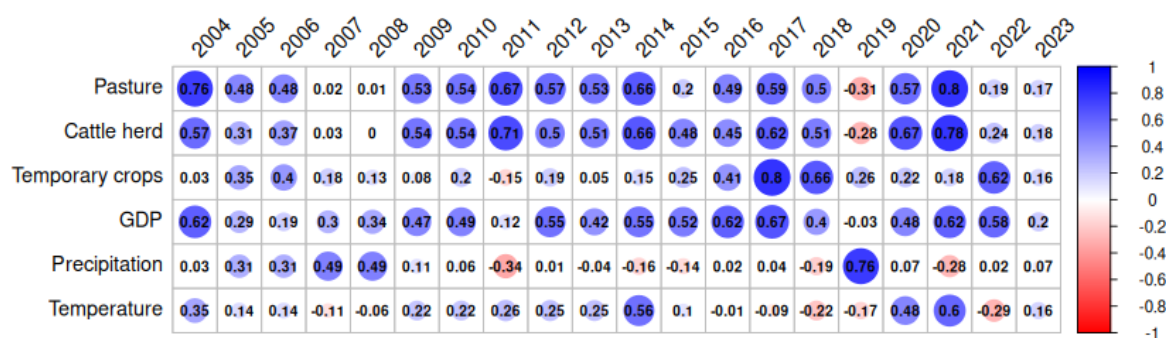
especially with the increase in plantations located near pulp and paper industries (Silveira et al., 2022).

The dynamics identified in this study present elements consistent with forest transition theory. Land-cover and land-use data indicate relative stability or partial recovery of native vegetation over the analyzed period. Forest Formation decreased only slightly, from 26.00% of the area in 2004 to 25.97% in 2023, maintaining a similar level of coverage. However, secondary vegetation within the analyzed area increased from 16.25% in 2004 to 16.63% in 2023. This pattern occurred simultaneously with the reduction of pasture areas, which declined from 71.10% in 2004 to 68.54% in 2023, indicating changes in land cover, land use, and economic dynamics, also identified by Silva et al. (2025). This stabilization in forest loss, associated with changes in the productive structure, suggests an intermediate stage of the forest transition process, characterized by a reduction in the direct conversion of forests into agricultural land, as discussed by Carvalho, Silva, and Souza (2024), Silva et al. (2025), and Souza et al. (2026).

In addition, elements associated with the land-sparing strategy can be identified, which is based on intensifying production in already converted areas while maintaining natural ecosystems. In this dataset, the Forest Formation class remained relatively stable throughout the analyzed period, decreasing from 26% in 2004 to 25.96% in 2023. In contrast, pasture areas showed a gradual reduction, declining from 43.31% in 2004 to 40.59% in 2023. At the same time, specialized agricultural uses expanded, such as coffee cultivation, which increased from 0.12% to 0.23% during the analyzed period, in addition to the expansion of planted forests, which grew from 3.12% in 2004 to 5.28% in 2023. These results indicate a reorganization of land cover and land use, as well as greater productive intensification in previously converted areas, a dynamic associated with the principles of land sparing, according to Silva et al. (2025), Silva Junior et al. (2025), and Souza et al. (2026).

After analyzing land cover and land use, it was identified that the Middle Southwest region presented the highest levels of Atlantic Forest deforestation in the state of Bahia, totaling 1,783.4 km<sup>2</sup> during the analyzed period. According to Silva et al. (2025), this region shows positive correlations between cattle herd size and deforestation, with coefficients ranging from 0.31 to 0.78, demonstrating the association between herd expansion and the intensification of forest-cover loss. Agricultural crops also showed positive correlations with deforestation, although with lower intensity, with coefficients ranging from 0.03 to 0.62. These results indicate that agricultural activity also contributes to this process, although less substantially when compared with livestock farming (Figure 9).

Figure 9 - Correlations with the Atlantic Forest deforestation of the Bahia Southwest Middle, 2025.



Source: Silva et al., 2025. Adaptation: the authors, 2025.

In the Middle Southwest region of Bahia, between 2004, 2014, and 2023, spatial transformations associated with deforestation dynamics and the replacement of native vegetation by anthropogenic land uses were identified, especially those related to extensive livestock farming. Although the data indicate relative stability in the proportion of the “Forest Formation” class, which increased slightly from 16.25% in 2004 to 16.63% in 2023, these results should be interpreted with caution. The maintenance of forest cover does not necessarily represent the effective conservation of native vegetation, since the mapping does not distinguish between primary and secondary forests or between degraded

fragments and well-preserved areas. Furthermore, this apparent percentage stability may mask ongoing fragmentation processes and biodiversity loss, with significant impacts on the ecological integrity of the Atlantic Forest biome.

The main anthropogenic land use identified in the region is pasture, which occupied 71.10% of the area in 2004 and decreased to 68.54% in 2023. This predominance indicates that extensive livestock farming remains the principal driver of landscape transformation, contributing to deforestation and hindering the natural regeneration of native vegetation.

The land-cover and land-use dynamics identified in the Middle Southwest region of Bahia present characteristics consistent with the land-sharing model, in which agricultural production occurs within fragmented landscapes that coexist with remnants of native vegetation. Forest Formation increased between 2004 and 2023, rising from 16.25% to 16.63% of the total area. During the same period, land cover and land use remained predominantly associated with livestock production, with 71.10% of the area occupied by pasture in 2004 and 68.54% in 2023. The Land-Use Mosaic class increased from 5.82% to 7.40%, indicating growing heterogeneity in land cover and land use. This spatial pattern characterizes landscapes in which agricultural activities coexist with forest fragments, forming productive mosaics associated with the land-sharing concept (Table 2).

Table 2 - Land coverage and use in the Atlantic Forest in the Bahia Southwest Middle, 2025

Class	Area in % (2004)	Area in % (2014)	Area in % (2023)
Forest Formation	16.25	16.40	16.63
Savanna Formation	6.32	6.78	6.87
Wetland	0.00	0.00	0.00
Pasture	71.10	69.40	68.54
Mosaic of Agriculture and Pasture	5.82	7.01	7.40
Urban Infrastructure	0.19	0.24	0.26
Other Non-Vegetated Area	0.00	0.00	0.02
Mining	0.00	0.00	0.00
River, Lake and Ocean	0.25	0.13	0.15
Mosaic of Crops	0.00	0.00	0.00
Coffee	0.04	0.06	0.09
Other Perennial Crops	0.00	0.00	0.01
Forest Plantation	-	-	0.02

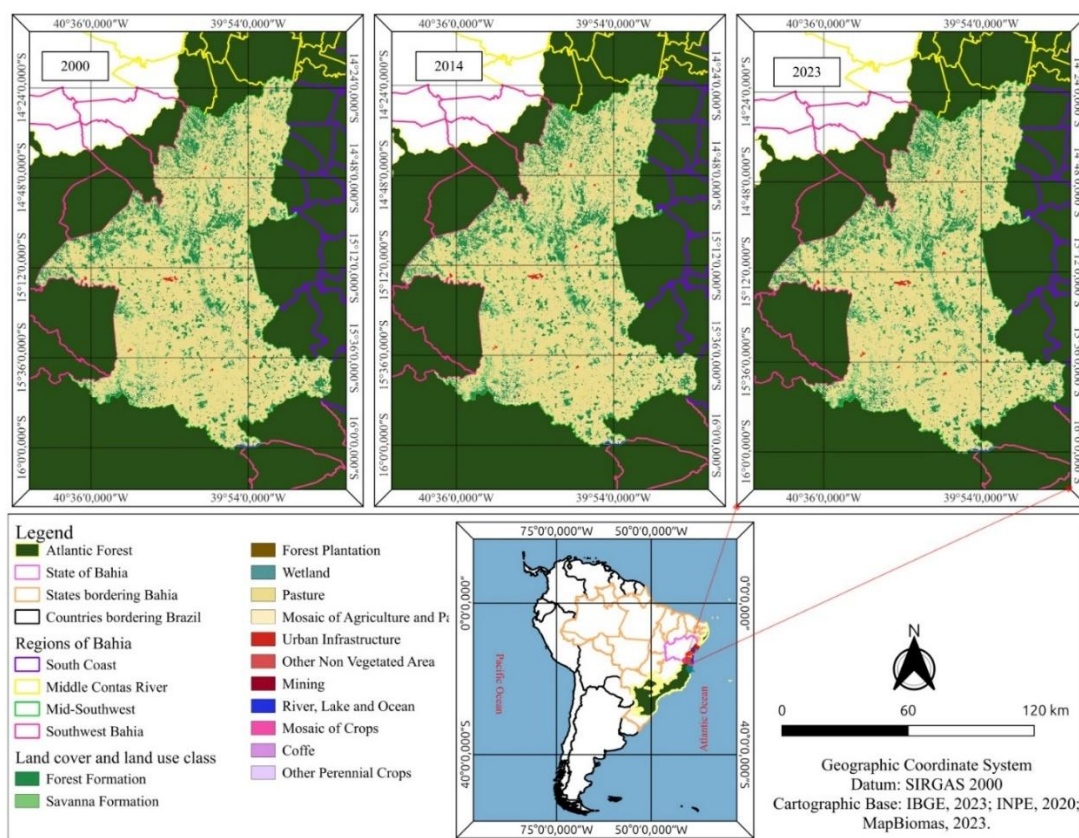
Source: the authors (2025).

Despite the low percentage representation of the Forest Planted (0.02%) and Coffee (0.09%) classes in overall land use in the Middle Southwest region of Bahia, values below 0.1% may appear insignificant when considered only in absolute terms. However, an analysis of the relative growth rates of these classes over the study period reveals important trends in land-use change. Even from a small initial territorial base, the proportional expansion of these activities indicates emerging processes of productive diversification and shifts in land-use strategies. Although planted forests constitute a type of forest land use, they differ substantially from the native Atlantic Forest in terms of biodiversity and ecological functions, as they are generally associated with silvicultural systems based on monocultures and simplified forest structures. Such characteristics may reduce functional diversity when compared to native forest ecosystems.

There was also an increase in perennial crops, particularly coffee cultivation, which expanded from 0.04% to 0.09%, along with other perennial crops whose cultivated area increased more than eightfold over the analyzed period. These data suggest the consolidation of new production arrangements, albeit on a relatively small scale, which may increase pressure on the remaining forest areas, especially in the absence of agroecological practices.

The expansion of urban infrastructure, although modest in percentage terms, increasing from 0.19% in 2004 to 0.26% in 2023, also deserves attention. The growth of the urban network, combined with the expansion of the road system, tends to intensify landscape fragmentation and facilitate access to forested areas, thereby promoting new cycles of deforestation. Other land uses, such as mining and non-vegetated areas, also showed limited growth, indicating a gradual intensification of land use and diversification of anthropogenic pressures on the territory (Figure 10).

Figure 10 - Land cover and land use in the Atlantic Forest in the Mid-Southwest region of the state of Bahia, 2025



Source: the authors (2025).

Therefore, the data reveal a landscape marked by relatively stable forest cover, yet under constant pressure from agricultural, forestry, and urban land uses. The conservation of the Atlantic Forest in the Middle Southwest region of Bahia depends on the implementation of integrated public conservation

policies, the promotion of sustainable production practices, and the strengthening of territorial planning tools capable of reconciling environmental protection with regional socioeconomic development. In this context, ecological restoration, the promotion of agroforestry systems, and the creation of ecological corridors constitute fundamental strategies to reverse fragmentation processes and ensure the maintenance of ecosystem services associated with the Atlantic Forest.

## FINAL CONSIDERATIONS

The results of this study provide robust evidence that deforestation dynamics in the Atlantic Forest biome of Bahia are associated with land-use patterns linked to livestock production. Throughout the analyzed period (2004–2023), pasture areas consistently represented the dominant land use, occupying more than 40% of the territory in 2023, while native forest formations remained below 26%. The general spatial correlation analysis revealed moderate to strong associations between deforestation and pasture expansion, cattle herd size, forestry activities, and population growth, confirming livestock farming as the principal driver of forest-cover loss in the region. Although agricultural crops and urban expansion also contributed to deforestation, their influence was comparatively lower and spatially more localized.

The year-by-year correlation analysis revealed an important temporal shift in these relationships. Correlations between deforestation and both pasture area and cattle herd size declined substantially over time, with values decreasing from approximately 0.52 in 2004 to 0.26 and 0.18, respectively, in 2023. This reduction suggests a gradual decoupling between livestock expansion and deforestation, possibly reflecting changes in production systems, including land-use intensification, productivity gains, and the adoption of integrated crop–livestock–forestry (ICLF) systems. These findings indicate that recent livestock expansion has increasingly relied on already cleared areas rather than direct forest conversion, representing a potentially positive trend toward more sustainable land-use practices.

The spatiotemporal analysis of land cover and land use further reinforces this interpretation. While the overall percentage of Forest Formation appeared relatively stable throughout the analyzed years, spatial patterns revealed ongoing fragmentation and replacement of native vegetation by pasture, planted forests, and agricultural mosaics. Planted forests, largely associated with eucalyptus cultivation, expanded from approximately 3.1% in 2004 to more than 5.2% in 2023 within the Atlantic Forest region of the state of Bahia, particularly in the Extreme South and Discovery Coast regions, highlighting the role of forestry-related economic activities in reshaping the landscape. At the regional scale, the Middle Southwest of Bahia stood out as the area with the highest accumulated deforestation, totaling more than 1,780 km<sup>2</sup>, largely driven by extensive livestock farming.

From an environmental perspective, the weak correlations between deforestation and climatic variables, such as precipitation and temperature, indicate that forest loss does not generate immediate or uniform climatic responses at the analyzed spatial scale. However, localized effects, particularly in densely populated or highly fragmented areas, remain plausible and require further investigation using longer climatic time series and finer spatial resolution. This study advances the understanding of the land-use drivers of deforestation while also highlighting the need for complementary analyses capable of evaluating climate–vegetation feedback mechanisms.

Overall, the findings underscore the complexity of deforestation processes in the Atlantic Forest of Bahia, where economic development, land-use intensification, and conservation coexist within a highly heterogeneous landscape. Public policies aimed at strengthening sustainable livestock systems, restoring degraded pastures, and expanding agroforestry and integrated production systems are essential to reduce pressure on the remaining forest fragments. Moreover, territorial planning strategies that promote ecological connectivity and prioritize conservation in critical regions are fundamental to ensuring the long-term resilience of the Atlantic Forest while maintaining regional socioeconomic development.

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