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EVALUATION OF DEFORESTATION IN THE MUNICIPALITY OF BRASIL NOVO IN THE STATE OF PARÁ - BRAZIL, USING MACHINE LEARNING TECHNIQUES

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Abstract

The agricultural frontier of the Brazilian Amazon, is undergoing significant changes in its land cover, primarily driven by the expansion of cattle ranching and cocoa cultivation. Through the analysis of Landsat 8 satellite images and the WorldCover 10m 2020 product, combined with climatic and socioeconomic data, this study investigated land use dynamics between 2015 and 2023, on the municipality of Brasil Novo. The results revealed a substantial reduction in forest cover, with the expansion of pasturelands as the main driver of deforestation. The temporal analysis of the Normalized Difference Vegetation Index (NDVI) indicated interannual variations in vegetation cover, associated with extreme weather events and anthropogenic pressure. Although the municipality still maintains 43.8% of forest cover, with the Arara Indigenous Land being a notable example, the pressure on natural resources demands the implementation of public policies and sustainable management practices to mitigate environmental impacts and ensure the conservation of Amazonian biodiversity.

Keywords: Amazon, NDVI, remote sensing, climate change, livestock, land use.

Resumo / Resumen

AVALIAÇÃO DO DESMATAMENTO NO MUNICÍPIO DE BRASIL NOVO NO ESTADO DO PARÁ - BRASIL, UTILIZANDO TÉCNICAS DE MACHINE LEARNING

O município de Brasil Novo, localizado na fronteira agrícola da Amazônia, experimenta significativas mudanças em sua cobertura do solo, impulsionadas principalmente pela expansão da pecuária e do cultivo de cacau. Através da análise de imagens de satélite Landsat 8 e do produto da ESA WorldCover 2020, combinada com informações climáticas e socioeconômicas, este estudo investigou as dinâmicas do uso da terra no período de 2015 a 2023. Os resultados revelaram uma redução substancial da cobertura florestal, com a expansão das áreas de pastagem como principal motor do desmatamento. A análise temporal do Índice de Vegetação por Diferença Normalizada (NDVI) indicou variações interanuais na cobertura vegetal, associadas a eventos climáticos extremos e à pressão antrópica. Embora o município ainda mantenha 43,8% de cobertura florestal, com destaque para a Terra Indígena Arará, a pressão sobre os recursos naturais exige a implementação de políticas públicas e práticas de manejo sustentável para mitigar os impactos ambientais e garantir a conservação da biodiversidade amazônica.

Palavras-chave: Amazônia, NDVI, sensoriamento remoto, mudanças climáticas, pecuária, uso da terra.

EVALUACIÓN DE LA DEFORESTACIÓN EN EL MUNICIPIO DE BRASIL NOVO EN EL ESTADO DE PARÁ - BRASIL, UTILIZANDO TÉCNICAS DE MACHINE LEARNING

El municipio de Brasil Novo, ubicado en la frontera agrícola de la Amazonía, experimenta cambios significativos en su cobertura del suelo, impulsados principalmente por la expansión de la ganadería y el cultivo de cacao. Mediante el análisis de imágenes satelitales del Landsat 8 y el producto ESA WorldCover 2020, combinado con información climática y socioeconómica, este estudio investigó las dinámicas del uso de la tierra en el período 2015-2023. Los resultados revelaron una reducción sustancial de la cobertura forestal, con la expansión de las áreas de pastizales como principal motor de la deforestación. El análisis temporal del Índice de Vegetación por Diferencia Normalizada (NDVI) indicó variaciones interanuales en la cubierta vegetal, asociadas a eventos climáticos extremos y a la presión antrópica. Aunque el municipio todavía mantiene un 43,8% de cobertura forestal, destacando la Tierra Indígena Arará, la presión sobre los recursos naturales exige la implementación de políticas públicas y prácticas de manejo sostenible para mitigar los impactos ambientales y garantizar la conservación de la biodiversidad amazónica.

Palabras-clave: Amazonía, NDVI, teledetección, cambio climático, ganadería, uso de la tierra.

INTRODUCTION

The Trans-Amazonian highway, one of the largest national integration projects in Brazil, which has profoundly shaped the territorial dynamics of the Legal Amazon. The implementation of agrarian and land policies along the Trans-Amazonian Highway significantly accelerated deforestation, contrary to the expectation of a more gradual advance in the first years of occupation (WATRIN et al., 2020).

The occupation process promoted by the National Institute of Colonization and Agrarian Reform (INCRA) along the Trans-Amazonian Highway caused a drastic transformation in the local landscape. Colonization was characterized by rapid population growth, resulting in the emergence of small towns along the highway, evidencing both the territorial occupation and the socioeconomic dynamics that drove development in the region (CÔRTES; D'ANTONA; PERZ, 2024; FOLHES; SERRA, 2023).

Land use on the Trans-Amazonian is shaped by several factors, including time of occupation and proximity to urban centers. Older, urbanized areas tend to have less vegetation cover. However, the sense of collectivity in local communities can act as a factor of environmental protection (CÔRTES; D'ANTONA; PERZ, 2024). The spatial dimension is a determining factor in human decisions, influencing everything from the choice of housing to the location of economic activities. About 80% of these decisions are shaped by spatial considerations, directly impacting land use and land cover (BENZOUGAGH et al., 2024).

To mitigate the effects of deforestation and create income alternatives for populations along the Trans-Amazonian Highway, the Executive Committee of the Cocoa Farming Plan (CEPLAC) encouraged the planting of forest species in cocoa agroforestry systems. This practice was mandatory for farmers who participated in its technical assistance programs (FOLHES; SERRA, 2023).

In 2013, Brasil Novo had 13,685 hectares of cocoa planted in agroforestry systems, but only 38.75% were in production. The average productivity of 602 kg/ha was significantly below the 900 kg/ha recorded in neighboring municipalities (MENDES, 2009).

Many farmers in the municipality diversify their sources of income, combining cattle raising with cocoa cultivation. This strategy makes it possible to minimize the risks associated with the fluctuation of market prices of each product (FOLHES; SERRA, 2023). Cattle farming is the main agricultural activity in the municipality, contributing significantly to the generation of income and jobs.

Comparing livestock with cocoa agroforestry systems in the municipality, it is noted that agroforestry systems maintain an ecological balance in relation to land use (BEZERRA et al., 2018). In addition to offering productive opportunities, these systems play a vital role in environmental recovery. Integrating trees, agricultural crops, and/or animal husbandry, they promote biological diversity, improve soil and water quality, and contribute significantly to climate change mitigation. Agroforestry systems also provide habitats for local fauna and encourage sustainable agricultural practices, representing a holistic approach to land management that balances food production with environmental conservation (NASCIMENTO; ALVES; SOUZA, 2019).

Calibrated space technologies provide accurate and up-to-date data to monitor changes in land use, understand human dynamics, and track local climate change, contributing to environmental management and territorial planning (CÔRTES; D'ANTONA; PERZ, 2024; MACHADO et al., 2023; QIN et al., 2024).

Calibrated spatial mapping products, such as satellite imagery from the ESA WorldCover 2020 mission, demonstrate high accuracy for monitoring changes in forest cover, especially at altitudes between 200 and 3000m. Recent studies in Southeast Asia have revealed that these products have a forest classification accuracy of 74.4%, making them valuable tools for mapping deforestation areas, assessing forest fragmentation, and monitoring natural regeneration (LIU et al., 2023).

This study aims to analyze the changes in land cover in the municipality of Brasil Novo between 2015 and 2023, adopting an integrated approach that combines the use of the Normalized Difference Vegetation Index (NDVI), the WorldCover 10m 2020 product, and Machine Learning models with the Random Forest algorithm. In addition to quantifying these changes, we sought to understand the relationships between land cover, climatic variables and anthropogenic activities, such as agriculture, in order to identify the main drivers of landscape transformations.

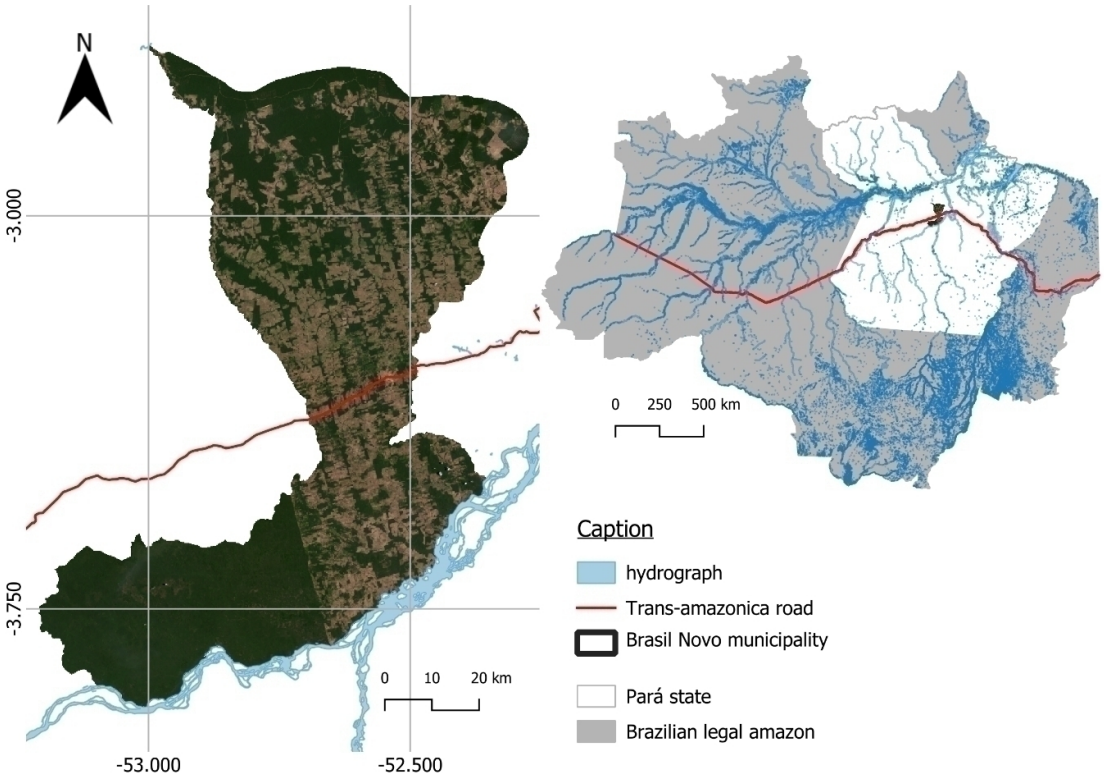
METHODOLOGY

This study employs a multisensory approach to investigate the dynamics of the landscape in Brasil Novo. The analysis integrates time series of Landsat 8 images (2015-2023), secondary data on socioeconomic and environmental variables, and remote sensing products for land cover mapping.

Field of study

The study area comprises the municipality of Brasil Novo, located in the southwestern region of the state of Pará, with geographic coordinates 3°17' 56" S and 52° 34'12" W, and an average altitude of 190 meters. Located on the banks of the Trans-Amazonian Highway (BR 230), the municipality has a territorial extension of 6,362.575 km² and an estimated population of 15,690 inhabitants (IBGE, 2017). It is bordered to the north by Porto de Moz, to the south and east by Altamira, and to the west by Medicilândia (Figure 1). This strategic location, associated with the presence of the Trans-Amazonian highway, has significantly influenced the dynamics of land occupation and use in the region.

Figure 1 – Image in RGB of Brasil Novo's municipality location in the state of Pará and in the Brazilian Amazon



Source: IBGE (2022), Agência Nacional das Águas (ANA), Agencia Nacional de Transporte Terrestre (ANTT) and Landsat 8.

Acquisition of images, data and libraries for processing

We used Landsat 8 satellite images, collected between 2015 and 2023, with high quality (Tier 1 and Real-Time) and low cloud level (maximum 30%). These images were adjusted to cover exactly the area of the municipality and went through a filtering process to remove the remaining clouds, ensuring greater accuracy in the results.

Climate data were collected from the TerraClimate platform for the municipality of Brasil Novo in the period from 2015 to 2023, including maximum and minimum temperature, precipitation, evapotranspiration, soil moisture and water deficit. At the same time, agricultural data were obtained from the Brazilian Institute of Geography and Statistics (IBGE) regarding the number of cattle and the cocoa planted area for the years 2015 to 2022. The choice of these variables is justified by the importance of cattle ranching and cocoa cultivation for the local economy. It is important to note that no agricultural data were found available in the IBGE for the year 2023, which limits the analysis to the period from 2015 to 2022.

The data analysis was carried out in an integrated way, combining the flexibility of the Google Earth Engine platform with the data processing capacity of the Python language. The geobr libraries (PEREIRA; GONCALVES, 2024), geemap (WU, 2020), geopandas (JORDAHL, 2014), earthpy and earthpy.plot (WASSER et al., 2019) were used for the spatial manipulation and analysis of satellite images. The scikit-learn library (PEDREGOSA et al., 2011) provided the necessary tools for the application of machine learning techniques, such as principal component analysis (PCA), and the pandas library (MCKINNEY, 2010) allowed the organization and analysis of tabular data. The visualizations of the results were performed using the matplotlib.pyplot (HUNTER, 2007) and seaborn (WASKOM et al., 2017) libraries.

Data processing

In order to ensure the accuracy of the analyses, the study area was delimited based on the official polygon of the municipality of Brasil Novo (IBGE code 1501525), obtained for the year 2022 through the geobr library. The geoJSON polygon was converted to 'ee' (Earth Engine) format to extract the images corresponding to the area of interest.

Initially, the Normalized Difference Vegetation Index (NDVI) was calculated using the near-infrared (NIR, band 5) and red (band 4) bands of the satellite images. NDVI values vary between -1 and 1, with values closer to 1 indicating higher vegetation density. After calculating the NDVI for each image of the time series, the annual median image was calculated, which represented the state of the vegetation throughout the year. NDVI anomalies were analyzed according to time series.

To map the different land cover classes in the municipality of Brasil Novo, a supervised classification was employed using the Random Forest algorithm. The red, green and blue bands (B4, B3 and B2, respectively) of the satellite images were used as explanatory variables to discriminate the different classes.

The European Space Agency's (ESA) WorldCover 10m 2020 product served as a reference for the creation of the training dataset. From this product, 100 reference points were collected, representative of the different land cover classes presents in the study area. These points were used to train the Random Forest model, ensuring consistency of the classification with the global WorldCover classification.

The training period, which covered the years 2015 to 2023, was crucial for the algorithm to learn to identify the different land cover classes and their dynamics over time. This temporal approach allowed to increase the robustness of the model and ensure a more accurate classification of the images. After training, the model was applied to all images of the study area to generate classification maps, which represent the spatial distribution of land cover classes at each time moment.

To unravel the complex relationships between land cover, climatic and economic data, a multivariate statistical approach was employed. Initially, a Nemenyi test of multiple comparisons of means was used to identify whether the means of the numerical variables differed significantly between the different land cover classes. Then, to quantify the strength and direction of the linear associations between all variables, Pearson's correlation coefficients were calculated.

In order to simplify the analysis and identify the main patterns of variation in the data, a principal component analysis (PCA) was performed. PCA has made it possible to reduce the dimensionality of the data, transforming a large set of variables into a smaller number of principal components, which are new uncorrelated variables that capture most of the original variability of the data. These main components, in turn, were used to explore the relationships between the different land cover classes and climatic and economic factors.

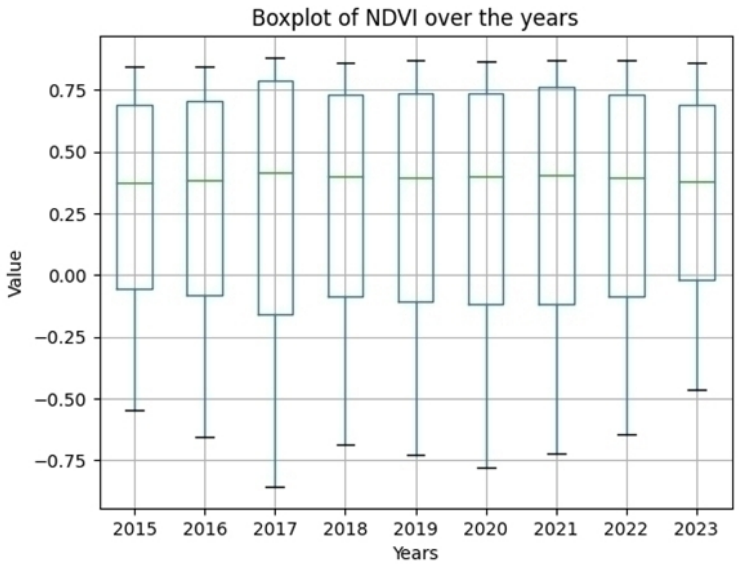
RESULTS

A análise espacial abrangeu uma vasta área na Amazônia Legal, o que exigiu a junção de um grande número de imagens (52 imagens) e seu posterior processamento. A elevada cobertura de nuvens na região, estimada em 30% nas imagens utilizadas neste estudo, representou um desafio significativo. Para minimizar os impactos da nebulosidade, foram criadas máscaras para excluir as áreas nubladas, permitindo uma análise mais precisa da cobertura vegetal. No entanto, o processamento de imagens de grande área pode introduzir erros como deslocamentos de pixels e perda de informações, os quais foram cuidadosamente considerados

The spatial analysis covered a vast area in the Legal Amazon, which required the gathering of a large number of images (52 images) and their subsequent processing. The high cloud cover in the region, estimated at 30% in the images used in this study, represented a significant challenge. To minimize the impacts of cloudiness, masks were created to exclude cloudy areas, allowing a more accurate analysis of vegetation cover. However, processing large-area images can introduce errors such as pixel shifts and information loss, which have been carefully considered

The NDVI statistics for the municipality of Brasil Novo indicate that, on average, vegetation cover remained relatively stable over the period from 2015 to 2023 (Figure 2). However, the quartile analysis reveals interannual variations in vegetation cover, possibly related to climatic events and anthropogenic pressure.

Figure 2 – NDVI Boxplot over the years 2015 and 2023

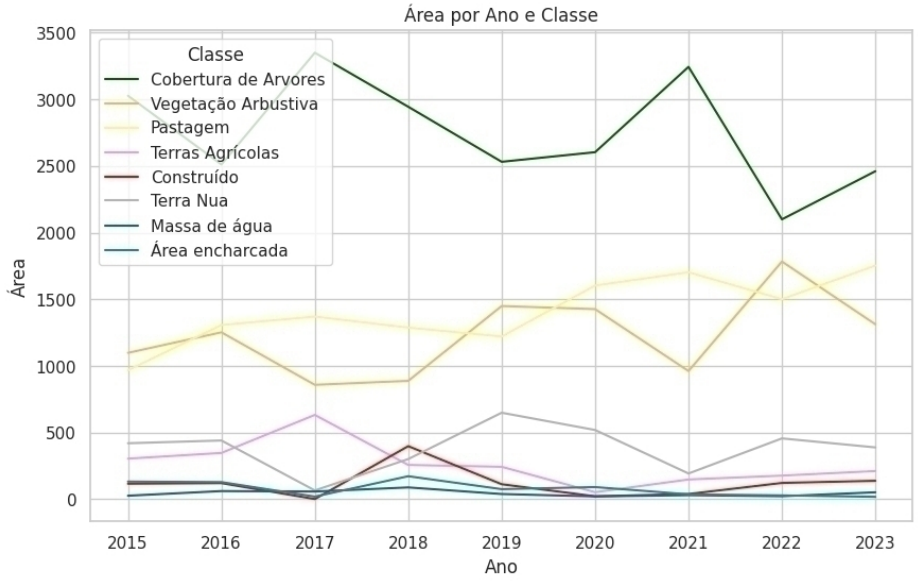


Source: Authors

The analysis of NDVI data revealed that the year 2017 had the highest average (0.75), indicating a denser and more vigorous vegetation cover. Then, 2021 recorded an average of 0.72. On the other hand, the years 2022 and 2015 had the lowest average (0.63), suggesting a possible reduction in vegetation cover or a less vigorous state of vegetation health in these periods.

The study of land cover over the time series indicates a significant forest area in the municipality, although a trend of continuous reduction is observed, suggesting deforestation and conversion to other uses, mainly pastures. The other classes, such as agricultural land, built areas and bare areas, show less expressive variations, indicating processes of urban expansion and agriculture on a smaller scale (Figure 3).

Figure 3 – Line graph of land cover in the municipality of Brasil Novo for the years 2015 to 2023, based on Landsat 8 image classification, with training on WorldCover 10m 2020 data.

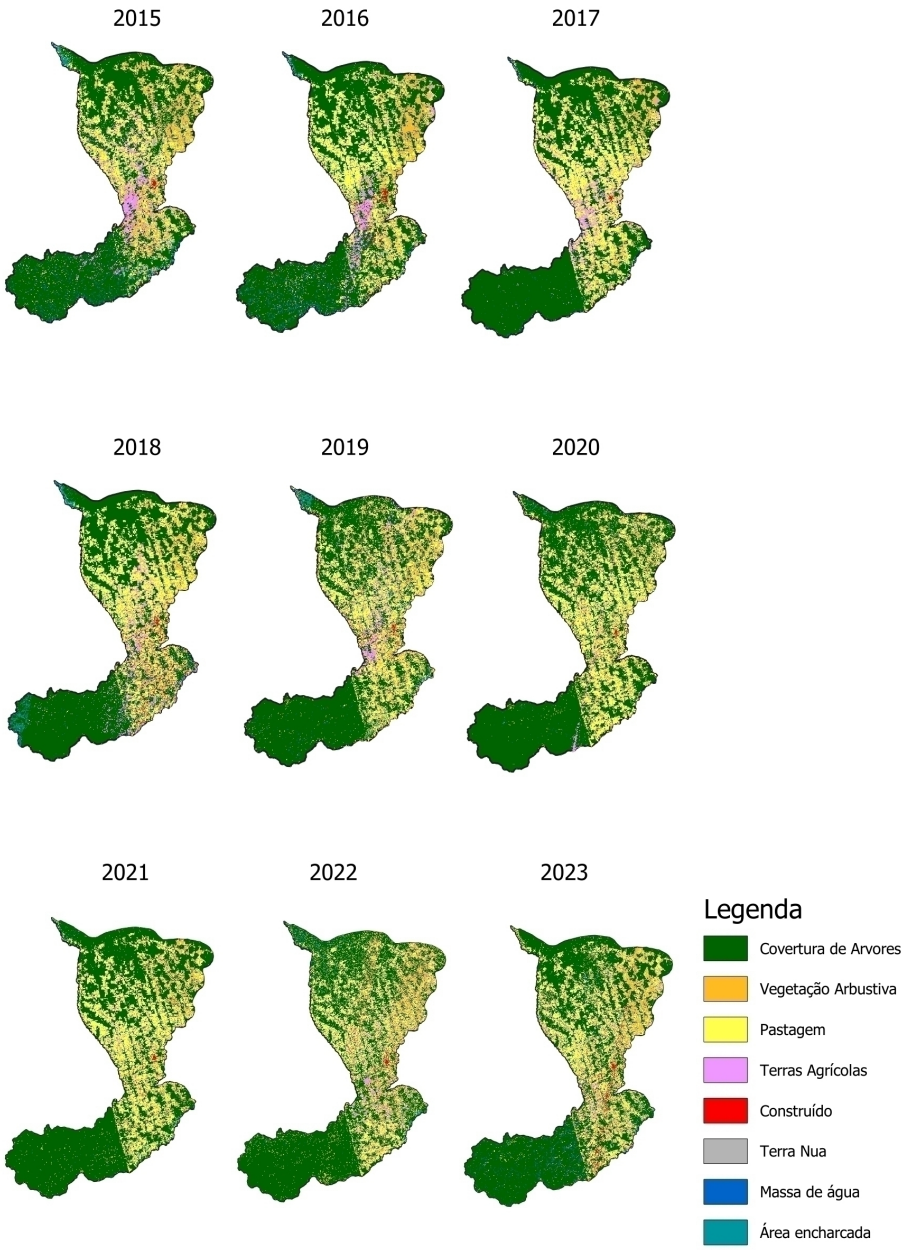


Source: Authors

The analysis of satellite images revealed a process of conversion of areas of shrubby vegetation and natural vegetation cover into pastures, especially in the northeast region of the municipality (Figure 4). Concomitantly, a progressive reduction in agricultural areas was observed over the years, especially in the southwestern portion. It is important to emphasize that the presence of clouds significantly interfered with the accuracy of the identification of vegetation cover in some areas and periods.

Image processing, even of a single image, is subject to distortions, such as those observed in the sudden increase in the built-up area in 2018. These distortions can compromise the accuracy of the analyses

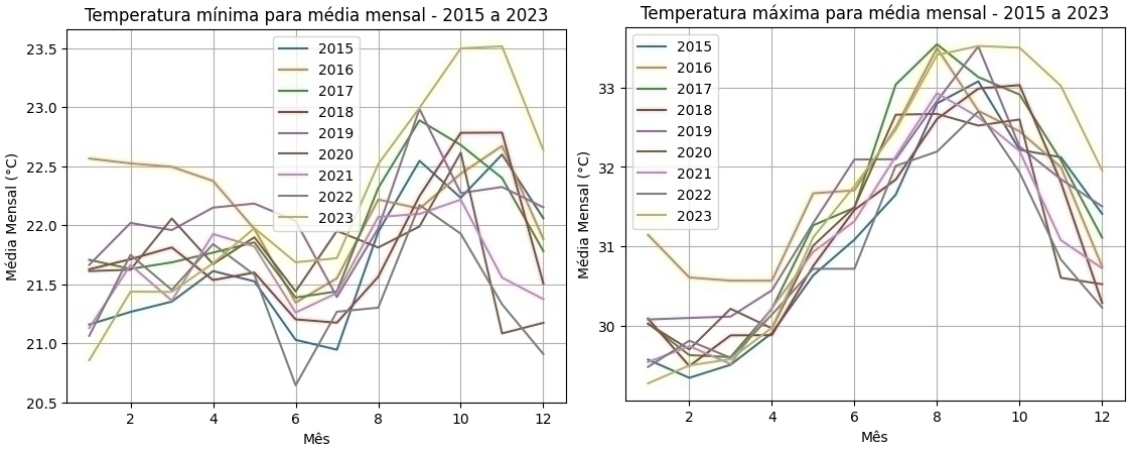
Figure 4 - Mapping of land cover in the municipality of Brasil Novo for the years 2015 to 2023, based on Landsat 8 image classification, with training in WorldCover 10m 2020 data.



Source: Authors

To better understand the dynamics of land use and land cover, an environmental analysis was carried out that considered the climatic variables of temperature and precipitation. The data revealed a gradual increase in the monthly average temperature and, especially, in the maximum temperatures over the period, indicating a warming process (Figure 5). This trend, combined with the occurrence of temperature peaks in certain years, suggests the intensification of extreme events such as heat waves. Seasonal temperature variation remains characteristic of tropical regions, with the warmest months concentrated in the middle of the year. However, the increase in maximum temperatures indicates an increase in thermal amplitude and a potentially warmer and drier climate, which may favor the occurrence of droughts and influence the dynamics of vegetation and land use.

Figure 5 - Analysis of temperature over the years 2015 to 2023, taken from the TERRA CLIMA platform of the University of Idaho.

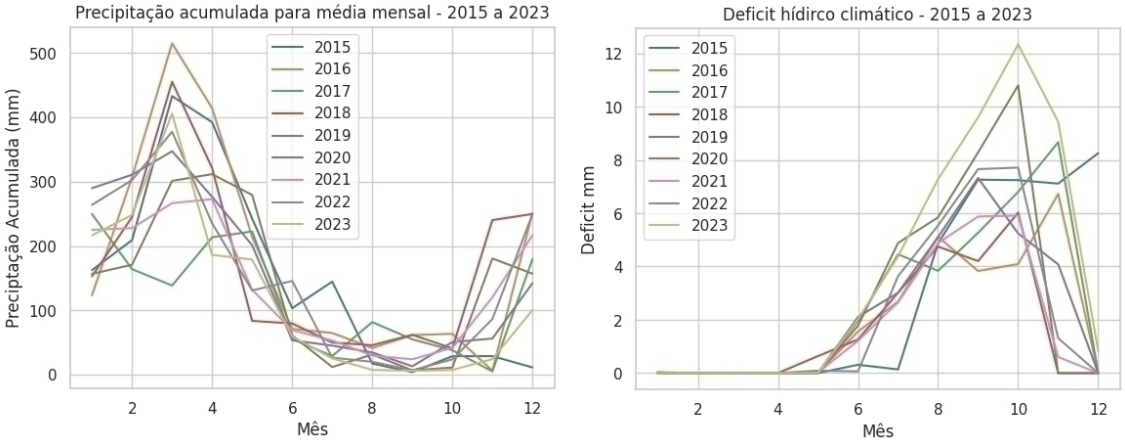


Source: Authors

Rainfall in the study area showed a clear seasonality, with peaks in the months of December to March and lower values between June and August. Analysis of data from 2015 to 2023 revealed a strong influence of El Niño and La Niña events on interannual rainfall variability (Figure 6). The years 2015 and 2016, characterized by El Niño events, showed a significant increase in rainfall volumes, especially during the summer months. On the other hand, the years 2020 and 2021, marked by La Niña events, were associated with a reduction in precipitation, with greater intensity in the winter months.

The analysis of the entire time series can identify trends of increase or decrease in the average annual rainfall, which can indicate long-term climate change. Prolonged periods of water deficit can cause water stress in plants, leading to reduced growth and, in extreme cases, mortality. The lack of water can intensify erosion and desertification processes, affecting soil fertility and the carrying capacity of vegetation.

Figure 6 - Analysis of precipitation and water deficit over the years 2015 to 2023, taken from the TERRA CLIMA platform of the IDAHO university.

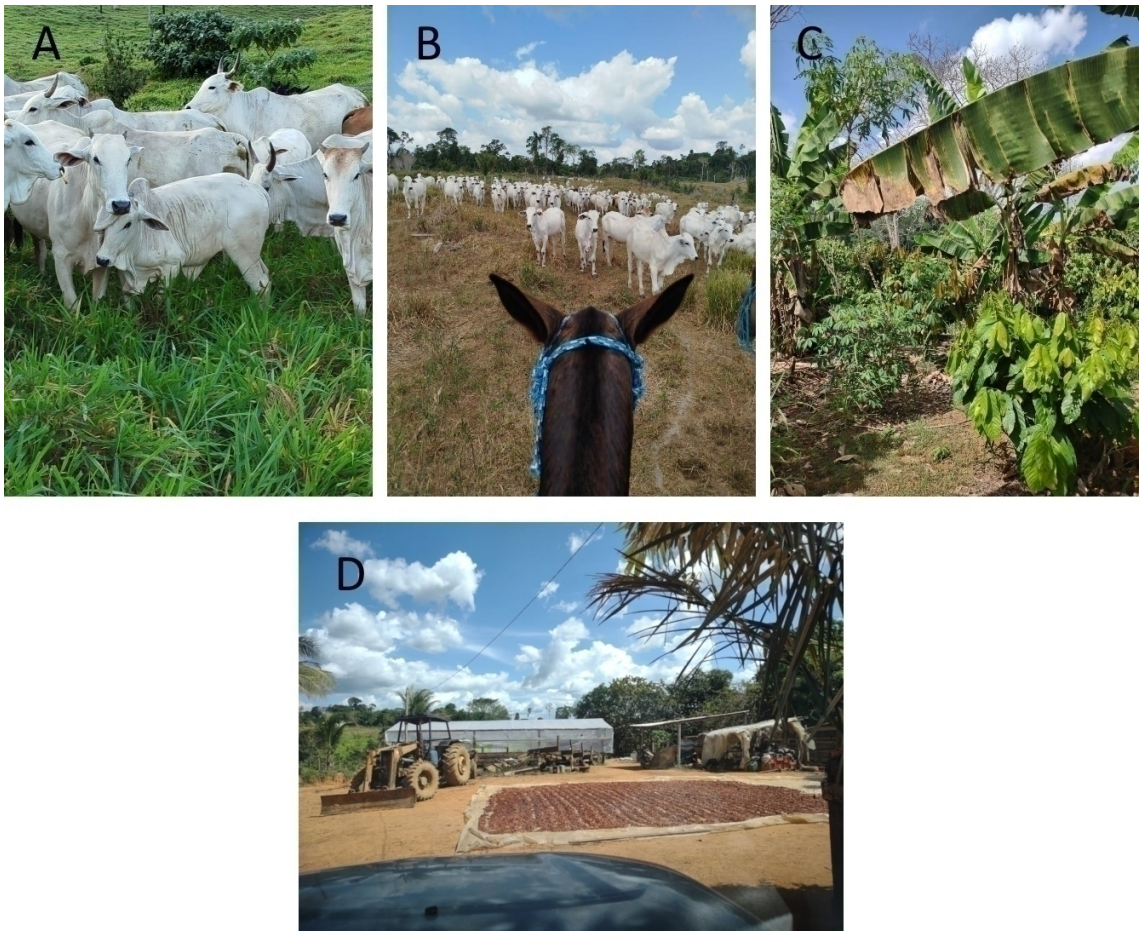


Source: Authors

The main land use activities in the municipality are the raising of large animals and the cultivation

of cocoa. Historically, cocoa was grown in agroforestry systems, which associated cocoa production with other tree species. However, with the introduction of more productive cocoa clones, the trend has been towards the adoption of monoculture systems (Figure 7).

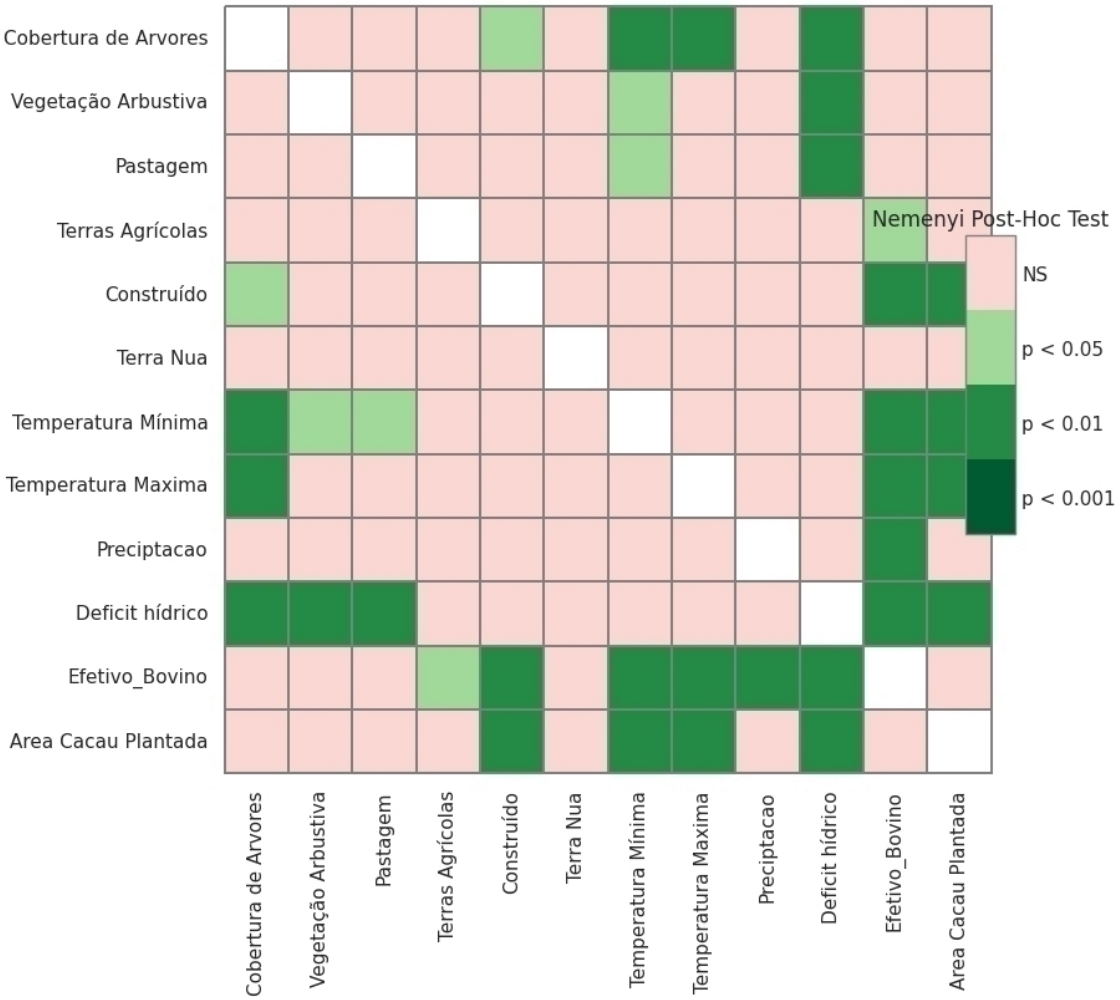
Figure 7 - Photo of the main activities of the municipality of Brasil Novo, where images A and B represent Cattle Farming, C cocoa farming in agroforestry systems recommended by CEPLAC and D structure used for use in cocoa farming for a medium farmer.



Source: Images A and B (Ozildo Barbosa – Municipal Secretariat of Agriculture and Mining of Brasil Novo - SEMAM) and C and D (Thiago Leão – Secretariat of Agricultural Development of the state of Pará - SEDAP).

After non-parametric post-hoc analysis, the results indicated that the type of soil cover directly influences the maximum temperature in the studied area. Grassland and farmland are more sensitive to variations in precipitation and suffer more from water shortages. In addition, human activities, such as cattle ranching and cocoa cultivation, significantly shape the landscape, altering the distribution of natural vegetation (Figure 8).

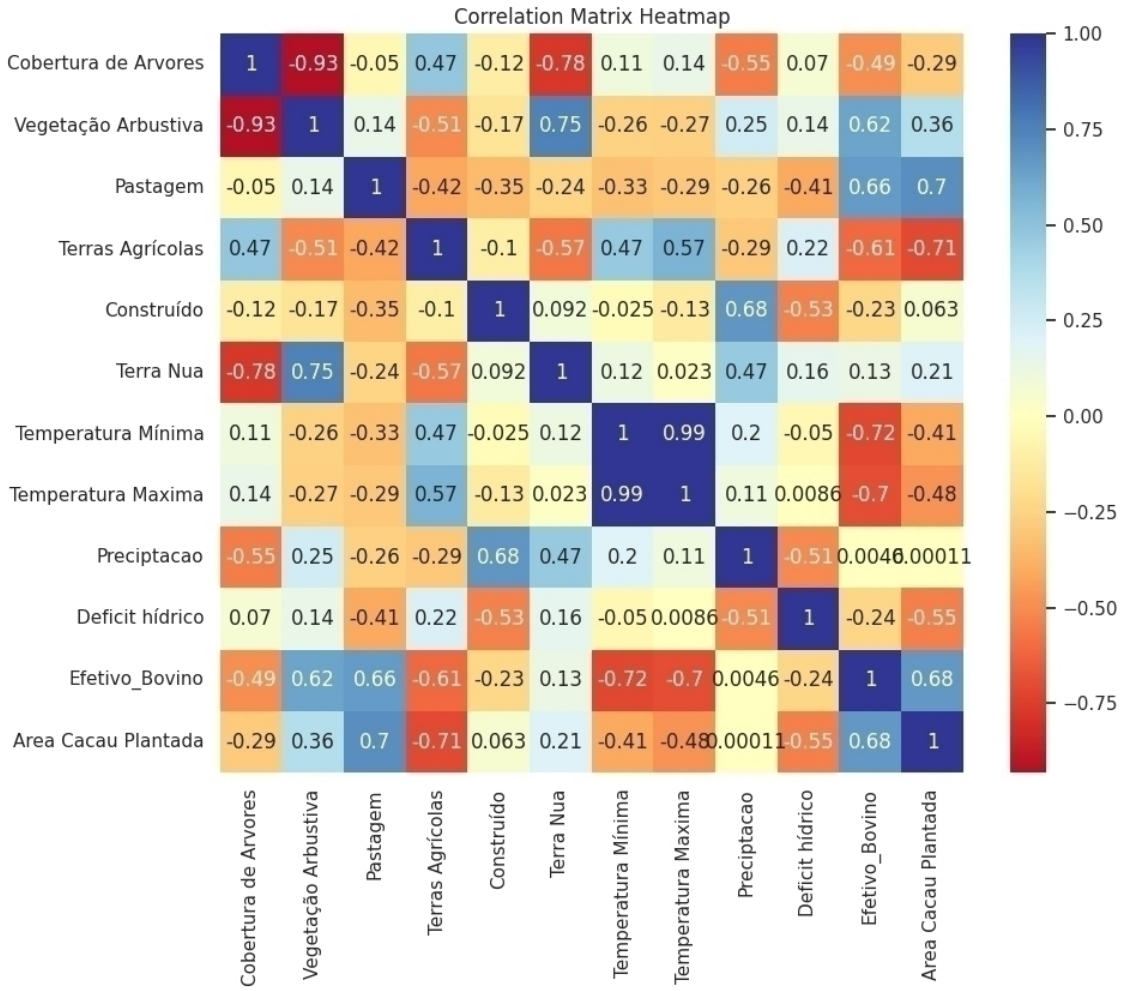
Figure 8 - Nemenyi's test for analysis of the environment, land cover and land use in the municipality of Brasil Novo-Pará-Brazil.



Source: Authors

With the real significance, it was possible to proceed to an analysis of the correlation between the variables. The correlation analysis revealed an inverse relationship between vegetation cover and pasture areas, agricultural land and built-up areas, indicating a process of conversion of natural areas for anthropogenic purposes. Temperature showed a positive correlation with pasture and agriculture areas, suggesting that warmer regions are associated with greater expansion of these activities. On the other hand, rainfall showed a positive relationship with forest cover, evidencing the importance of water for the maintenance of native vegetation. The strong correlation between pasture area, cocoa cultivation area and cattle herd indicates that the expansion of cattle ranching is the main driver of the conversion of natural areas into pastures, possibly to the detriment of other covers, such as the forest (Figure 9).

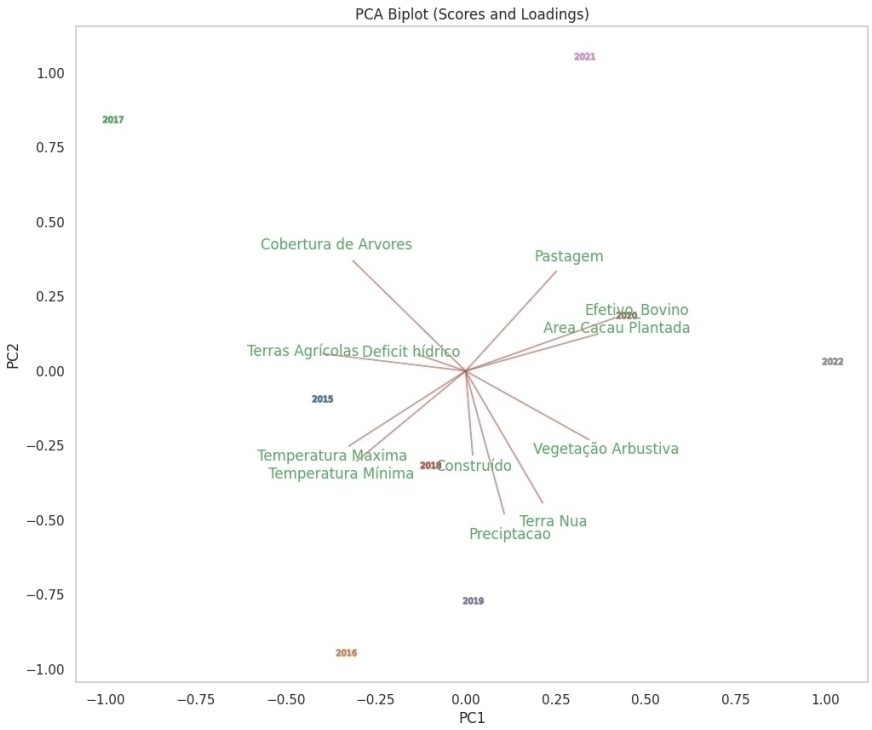
Figure 9 - Correlation between environmental information, land cover and use. For the municipality of Brasil Novo – Pará – Brazil.



Source: Authors

Two-dimensional principal component analysis (PCA), based on environmental, land cover and land use variables, explained 62.41% of the variability of the data. The first major component (PC1) is associated with an anthropization gradient, reflecting the intensification of land use and the conversion of natural areas into agricultural areas and pastures. The second principal component (PC2) is related to a climate gradient, capturing variations in precipitation and temperature. Throughout the period analyzed (2015-2022), there was a gradual increase in anthropization, evidenced by the trajectory of the points in the positive direction of PC1. The expansion of cattle ranching and cocoa cultivation, strongly correlated with pasture area, is the main driver of this transformation. Climatic conditions also showed variability over time, with the years 2019 to 2021 standing out as the beginning of anthropogenic pressures and the years 2015 to 2017 for wetter conditions (Figure 10).

Figure 10 – Principal Component Analysis of environmental factors, land cover and land use



Source: Authors

DISCUSSION

The high frequency of cloud cover in the Amazon represents a significant challenge for the analysis of satellite imagery. The presence of clouds compromises data quality and limits the use of optical images, especially when working with large volumes of data (IORA et al., 2021; OLDONI; SANCHES; PICOLI, 2022). In humid tropical forests, such as the Amazon, cloudiness is a chronic limiting factor for remote monitoring (BERTRAND et al., 2023).

The temporal analysis of NDVI in our study area did not reveal large variations in annual averages, differing from results found in other surveys, such as that of (OLUWAJUWON et al., 2021), who identified significant reductions in NDVI in southwestern Nigeria, associated with increased deforestation. Analysis of high-resolution imagery, conducted between 2001 and 2020 in Indonesia, revealed a direct correlation between the loss of vegetation cover in rapidly growing cities and the decrease in NDVI. Concomitantly, cities that implemented vegetation recovery measures showed an increase in NDVI, evidencing the effectiveness of these actions (FURUSAWA et al., 2023).

Due to climate effects, control over land use and advance on forest are extremely important. Reforestation programs in Pakistan have shown increased NDVI with reforestation activities (ALI AROOJ et al., 2021).

The high NDVI values found in our study area are indicative of significant vegetation cover, especially in environmental preservation areas, such as the Arara Indigenous Land, which occupies 1/4 of the municipality of Brasil Novo. The legal protection of this area and the presence of forests, contributed to the maintenance of the NVDI.

In the study region, characterized by a tropical climate with a well-defined dry season, the rainfall regime exerts a significant control over the vegetation dynamics. NDVI values can show a strong positive correlation with precipitation, with peaks during the months of higher rainfall and reductions during the dry season (GUTIERREZ-CORI et al., 2021). This relationship indicates that water

availability is a limiting factor for vegetation growth and correlates with land cover use.

The analysis of the data indicated a gradual increase in the water deficit and the thermal amplitude in the study area. Studies carried out in the Brazilian semi-arid region have also shown a positive relationship between these two variables, suggesting a possible correlation. However, it is important to highlight that this relationship is not universal and may vary according to the specific characteristics of each ecosystem (LUZ; GALVINCIO, 2023).

The correlated data indicated that forest areas are being converted into pastures and shrub regions. The main cause of the reduction in forest areas is the expansion of agriculture. According to (OTHMAN et al., 2018), the reduction of forest areas is mostly caused by the replacement of forest areas by areas intended for agriculture.

It is important to highlight that, in 2008, state policies to support cocoa farming in the Trans-Amazonian region were intensified. As a result, old pasture areas were gradually replaced by shaded cocoa plantations in agroforestry systems (AFS). During this transition in the production system, cattle ranching advanced into the forest, driven by logging (FOLHES; SERRA, 2023).

The growth of agricultural activity, especially the expansion of cattle raising, has shifted the agricultural frontier to the southwest of Pará (CASTELO; ADAMI; SANTOS, 2020). Directly impacting the municipality of Brasil Novo and contributing to the loss of forest areas.

The municipality maintains a forest cover of approximately 43.8%, with more than half of this area destined to the Arará indigenous reserve, another municipality (Novo Progresso) in the Trans-Amazonian region has a much higher forest preservation rate, reaching 80% (ROSÁRIO et al., 2021). This contrast is remarkable, especially considering that both municipalities are subject to pressure from the expansion of cattle ranching.

It is important to highlight that cattle ranching conducted with inefficient techniques has contributed to the suppression of forest areas. However, when more efficient techniques are implemented, deforestation tends to decrease (PELLENZ; ALMEIDA; LIRIO, 2021).

CONCLUSION

The analysis of land cover and environmental changes in the municipality of Brasil Novo, Pará, revealed a complex and dynamic scenario. The combination of remote sensing data, climate information, and land use data has made it possible to identify significant trends and patterns.

The region, although still predominantly covered by forest, has experienced a gradual process of deforestation and conversion of natural areas for agricultural and pastoral purposes. The expansion of cattle ranching, in particular, stands out as the main driver of changes in land cover, driven by economic and socio-environmental factors.

The temporal analysis of the NDVI indicated interannual variations in vegetation cover, possibly related to extreme weather events and anthropogenic pressure. Climate change, with rising temperatures and intensifying extreme events, can exacerbate the impacts of deforestation and land-use change, affecting water availability and ecosystem productivity.

The spatial analysis revealed a heterogeneity in the distribution of the different classes of land cover, with more preserved areas and others with greater anthropogenic pressure. The presence of protected areas, such as the Arará Indigenous Land, contributes to the maintenance of forest cover and biodiversity.

It is essential that public policies and environmental management measures are implemented to mitigate the impacts of deforestation and promote the conservation of the Amazon rainforest. Continuous monitoring of land cover, promoting sustainable agricultural practices, and strengthening environmental management are essential to ensure the sustainability of the region.

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