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Article

Spatio-temporal dynamics of sugarcane-to-pasture succession from 2013 to 2022 via orbital remote sensing in the North Forest Zone of Pernambuco

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Abstract: The use of geotechnologies combined with remote sensing has become increasingly essential and important for efficiently and economically understanding land use and land cover in specific regions. The objective of this study was to observe changes in agricultural activities, particularly agriculture/livestock farming, in the North Forest Zone of Pernambuco (Mata Norte), a political-administrative region where sugarcane cultivation has historically been the backbone of the local economy. The region's sugarcane biomass also contributes to land use and land cover observations through remote sensing techniques applied to digital satellite images, such as those from Landsat-8, which was used in this study. This study was conducted through digital image processing, allowing the calculation of the Normalized Difference Vegetation Index (*NDVI*), the Soil-Adjusted Vegetation Index (*SAVI*), and the Leaf Area Index (*LAI*) to assess vegetation cover dynamics. The results revealed that sugarcane cultivation is the predominant agricultural and vegetation activity in Mata Norte. Livestock farming areas experienced a significant reduction over the observed decade, which, in turn, led to an increase in agricultural and forested areas. The most dynamic spatiotemporal behavior was observed in the expansion and reduction of livestock areas, a more significant change compared to sugarcane areas. Therefore, land use and land cover in this region are more closely tied to sugarcane cultivation than any other agricultural activity.

Keywords: geoprocessing; land use and land cover (LULC); vegetation indices; landsat-8; plants

1. Introduction

Sugarcane cultivation in the Northeast of Brazil has historically experienced cycles of success and production declines, primarily influenced by edaphoclimatic conditions. Along the coastal region of the state of Pernambuco, sugarcane has adapted well to the local soil, temperature, and humidity conditions, making this agricultural activity, for many years, one of the sole sources of employment and income in the region [1].

Although sugarcane cultivation remains consolidated in the Mata Norte region, decreasing rainfall and rising temperatures have become limiting factors that have directly impacted the productivity and yield of this crop in recent years. Additionally, there is a lack of investment in irrigation technologies, fertilization, and soil management in some planted areas, especially those located in remote or rugged terrain [2] (pp. 3025–3050).

Despite the continued dominance of sugarcane in Mata Norte, the region has faced increased temporal variability due to climate change in recent years. The period from 2013 to 2018 recorded the lowest average precipitation levels, directly affecting the productivity of cultivated areas and raising concerns about adaptation to the 21st century's new climatic realities [3].

Human activities related to the use of natural resources have increasingly contributed to climate change, influencing significant changes in land use and land cover (LULC). To monitor these changes, remote sensing technologies are employed, using satellite imagery and various parameters to identify, for example, the spatial and temporal dynamics of sugarcane areas transitioning to pasture [4] (pp. 362–388).

As sugarcane cultivation became established in the humid and coastal tablelands of Mata Norte, livestock farming prevailed in the more inland regions of Pernambuco, which feature transitional edaphoclimatic conditions approaching the semi-arid climate. The boundary areas between Mata Norte and the Agreste region, for example, are heavily influenced by livestock farming. In recent years, areas previously used for sugarcane have been converted to pastures for cattle grazing, particularly on slopes and in regions affected by droughts, which consequently showed low productivity and profitability [5] (pp. 78–79).

The climate challenges faced in this region are influenced by the El Niño phenomenon, which caused increased temperatures, higher evapotranspiration rates, and reduced rainfall over all or part of Mata Norte. Specifically, 2016 was considered the driest year observed, and these conditions directly impacted sugarcane productivity, reduced the cultivated area, and threatened the survival of sugar-energy plants [6] (pp. 193–206).

Abiotic stress resulting from conditions outside the observed norms becomes unfavorable for sugarcane cultivation, leading to the replacement of these areas with natural or planted pastures. Even when managed in rainfed conditions, pastures in this region are favorable for livestock activities and profitable due to lower operational costs and the proximity to consumer markets [7].

In agricultural fields, the succession of any activity may be influenced by various factors, as observed with eucalyptus [8], including new climatic challenges. The hypothesis of this study is that the effects of climate change, especially decreased rainfall, may directly impact sugarcane cultivation, forcing its partial or total replacement with pastures that emerge as an alternative in Mata Norte.

This research also aims to evaluate the spatial-temporal patterns of spectral behavior using vegetation indices (*NDVI*, *SAVI*, and *LAI*) and LULC data, focusing on agricultural areas. It seeks to identify the transition from sugarcane to pasture areas using remote sensing and satellite data in Pernambuco's Zona da Mata region between 2013 and 2022.

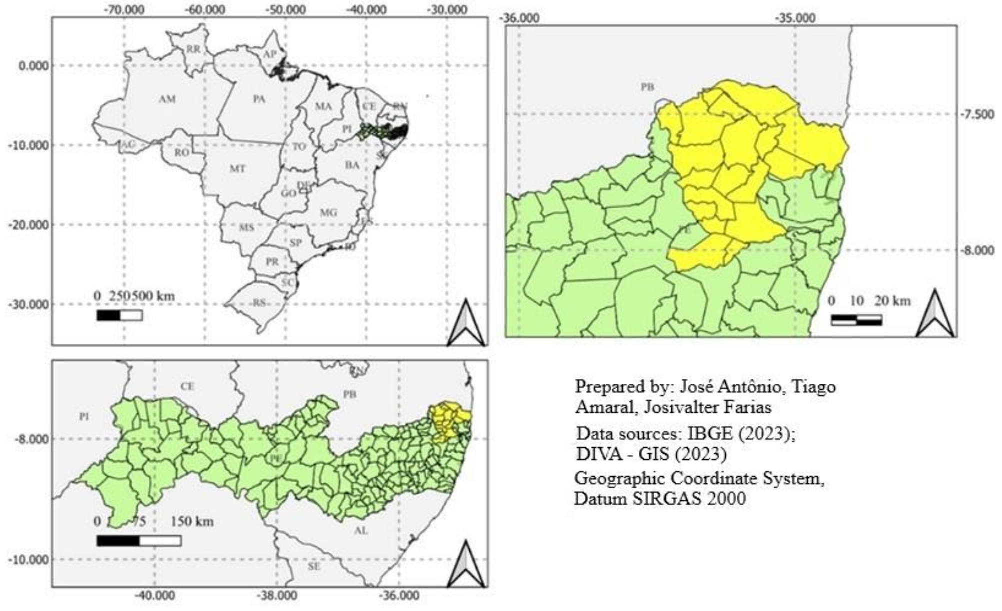
And the general objective was to analyze the succession progress from sugarcane to pastures in the Mata Norte region of Pernambuco from 2013 to 2022; Conduct an *NDVI* survey for the period from 2013 to 2022. Analyze the Leaf Area Index (*LAI*) for sugarcane and pasture during the period from 2013 to 2022; Compare *NDVI*, *LAI*, and climatic conditions with Collection 8 of MapBiomas Brazil.

2. Materials and methods

2.1. Description of the study area

The study area of this research is located in the political-administrative macro-region of the Zona da Mata in the State of Pernambuco, a region subdivided into two parts (Mata Norte and Mata Sul), both predominantly characterized by sugarcane cultivation. The predominant climate in this region of the Pernambuco forest is classified according to Köppen’s classification as As, which refers to a hot and humid tropical climate with a dry winter season. Rainfall corresponds to the rainy season rather than winter per se, with annual precipitation levels exceeding 1,600 mm in standard or very rainy years [9].

The Mata Norte region encompasses several municipalities with similar morphoclimatic conditions, as well as socioeconomic and land use and occupation characteristics. The original vegetation is Atlantic Forest, and the predominant crop is sugarcane. This region, outlined in **Figure 1**, comprises 19 municipalities: Aliança, Buenos Aires, Camutanga, Carpina, Chã de Alegria, Condado, Ferreiros, Glória do Goitá, Goiana, Itambé, Itaquitinga, Lagoa de Itaenga, Lagoa do Carro, Macaparana, Nazaré da Mata, Paudalho, Timbaúba, Tracunhaém, and Vicência [10].



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Data sources: IBGE (2023); DIVA - GIS (2023)
Geographic Coordinate System, Datum SIRGAS 2000

Figure 1. Spatial location of the North Forest Zone (Mata Norte) in the state of Pernambuco, Brazil.

For the contributions and development of this study, the cartographic base or Shapefile provided by the Brazilian Institute of Geography and Statistics (IBGE) [11] was used to define the boundaries of the study area and municipal limits using the ‘clip()’ method, which enabled the visualization of the scene restricted to the municipal boundaries of the study area. Subsequently, time intervals were created for image generation through the collection of images from the Landsat-8 satellite

(Collection 8) for surface reflectance. These images were captured monthly to select the clearest possible images, and an image for each year from 2013 to 2022 was created for *NDVI*, *SAVI*, and *LAI* indices.

The data collection began on 20 September 2023, and the *NDVI*, *SAVI*, *LAI*, and MapBiomas indices were generated on 18–20 and 22 November 2023, respectively. The resolution of the images was 30 m, and all were processed in Google Earth Engine. A metadata filter was applied to reduce the influence of clouds on the scenes, aiming to obtain scenes with less than 3% cloud cover. This cloud filtering allowed for images with reduced atmospheric influence for each year, and the scene values were converted to surface reflectance values.

The 'merge()' method was used for image overlay or combination, which allows the creation of a single block of scenes for all months of each year to form a composite image for each year from 2013 to 2022. Additionally, the 'mean()' method was applied to this set of scenes to generate an average pixel for each pixel in the image set, providing a representation of the study area using average pixels over the studied time interval.

Thus, manipulating the mean bands present in this sensor system made it possible to capture critical visual information about the Earth's surface components by transferring the red band to near-infrared wavelengths, analyzing the relationship between the green band and red wavelengths, and finally examining the blue band in relation to green wavelengths. This resulted in vegetation cover representation for the study area based on average pixels over the studied time interval [12].

Using ERA5 Ag data from the Climate Engine platform [12], it is possible to observe the region's climatic behavior from 2013 to 2022 in **Figure 2** below. Precipitation shows significant variation, with peaks during the rainy season and periods of more intense rainfall. Atmospheric water demand, represented by reference evapotranspiration (ETo), remains stable throughout the year, with minor monthly variations. Maximum and minimum temperatures follow a similar pattern with seasonal fluctuations, differing only in their ranges.

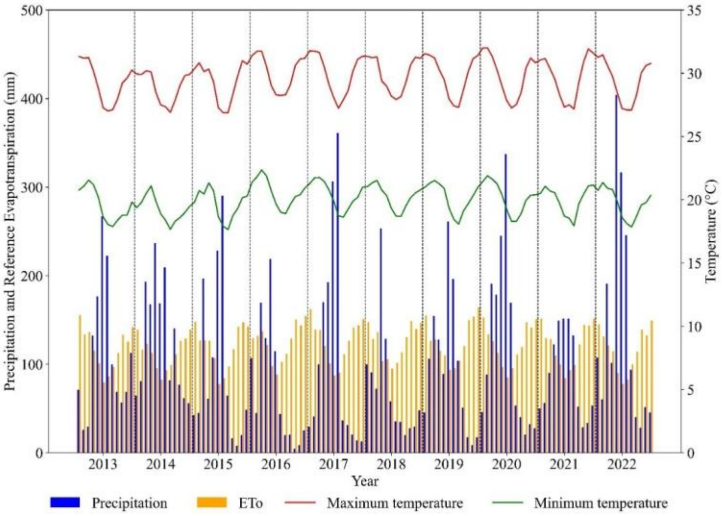


Figure 2. Monthly distribution of precipitation (mm), reference evapotranspiration (ETo) (mm), maximum and minimum temperature (°C) in the Mata Norte, State of Pernambuco, Brazil, from 2013 to 2022.

2.2. Satellite data (landsat-8 OLI sensor)

Using data from the Landsat-8 satellite with the OLI (Operational Land Imager) sensor, land surface images were generated with a revisit frequency of approximately 16 days. Thematic land cover and land use maps for Mata Norte were developed using multitemporal data series in GeoTIFF format with a spatial resolution of 30 m [13].

The average pixel value of the images was calculated for all Landsat-8 bands within the study area boundaries to provide critical information on vegetation cover, including areas such as environmental reserves, agricultural zones, livestock areas, and others. This calculation was based on the annual digital processing of average pixels, where orbital images were digitally processed pixel by pixel on the Google Earth Engine (GEE) platform.

2.3. Normalized difference vegetation index (*NDVI*)

It is a widely used remote sensing index for vegetation, designed to quantify areas of low, medium, and high vegetation within a given area. This index has broad applications for quantifying vegetation presence in environmental protection areas, agricultural crops, and land use changes [14] (pp. 1077–1084).

Proposed by Tucker [15] (pp. 127–150), the *NDVI* as defined by Equation (1) reflects variations in green canopy cover through the ratio of the difference between near-infrared (band 5) and red (band 4), where *NIR* represents the spectral reflectance of band 5 and *RED* represents the spectral reflectance of band 4.

$$NDVI = \left(\frac{NIR - RED}{NIR + RED}\right) \tag{1}$$

As a result, *NDVI* values can range from −1 to +1, with positive values indicating a greater presence of healthy vegetation and negative values indicating areas with little or no vegetation.

2.4. Soil-adjusted vegetation index (*SAVI*)

The *SAVI* (Soil-Adjusted Vegetation Index) was developed by Huete [16] (pp. 295–309). It is an index that uses the same multispectral bands as *NDVI*, but it takes into account the presence of exposed soil in the area, meaning it tends to reduce the effects of soil on the surface and aims to improve the values found in *NDVI*.

According to [14] (pp. 1077–1084), the equation differs from *NDVI* in the term (1 + *L*), where *L* is a constant. (*NIR*) refers to the band corresponding to near-infrared reflectance; (*RED*) refers to the band corresponding to red reflectance; (*L*) is an adjustment factor, considered an empirical constant that aims to minimize the sensitivity of the vegetation index to reflectance variations of soil types, and can be calculated according to Equation (2):

$$SAVI = \frac{(1 + L) \times (NIR - RED)}{(NIR + RED + L)} \tag{2}$$

where *L* is the soil adjustment factor. *NIR* and *RED* are the Near Infrared and Red bands, respectively. This study used an *L* of 0.5. According to Huete's methodology [16] (pp. 295–309), the *L* factor can have variable values. According to the author, the values can range from 0 to 1, representing the following: Low vegetation densities can use a value of 1, medium vegetation densities a value of 0.5, and high vegetation densities a value of 0.25.

2.5. Leaf area index (*LAI*)

The Leaf Area Index (*LAI*) plays a significant role in processes such as canopy interception, where it estimates the biomass of the entire vegetative part of the plant. *LAI* is the ratio between the leaf area of the entire vegetation and the unit area in which the vegetation is located, obtained by Equation (3) [17].

$$IAF = \frac{-log\left(\frac{1.27 - SAVI}{1.10}\right)}{1.20} \tag{3}$$

The Leaf Area Index (*LAI*) is a valuable index used to predict crop growth, estimate foliage coverage, and assess vegetation health. The *LAI* values range from 0 to 3.5. For example, values of 0.5 indicate a vertical canopy structure; values of 1 indicate a spheroid canopy, while values close to 3 indicate a horizontal canopy. These values provided more information on how they were compared with real data [18].

2.6. Land use and land cover (LULC) data—MapBiomas Brazil

MapBiomas Brazil monitors land cover and land use in the country. It is also a project responsible for producing maps and providing annual data on land cover and use since Brazil's re-democratization in 1985. The data includes deforestation, vegetation, pastures, and other land uses, with the aim of analyzing transformations in the Brazilian territory and combating climate change [19].

An extension of MapBiomas is the land cover and land use data (LULC), which, in addition to being available on this platform, is also accessible on Google Earth Engine and QGIS. With this data, it is possible to analyze the effects of changes in land cover and use on spatiotemporal variation. For the 10 years of study, *NDVI*, *LAI*, and the MapBiomas Collection 8, from the years 2013 to 2014, were used, including classes 1, 3, 4, and 5.

It was observed in **Figure 2** that the region's climatic behavior from 2013 to 2022 showed high precipitation variability, with peaks during the rainy season and occasional periods of intense rainfall, while other periods exhibited low precipitation. Consequently, the plants experienced higher water deficits. These changes in climate patterns have been observed in recent years under the influence of climate change. The increasing recurrence of extreme rain or drought events strengthens the region's temporal seasonality [20] (pp. 969–980).

The author [21] highlights that precipitation seasonality has a significant influence on the dynamics of soil water availability and, consequently, on plant vigor. This factor influences the data analyzed during vegetation cover observations using *NDVI*. For example, precipitation values during the 2013–2022 period (**Figure 2**) corresponded to years of lower and higher vegetative vigor indices based on precipitation data, respectively.

3. Results and discussion

Geospatial information was extracted by determining vegetation spectral indices at the surface, resulting in the highlighted thematic maps. The indices detected changes in vegetation behavior, especially in sugarcane and pasture areas over the study periods in this region, which has historically been linked to the sugarcane industry.

The authors [22] (pp. 70–90) identified changes in agricultural production in the Zona da Mata region of Pernambuco from 2000 to 2020. There was a reduction in harvested sugarcane area (−0.30 annual growth), making way for other crops such as guava and grape, which showed annual growth rates of 13.23% and 1.79%, respectively. These results highlight significant variations in agricultural production dynamics in this region.

Other authors also highlight the production of eucalyptus on hillside areas that were previously occupied by sugarcane. According to [23] (pp. 7004–7023), there is now a need for the sugarcane industries to adapt to the country’s current environmental legislation, which recognizes the importance of contributing to carbon sequestration instead of burning sugarcane fields.

Table 1 below, using 2012 as a reference point, primarily shows a slight reduction or stabilization in sugarcane areas. Meanwhile, pasture areas exhibit more dynamic trends, increasing and decreasing over time, and agricultural areas—which generally encompass fruit crops, vegetables, and other types—show varied changes.

Table 1. Area in hectares of the main geographic observations in the region detected by remote sensing data.

Year	Forest	Non-forest Natural Formation	Livestock	Agriculture	Non-vegetated Area	Water Bodies	Sugarcane
Hectare							
2012	**36,451.08**	**184.41**	**56,260.44**	**163,781.82**	**5473.53**	**4921.92**	**59,632.74**
2013	36,658.98	205.11	62,982.09	157,444.11	5657.13	4761.09	58,997.07
2014	36,775.53	216.54	62,877.96	157,192.65	6161.4	4555.71	58,925.79
2015	37,087.65	217.08	62,517.69	157,203.72	6356.16	4476.06	58,848.03
2016	37,215.45	226.08	61,209.81	158,351.67	6517.89	4524.21	58,661.1
2017	37,908.0	253.62	57,899.79	161,047.17	6813.99	4512.33	58,272.39
2018	37,859.4	280.17	53,840.34	164,575.26	7313.76	4585.05	58,252.86
2019	38,806.92	295.47	51,227.55	166,017.15	7560.63	4549.05	58,250.07
2020	38,960.73	318.69	49,611.33	167,391.18	7666.56	4526.1	58,232.7
2021	39,825.63	314.64	48,532.86	167,709.33	7678.98	4410.36	58,235.85
2022	44,994.42	328.5	48,342.06	161,760.15	8139.6	4874.85	58,267.71

The sugarcane area in 2013, the initial year of analysis, was already smaller compared to the previous year, 2012, demonstrating that this trend had already been observed, corroborating the findings of authors who highlighted the reduction of planted and harvested sugarcane areas. Therefore, there was a significant slight reduction ($P < 0.05$), according to the Mann-Kendall statistical test, from 59,632.74 ha in 2012 to 58,267.71 ha in 2022 (**Figure 3**).

It was observed that livestock areas in 2013 had already increased compared to the previous year and continued growing until 2016, after which they began to decrease until the last year of evaluation, with a significant reduction ($P < 0.05$) and a Kendall coefficient (τ) of −0.82. This sharp decline in pasture areas may have been influenced by a severe drought during that period, which peaked that year, according to authors [3]. This condition may have contributed to pasture degradation, especially as these areas were traditionally cultivated in the humid zones of Pernambuco's Mata region with *Brachiaria decumbens* for cattle grazing.

By the authors [24] Pointed out that, among many factors contributing to pasture degradation in Brazil, particularly in Pernambuco, the primary one is environmental conditions. For healthy pasture production, plants require favorable temperature, light, and moisture conditions.

Beyond climatic factors, the spatiotemporal dynamics of vegetation are influenced by anthropogenic agricultural activities. Areas where sugarcane fields were converted to pastures later transitioned to other activities, as observed in **Table 1**, including the growth of forest and agricultural areas, particularly fruit farming.

The classes "Forest", "Agriculture", and "Non-vegetated Areas" grew significantly ($P < 0.05$). The "Forest" class stands out for two reasons: First, the preservation of native forest fragments protected by environmental laws, and second, the increasing prominence of eucalyptus production in recent years.

Corroborating [25], an investigative review of recent literature revealed that a process of territorial restructuring is underway in the Mata region of the Northeast, particularly in the states of Alagoas and Pernambuco. This is due to the establishment of monoculture forestry plantations, especially on steep slopes previously cultivated with sugarcane.

This agricultural reality is mirrored in similar conditions described by other authors. In the neighboring state of Alagoas, Brazil, eucalyptus cultivation areas have expanded over the past 10 years, replacing sugarcane due to a reduction in cultivated area, productivity, and sugar production tonnage—primarily driven by climate change [26].

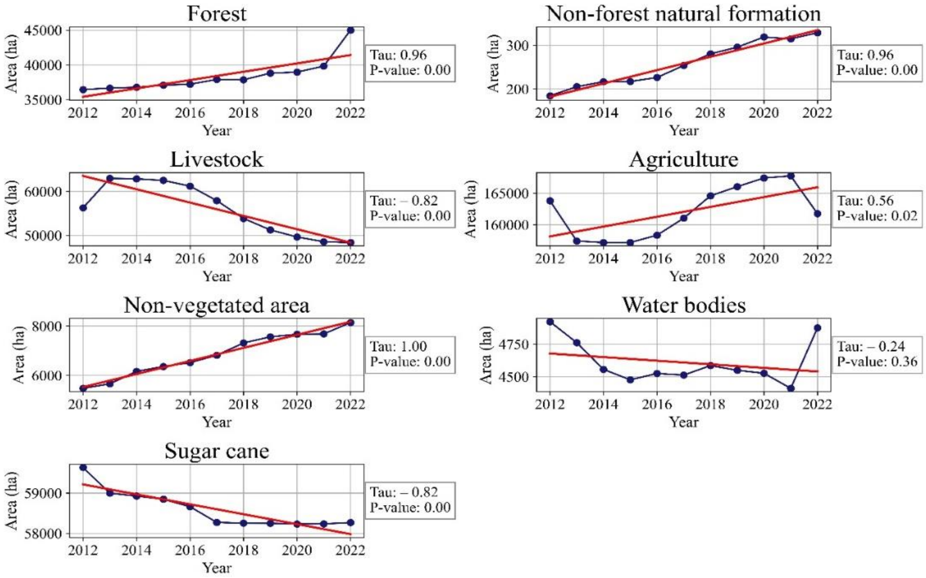


Figure 3. Trend of land use and land cover (LULC) classes according to the Mann-Kendall statistical analysis for the Zona da Mata Region (2012 to 2022).

As described in the methodology, during the 10-year study period, there were years with normal precipitation and years of drought, particularly between 2015–2019 (**Figure 2**), which was an unusual condition for the region and may have contributed to the observed reduction in pastures. **Figure 3** presents a graph summarizing all the results of the behavior described.

In general, pasture productivity in the Zona da Mata Norte region of Pernambuco is markedly seasonal, with the primary long-term physical stress being the dry season, during which forage becomes scarce or non-existent, directly reflected in near-zero *NDVI* values [27] (pp. 1–7).

In **Figure 4** below, the transition matrix of land use classes between 2012 and 2022 shows that although there was a reduction in sugarcane area, 97.4% of its original 2012 area was maintained, while 2.3% of the area was converted to the ‘Agriculture’ classification. The livestock class retained only 60.5% of its 2012 area, with 36.3% of its initial area being converted to ‘Agriculture’ by 2022. Additionally, 90.4% of forested areas were preserved, as well as over 90% of the non-vegetated areas from their original 2012 extent.

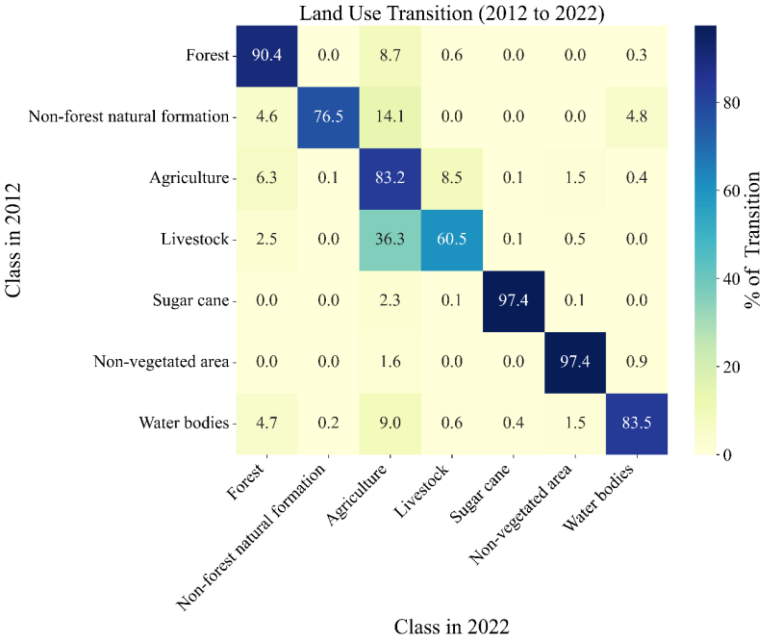


Figure 4. Land use and land cover class transition matrix from 2012 to 2022 in the Zona da Mata of Pernambuco.

The observed climate influence raises concerns about the recurrence of anomalies in climatic patterns, which has become increasingly worrisome for the modulation of rainfall variability in the region. According to the temporal recurrence of such phenomena, they determine whether they are considered low or high frequency, which can affect the entire agricultural production chain and compromise the accuracy of remote sensing indices [6] (pp. 193–206).

In alignment with the presented data, **Figure 5** illustrates *NDVI* maps over a temporal variation, showing that in 2013, there was a predominance of preserved areas and sugarcane cultivation areas. However, starting in 2014, a clear trend of degradation emerged, with exposed soil areas becoming more prevalent. These results emphasize the *NDVI*'s sensitivity to green-toned areas.

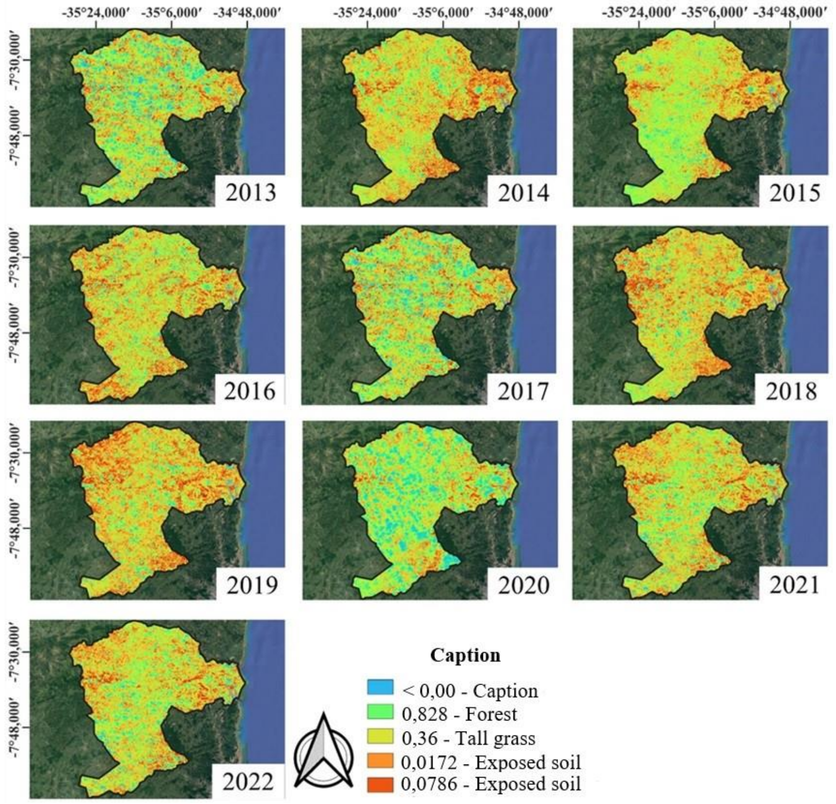


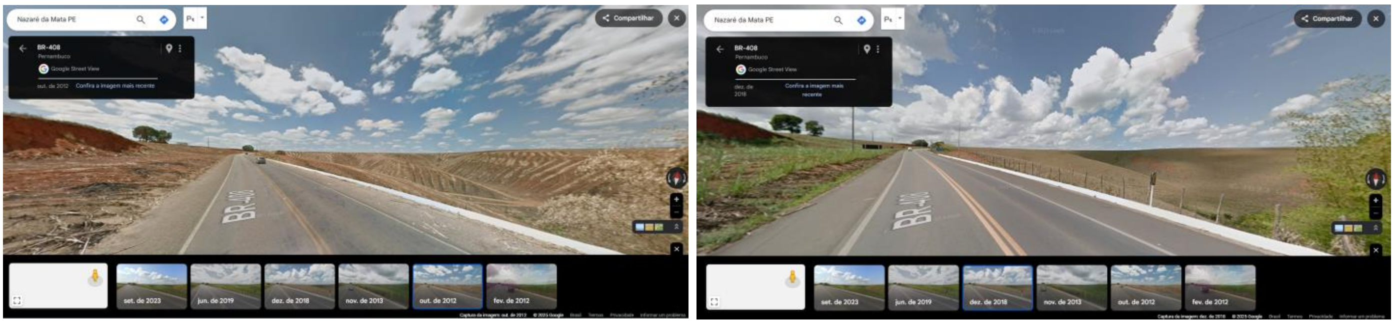
Figure 5. Spatiotemporal distribution of *NDVI* (normalized difference vegetation index) for the Zona da Mata of Pernambuco from 2013 to 2022.

Exposed soil is represented by orange and red tones, with a clear increase and decrease in these areas over the 10-year period. The factor contributing to this *NDVI* observation is the predominance of sugarcane cultivation in the region, as it leaves areas without vegetation for long periods, particularly during the harvest season [28] (pp. 841–855).

Another factor influencing this *NDVI* analysis is the presence of pasture areas, shown as tall grass with yellowish tones. In areas with cattle, trampling on pastures leads to soil exposure, which may also be related to degraded pastures, especially in the western portion of the studied region. This area already had livestock activity in the early years of the study, starting in 2012.

Additionally, exposed soil may result from the discontinuation of sugarcane production in areas where cultivation is no longer viable, primarily due to drought, leading to a phenomenon referred to as "abandonment" or "scrapping", where the land is later converted into pasture. However, the most significant contributor to exposed soil is sugarcane cultivation, where exposed areas become evident after harvest, as noted by Moura [29].

In **Figure 6** below, it is possible to observe an example of soil exposure in the municipality of Nazaré da Mata—PE, showing the same area but with different crops and seasons. In **Figure 6A**, the area previously had sugarcane in 2012, presenting exposed soil after harvest. In **Figure 6B**, taken years later in 2018, the area has been converted into pasture, which also shows fragments of exposed soil.



(A) **(B)**

Figure 6. Soil exposure. **(A)** sugarcane harvested area in 2012; **(B)** degraded pasture in 2018.

Source: Google Maps (2025), Nazaré da Mata—PE. Coordinates: 7°43′55.3″ S 35°14′12.6″ W [30].

The observation of green tones over native forest (**Figure 3**) corroborates with authors [7], who observed that even in years of severe droughts, there was an exception for the Zona da Mata, where a predominance of green vegetation tones was observed between 2012 and 2017, compared to other regions during a drought period. This occurs due to its location, as the vegetation native to the Mata Norte is composed of Atlantic Forest, and this biome has survived in fragments throughout years of agricultural exploitation in the region [29].

It is important to highlight [31] when examining changes in vegetation and soil, observing that on days with precipitation, the *NDVI* showed higher values. Moreover, humidity conditions can cause changes in reflectance, while on days without precipitation, the indices were lower. Therefore, to better understand the values found in the *NDVI*, the *SAVI* was used, considering an adjustment value for *L* of 0.5, which is used for areas with medium vegetation density.

After this analysis, the *IAF* index was applied, an important tool that shows higher values in areas where the vegetation had greater biomass, ensuring the reliability of the results. However, this study observed that cloud cover is frequent throughout the year, which restricted the quantification and precise analysis of vegetation in the study areas. Additionally, the spatial and temporal resolution of the Landsat images used to generate the vegetation indices should also be considered.

Ling et al. [32] also reported the presence of clouds as limiting factors when working with satellite data. Furthermore, the spatial and temporal resolution of the Landsat images used to generate vegetation indices should also be considered, as, for example, smoothing the *NDVI* values at lower resolutions leads to significant underestimations in heterogeneous landscapes [33].

To deepen the results of this study, future analyses using satellites with higher frequency passes and better spatial resolution represent a promising alternative. This is because it was observed that areas occupied by eucalyptus are generally located on slopes, and *NDVI* is the most commonly used indicator recently, as it partially reduces the effect of topography and presents a linear measurement scale between −1 and 1 [23] (pp. 7004–7023).

The few remaining forest areas in the region are typically for environmental preservation and eucalyptus plantation production, both predominantly on slopes.

Figure 7 below presents information on native forests highlighted by the red tone through the Leaf Area Index (*IAF*).

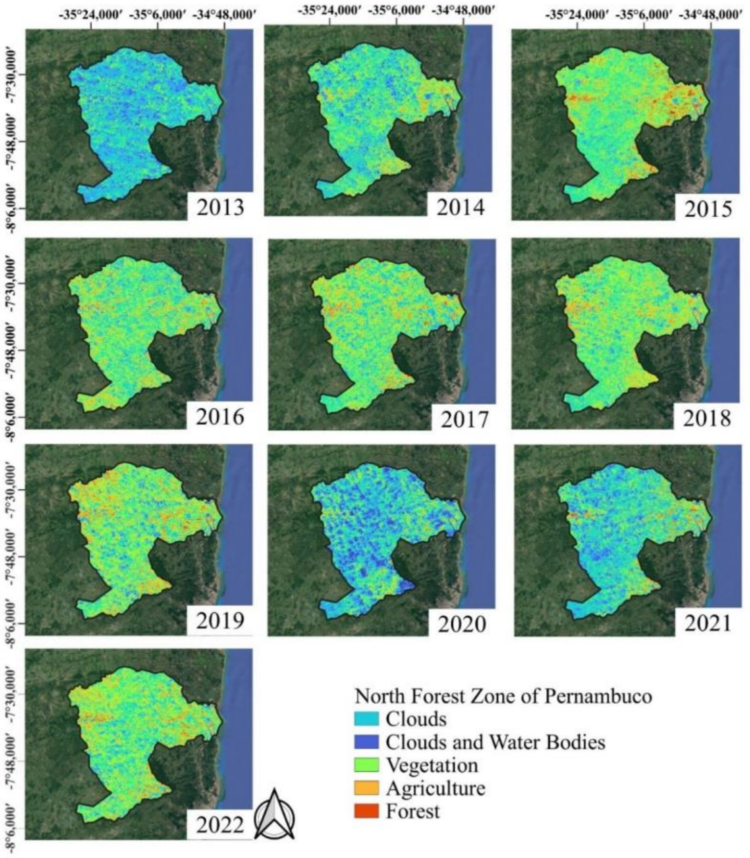


Figure 7. Spatio-temporal distribution of the *LAI* (leaf area index) for the Mata Norte region of Pernambuco from 2013 to 2022.

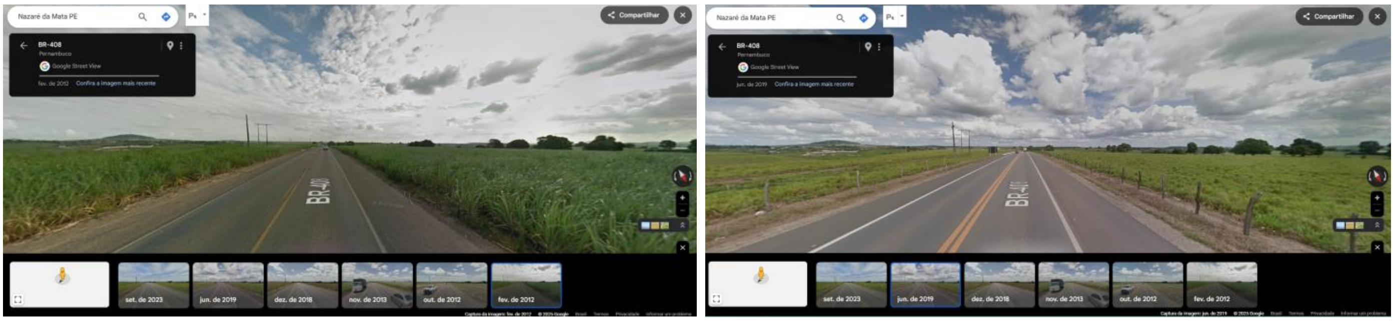
Cloud cover was more present in some images during the average of a year than in others (2013, 2014, 2020, 2021), and to mask this effect, a 3% filter was applied. Nevertheless, a few forest areas were still noticeable, which are actually fragments of the original native forest. These forest areas and degraded riparian forests lose their ability to naturally revert to their original state or a state of equilibrium, becoming areas that do not have the capacity to replenish organic matter in the soil, soil fertility, or seed banks. Moura [29] correlated field data with images obtained from the vegetation cover index for the municipality of Macaparana, finding that there are fully isolated fragments, often close to sugarcane plantations.

The authors [34] clarify that, despite the GEE being a cloud-based platform with free processing, issues can still arise due to cloud cover when capturing scenes with orbital sensors. On the other hand, GEE not only facilitates the inclusion of algorithms that mitigate this issue but also allows us to filter scenes that have less atmospheric influence, for example, using a filter with images that have 3% cloud influence.

The data from the *IAF* confirm the results of the increase in forest areas and the reduction of livestock activities located in the municipalities further west of the region. In other areas, [28] (pp. 841–855) detected the use of sugarcane burning in the Zona da Mata of Pernambuco, confirming the presence of the crop even after the harvest period. This also supports the idea of the recovery of sugarcane areas after periods of drought, as the *IAF* presented a higher vegetation index.

The *NDVI* indicated a slight fluctuation in vegetation over the years, ranging from 0.23 to 0.34. On the other hand, the *IAF* showed an increasing trend until 2020, followed by a slight decline in the following years, with values ranging from 0.13 to 0.30. The CV (%) for *IAF* showed a high variation over time, indicatiBng greater susceptibility to fluctuations compared to the *NDVI*. The data accurately reflect the vegetation dynamics in the region, such as volatility in vegetation cover patterns, possibly influenced by land-use changes.

Figure 8 below shows, along on BR 408 near the city of Nazaré da Mata—PE, this land-use change from sugarcane cultivation in 2012 (**Figure 8A**) to pasture in 2019 (**Figure 8B**).



(A) **(B)**

Figure 8. Land use change. **(A)** sugarcane area in 2012; **(B)** pasture area in 2019.

Source: Google Maps (2025), Nazaré da Mata—PE. Coordinates: 7°47′06.4″ S 35°14′29.2″ W [30].

Table 2 below presents the statistical results and quantitative variability of the time series related to the *NDVI* and *IAF* extracted from GEE. The *NDVI* fluctuated between 0.23 and 0.34, while the *IAF* showed an increase until 2020, followed by a slight decline, varying between 0.13 and 0.30. The CV (%) of the *IAF* was higher, indicating greater variability than the *NDVI*. These data reflect the vegetation dynamics and possible land use changes in the region.

Vegetation indices were analyzed on an annual scale to standardize with the LULC data from MapBiomas, which are available only at this scale. However, vegetation is dynamic and varies according to the phenological phases of crops such as sugarcane and pasture [7]. Furthermore, monthly precipitation directly influences vegetation quality and, consequently, vegetation indices [20] (pp. 969–980).

A study evaluating the dynamics of these crops in the study area on a monthly scale could more accurately quantify the extent of these areas, as well as the succession and rotation of crops. Additionally, it is suggested that monthly indices could be used as input data in machine learning models for land use and land cover classification [35].

Table 2. Statistical analysis and quantitative variability of the time series for *NDVI* (normalized difference vegetation index) and *LAI* (leaf area index) in the Zona da Mata of Pernambuco. SD—standard deviation, CV (%)—coefficient of variation percentage.

NDVI					
Year	**Minimum**	**Maximum**	**Average**	**SD**	**CV(%)**
2013	−0.21	0.69	0.23	0.11	47.47
2014	−0.22	0.58	0.27	0.09	34.28
2015	−0.2	0.56	0.24	0.09	36.18
2016	−0.19	0.57	0.27	0.1	36.38
2017	−0.21	0.69	0.23	0.11	47.47
2018	−0.21	0.6	0.27	0.1	35.31
2019	−0.22	0.55	0.28	0.09	33.43
2020	−0.18	0.64	0.2	0.1	48.14
2021	−0.18	0.56	0.25	0.09	37.23
2022	−0.18	0.56	0.25	0.09	37.23
LAI (m^2m^{-2})					
Year	**Minimum**	**Maximum**	**Average**	**SD**	**CV(%)**
2013	−0.3	1.26	0.15	0.15	97.69
2014	−0.31	0.83	0.21	0.13	65.14
2015	−0.29	0.8	0.17	0.13	74.65
2016	−0.28	0.81	0.21	0.14	68.87
2017	−0.28	0.79	0.17	0.14	78.86
2018	−0.31	0.9	0.21	0.14	65.4
2019	−0.31	0.77	0.23	0.14	60.93
2020	−0.28	1.06	0.12	0.13	111.67
2021	−0.29	0.84	0.1	0.13	129.95
2022	−0.28	0.79	0.19	0.14	72.1

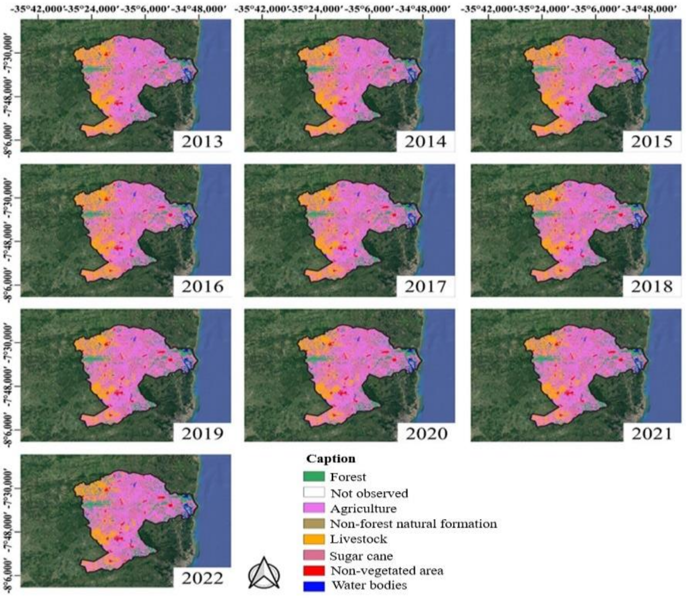


Figure 9. Dynamics of land use and land cover in the Mata Norte.

In addition to other functionalities, vegetation indices generated from satellite images can be used to predict the productivity of crops such as sugarcane, with the advantage of covering large areas [36].

To identify the main land use and land cover conditions, the dataset and thematic maps from the MapBiomas land cover collection were used, as shown in **Figure 9**. It is possible to observe, through the color palette of collection 8, that the main colors appearing are pink, yellow, red, and green, respectively representing agricultural and sugarcane areas, livestock farming, non-vegetated areas, and forest areas.

The authors [37] (pp. 573–595), studying the potential of the Zona da Mata and Agreste regions of northeastern Brazil for the implementation of integrated crop-livestock-forest systems, found the presence of pasture areas in the region, supporting the images collected.

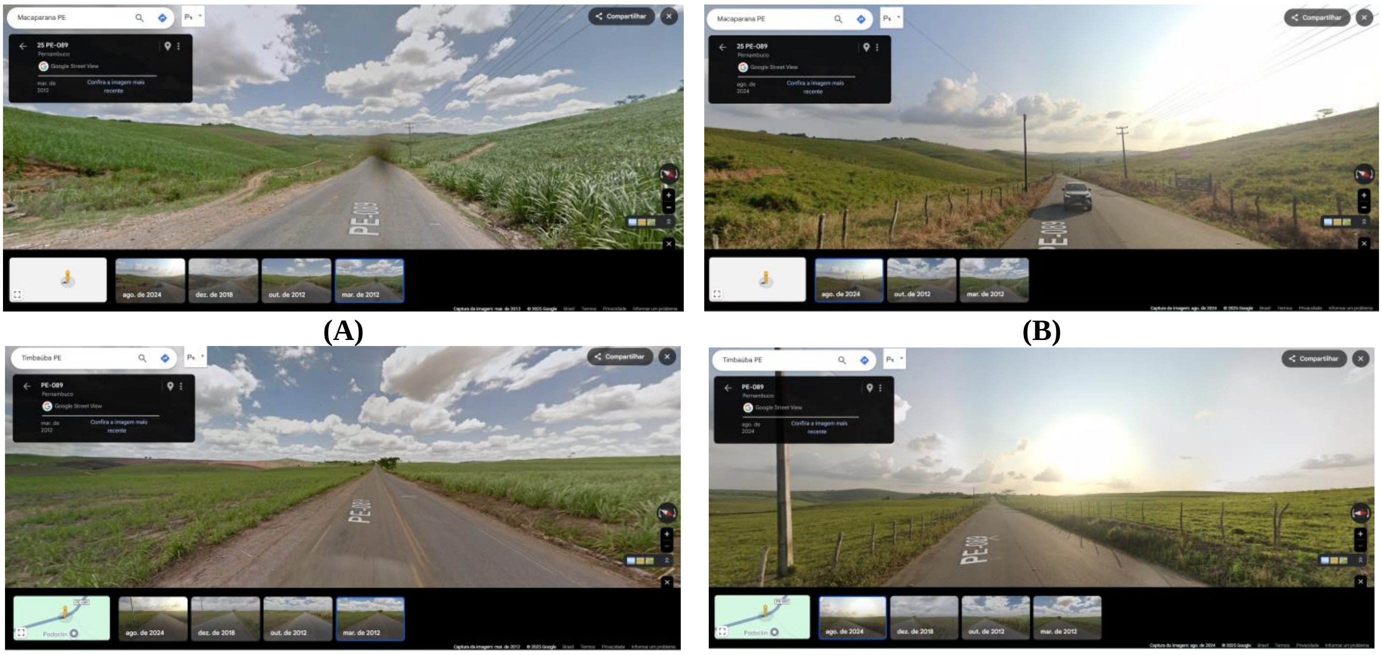
Since the work [38] (pp. 391–402) highlighted the importance of livestock farming in the Zona da Mata region of Pernambuco, even though sugarcane cultivation is predominant, these authors emphasized some positive aspects that encourage agricultural activities. Furthermore, today, livestock farming also represents an alternative land use when properly managed, as it provides vegetation cover, soil protection, and carbon sequestration. An interesting observation from **Figure 9** is the proximity of livestock and pasture areas, which are located more to the west of the region, bordering the Agreste region.

According to [39] (pp. 58–68), historically, the Agreste region has had livestock farming as its main activity, and because it is a transitional area, it exerts some influence on the Zona da Mata region, where sugarcane cultivation is the primary activity. The following **Figure 10** provides a snapshot of the municipalities within this region that showed the highest levels of livestock activity.

Figure 10. Municipalities with the highest livestock activity in the Zona da Mata region of Pernambuco.

This section of the figure was separated because it reveals an interesting pattern observed further south of the region. In the municipality of Glória do Goitá—PE, the data observed from **Figure 9** and **Table 1** initially showed larger pasture areas. After 10 years, these areas were reduced, while other municipalities, such as Macaparana—PE and Timbaúba—PE, developed livestock farming, converting areas previously occupied by sugarcane into pasture for cattle ranching.

The following **Figure 11A**,**B** shows the area near Macaparana, with sugarcane cultivation in 2012 (A) and pasture in 2024 (B). **Figure 11C**,**D** are near the city of Timbaúba, also showing sugarcane cultivation in 2012 (C) and, more recently in 2024, the area transformed into pasture (D).



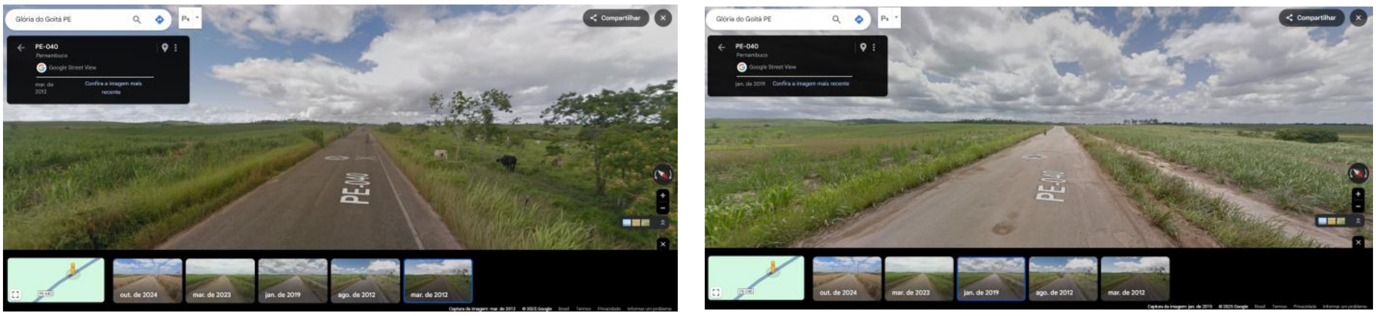
(A) **(B)**

(C) **(D)**

Figure 11. Land use change. **(A)** sugarcane area in 2012; **(B)** pasture area in 2024; **(C)** sugarcane area in 2012; **(D)** pasture area in 2024.

Source: Google Maps (2025), (A) and (B): Macaparana—PE. Coordinates: 7°33′47.0″ S 35°26′11.5″ W; (C) and (D): Timbaúba—PE. Coordinates: 7°33′05.6″ S 35°20′51.1″ W [30].

The opposite occurs in the municipality of Glória do Goitá—PE. Visually in **Figure 9** (LULC), a reduction in the yellow areas on the map, which correspond to livestock farming, is observed. Particularly from the year 2018 onwards, the return of the pink shade over the yellow areas is noticeable, indicating the return of sugarcane cultivation, which is considered one of the factors attributed to the return of the regular rainfall pattern. The following **Figure 12** shows this reality in the field, where A represents the situation in 2012, with pasture on one side of the highway, and B represents the same side, more recently, with sugarcane cultivation.



(A) **(B)**

Figure 12. Land use change. **(A)** area of sugarcane and pasture divided by the road; **(B)** total area whit sugarcane.

Source: Google Maps (2025), Glória do Goitá—PE. Coordinates: 8°00′12.3″ S 35°15′52.2″ W [30].

The author Lima [26] highlighted the pastoral potential of the Zona da Mata region for agricultural activities. However, by examining the images, a slight reduction in livestock farming areas can be observed, which may have occurred over the past decade, indicating the recovery and/or expansion of sugarcane areas after climate-induced drought events in the region.

During the period in question, the annual precipitation varied from 898 mm in 2018 to 1686 mm in 2022. This explains the return of sugarcane plantations in the MapBiomas thematic maps in recent years. The authors [9] state that these variabilities are a result of atmospheric factors such as low solar radiation intensity, high cloud cover, fluctuations in relative humidity, and atmospheric pressure oscillation.

In addition to precipitation as an important factor for the recovery of sugarcane, the growing areas of eucalyptus forests, also described by [40], have led to a new land occupation and use, contributing to the reduction of exposed soil areas. Another climatic variable that stands out in the development of environmental impact studies is air temperature. In all of these factors, the GEE demonstrates reliability in environmental data analysis, facilitating the identification of land use and land cover, as well as providing information according to the authors [41] (pp. 15280–15300).

Historically (1952–2018), some municipalities in the northern Zona da Mata of Pernambuco exhibited negative temperature anomalies, namely Macaparana (1.5 °C) and Buenos Aires (1.0 °C), as observed by Anjos [9]. This suggests lower temperatures in the region, which aligns with the results obtained on the map during the period of lower precipitation, affecting both pasture and sugarcane areas.

4. Conclusion

The results found contribute to the understanding of changes in the agricultural landscape and their relationship with climatic and anthropogenic factors, addressing an important issue in the dynamics of agricultural land use, particularly in a region where sugarcane cultivation is a fundamental economic activity. Therefore, the findings are valuable for policymakers, environmental and agricultural planners.

Although there was a slight decrease in sugarcane areas, it continues to dominate agricultural activity in the Zona da Mata Norte region of Pernambuco, maintaining 97.4% of its initial area from the years of this study. In contrast, the area dedicated to livestock activity remained at 60.5% of its initial area, showing a reduction over the course of the 10 years of study.

In the study area, livestock activity fluctuated, increasing and decreasing over the years, reflecting the recovery of areas for sugarcane cultivation and other types of agriculture, influenced by rainfall regimes and current sustainable markets. The dry period observed starting in 2016 was also correlated with the increase in forest areas, including planted forests, particularly those for eucalyptus cultivation, which other authors have also reported in the region.

In summary, the importance of satellite data over time is crucial for behavioral studies of agricultural activities, providing insights into how the environment is influenced by both anthropogenic and climatic factors in progress. This methodology can later be used for further comparisons.

To deepen the results of this study, future analyses using satellites with more frequent passes and better spatial resolution would represent a promising alternative. The *NDVI*, *SAVI*, and *IAF* values were ideal for meeting the objectives of this study, while cloud interference should be further studied to mitigate the effects of cloud cover on the images.

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