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Posted Date: 27 May 2026

doi: 10.20944/preprints202605.1889.v1

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Article

Spatio-Temporal Dynamics of Land Use and Cover in the MATOPIBA Region, Brazil (1985–2055)

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Abstract

This study analyzes the changes in land use and land cover over time in the Porto Nacional micro-region, situated in the MATOPIBA agricultural frontier, from 1985 to 2055. It emphasizes the increasing anthropogenic pressure on the ecosystems of the Brazilian Cerrado. The primary goal of this research is to understand how the territory has transformed and to project future scenarios related to agricultural expansion, urbanization, and unplanned land use. The methodology incorporates geoprocessing techniques, spatio-temporal analysis, data from the MapBiomas platform, remote sensing imagery, and time series analysis. Seven categories of land use and land cover were examined, with a focus on forest formations, savannas, agricultural areas, and pastures. Descriptive statistics, trend graphs, and regression methods were used to project changes through 2055. The results indicate a significant reduction in native vegetation, particularly in savanna formations, which is closely linked to the expansion of agricultural, livestock, and urban areas. The model used to simulate vegetation changes over time showed high reliability ($R^2 = 0.98$), forecasting that human expansion will continue to encroach on native vegetation through 2055. This underscores the urgent need for territorial planning and public policies to ensure the sustainability of the Cerrado.

Keywords: Cerrado biome; land use and cover; agricultural frontier; geoprocessing; remote sensing; spatio-temporal dynamics; territorial sustainability

1. Introduction

The analysis of land use and land cover dynamics over time and space has gained significant importance due to the changes in territory driven by human activities, particularly in the frontier regions of Brazilian agribusiness [1]. The Porto Nacional micro-region, situated in the state of Tocantins, is classified within the MATOPIBA geo-economic framework as one of its 31 micro-regions. This area represents a contemporary agricultural Brazilian frontier that includes the states of Maranhão, Tocantins, Piauí, and Bahia. Porto Nacional is a key territory for understanding the recent dynamics of agricultural expansion in the MATOPIBA [2].

MATOPIBA covers approximately 730 thousand km², which represents about 9% of Brazil's territory [3]. Primarily situated within the Cerrado biome, MATOPIBA has emerged in recent decades as a key frontier for the expansion of large-scale agriculture, particularly focused on producing grains such as soybeans and corn. This growth has been driven by public policies, private investments, and improvements in logistics infrastructure [4,5]. However, the intensification of production in this region has led to significant changes in the landscape, land tenure structure, and local ecological processes. Notably, these changes include soil degradation and the fragmentation of native ecosystems [6,7].

The Porto Nacional micro-region, the focus of this study, was characterized in 1985 by a land tenure structure dominated by livestock farming. At that time, the region had a low population density and limited economic significance [8]. However, with the establishment of the state of Tocantins in 1988, a process of territorial restructuring began. This development attracted migration flows and investments, which significantly changed land use and land cover in the region [9,10].

In 1985, savanna vegetation, characteristic of the Cerrado biome, dominated the landscape of this micro-region, covering more than two-thirds of the area [8]. However, over the next four decades, significant changes occurred as native areas were transformed for anthropogenic uses, primarily for agriculture, livestock, forestry, and urban expansion [9,11]. These alterations were largely driven by the establishment of hydroelectric power plants, the construction of highways, and the development of MATOPIBA as an agricultural production frontier [12].

Since MATOPIBA is situated within the important Brazilian biome, the Cerrado, which includes numerous river headwaters and fragile native vegetation, it is crucial to assess the impacts of agricultural expansion in this region. This study's main hypothesis is that the expansion of agriculture in the Porto Nacional micro-region, particularly since the 1990s, has significantly reduced native vegetation, particularly in savanna ecosystems, thereby compromising the ecological integrity of the Cerrado. Moreover, it is believed that the chaotic development of the micro-region, exacerbated by conflicts between economic growth and environmental conservation, has contributed to the degradation of natural environments. Thus, this study assumes that without regulatory interventions, the trends observed between 1985 and 2022 – specifically the increase in anthropized areas – will persist through 2055, further intensifying environmental and territorial impacts in the region.

The main objective of this study was to analyze the spatio-temporal dynamics of land use and land cover in the Porto Nacional/MATOPIBA micro-region from 1985 to 2055. We combined empirical data, geospatial analyses, and predictive modeling in our approach. Through a multi-temporal perspective, we aimed to understand the processes of land occupation, transformation, and environmental degradation associated with the expansion of the agricultural frontier. Our focus was on the implications of these changes for ecosystem sustainability and the challenges of territorial management. By providing both a historical and forward-looking overview of the changes that have taken place, this study aims to inform public policies, environmental planning, and conservation strategies that address the region's complexity and vulnerability.

2. Materials and Methods

2.1. Study Area

MATOPIBA is located at the geographical coordinates 02°00' S to 13°30' S and 42°00' W to 47°30' W, and covers an area of approximately 730,000 km². The site selected for the study comprises the Porto Nacional micro-region (Figure 1), which is located in the central region of the state of Tocantins between the coordinates 09°30' S to 11°00' S and 47°00' W to 48°30' W. This region corresponds to one of the 31 geoeconomic micro-regions that make up MATOPIBA. With an area of 21,197.73 km² [13] and comprising 11 (eleven) municipalities, the Porto Nacional micro-region has undergone intense transformations since the 1990s.

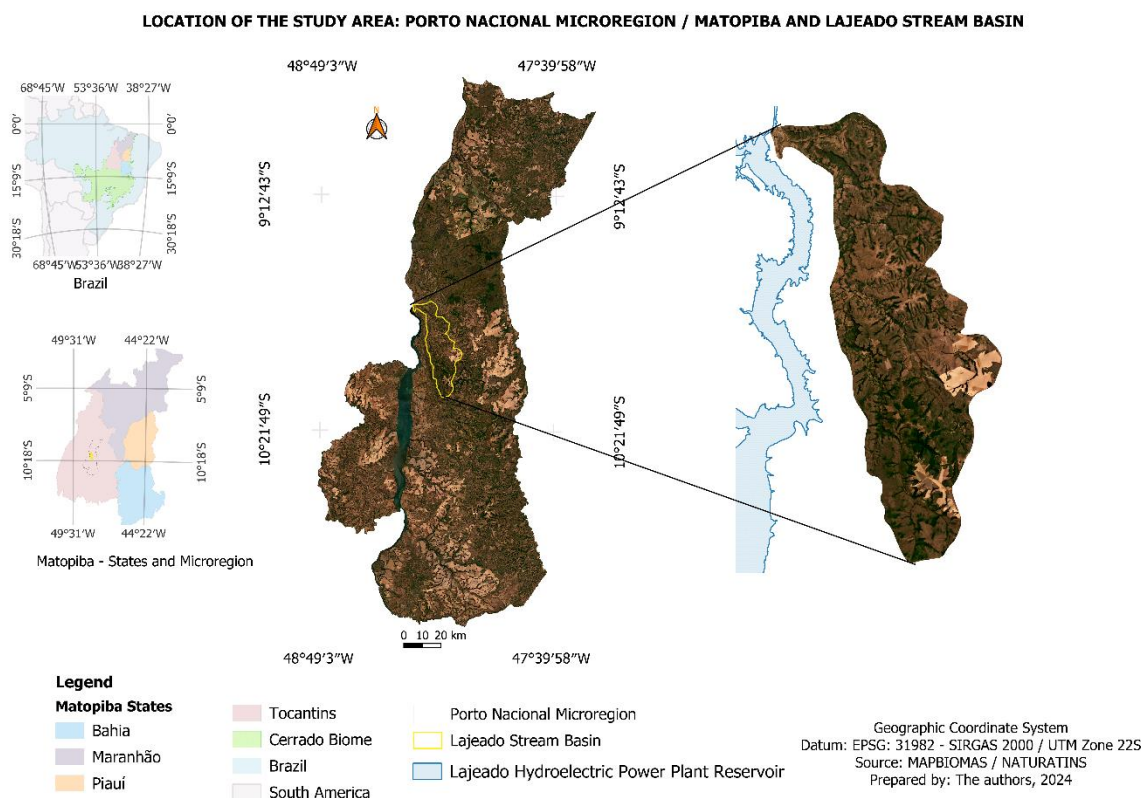


Figure 1. Location of the study area showing the Porto Nacional micro-region and the Ribeirão Lajeado sub-basin in the MATOPIBA region.

MATOPIBA is situated in a region that serves as a transition between different biomes. The majority of the area, about 91%, is covered by the Cerrado biome, while the Amazon biome accounts for ~7.3%, and the Caatinga biome covers ~1.7% [13]. About 86% of the vegetation in MATOPIBA consists of savanna formations, roughly 12% is forest formations, and ~2% is occupied by Caatinga and transitional xerophytic vegetation.

The region is dominated by a semi-humid tropical climate (~78% of the territory), with average temperatures above 18°C year-round and dry seasons lasting 4-7 months, generally coinciding with the winter season. The soils in the region generally have low natural fertility, and their profiles show an advanced degree of weathering, which is almost always associated with vast flat surfaces that make them suitable for agricultural mechanization [14].

2.2. Methodological Approach

The spatio-temporal analysis of land use and land cover in the Porto Nacional micro-region was conducted using satellite imagery from Collection 8 of the MapBioma project, which is available on the Google Earth Engine platform. This data, along with Digital Elevation Models (DEMs), was utilized to create thematic maps that physically characterize the study area. These maps support the analysis of territorial dynamics from 1985 to 2022, with a spatial resolution of 30 m.

The area being examined is located entirely within the Cerrado Morphoclimatic Domain. Therefore, this study focused exclusively on this domain and analyzed 14 land-use classes and native land cover. These classes include: forest formations; savanna formations; forestry; wetlands and marshes; open fields; pastures; sugarcane; mixed land use; urban areas; other non-vegetated areas; mining; rivers and lakes; soybeans; and other temporary crops.

The images were processed in the cloud using Google Earth Engine, utilizing Landsat mosaics from collections 5, 7, and 8, along with the MapBiomias user toolkit script (MapBiomias-user-toolkit-lulc.js). These images were generated at a scale of 1:250,000 and extracted with the following

parameters: Collection – 08; Tables – biome; Properties – name; Features – Cerrado; Data Type – coverage; Layers – from 1985 to 2022.

The raster images obtained were integrated into a Geographic Information System (GIS), along with vector data and other supporting information. QGIS software was used to reclassify the images based on the hexadecimal codes from the MapBioma Collection 8. Subsequently, the study area was spatially cropped based on the micro-region's shapefile, resulting in five land use and land cover classes, distributed in 10-year intervals for the first four periods and 7-year intervals for the last, covering the period from 1985 to 2022 (Figure 2).

Changes in land cover, whether an increase or a decrease, were analyzed by calculating the arithmetic mean of the examined values. The variation between periods was determined by calculating the ratio of the current area to the previous area, as illustrated in Equation 1.

$$X = \sum_1^4 \frac{X_n}{\eta}, \quad (1)$$

where X is the overall mean, X_n represents the differences in area across the different periods (1: 1985 minus 1995; 2: 1995 minus 2005; 3: 2005 minus 2015; 4: 2015 minus 2022), and η is the number of elements analyzed.

The data's accuracy was assessed using two complementary methods. The first considered the confidence interval, represented by two lines parallel to the prediction line, and the second used the coefficient of determination (R^2), which measures the correlation between observed and predicted data [15].

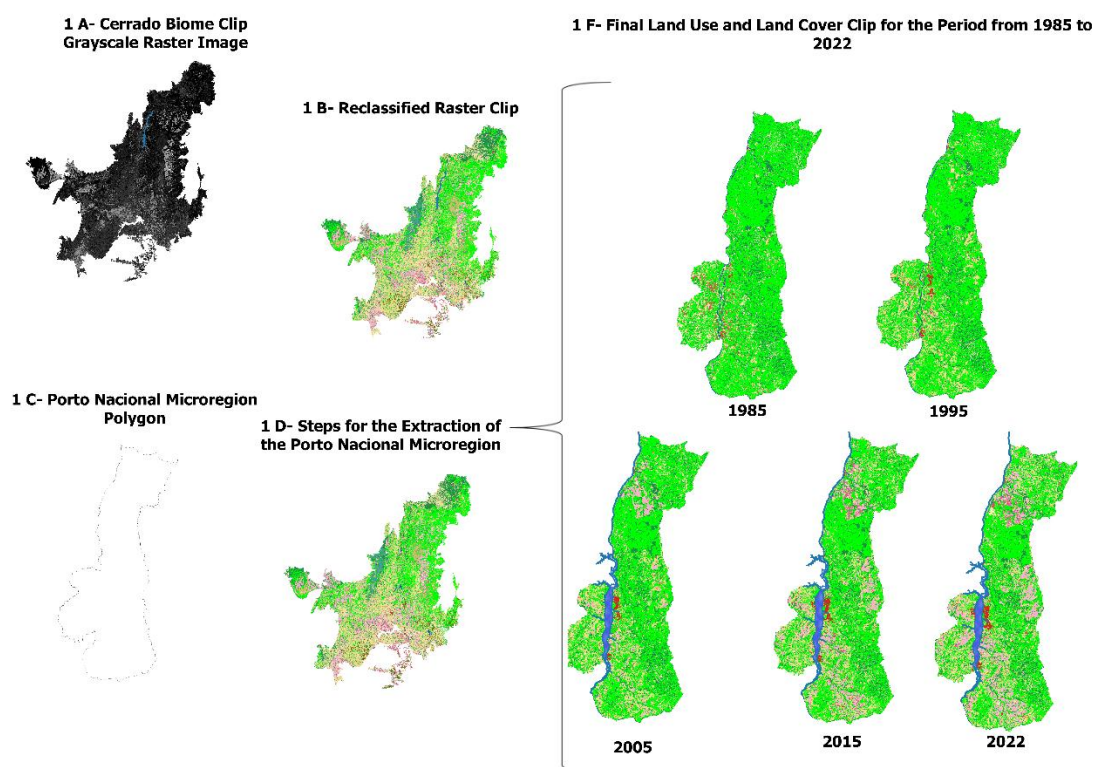


Figure 2. Methodological steps in the production of land use and land cover maps for the period from 1985 to 2020. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

3. Results

3.1. Spatio-Temporal Analysis of Land Use and Cover from 1985 to 2022

In 1985, the Porto Nacional/MATOPIBA micro-region covered 2,197.73 ha, accounting for 7.63% of Tocantins' area and 3.02% of the Matopiba region. Land cover was predominantly the Savanna Formation, occupying 66.36% of the territory and widely distributed throughout the region. The categories of rivers, lakes, wetlands, and marshes accounted for 0.68% and 0.79% of the total area, respectively, with the Tocantins River standing out in the western portion of the micro-region.

Forest and grassland formations accounted for 16.42% and 0.41% of the area, respectively, with forests more prevalent in valleys, slopes, and riverbanks, while grasslands occurred in isolated patches. Regarding land use, pastures occupied 3.23% of the area, concentrated mainly in the western, southwestern, and southern portions, while the mosaic of land uses covered 9.46% of the microregion.

Categories related to human activity accounted for approximately 15.34% of the study area, including pastures, mixed-use areas, other non-vegetated areas, and urbanized areas. The other non-vegetated areas category accounted for 2.48% of the study area, indicating the expansion of the agricultural frontier and increased deforestation, covering 526.20 km². Urbanized areas, on the other hand, accounted for only 0.17% of the microregion, or 35.10 km², indicating that the deforested area was about 15 times larger than the urban area during the analyzed period (Figure 3).

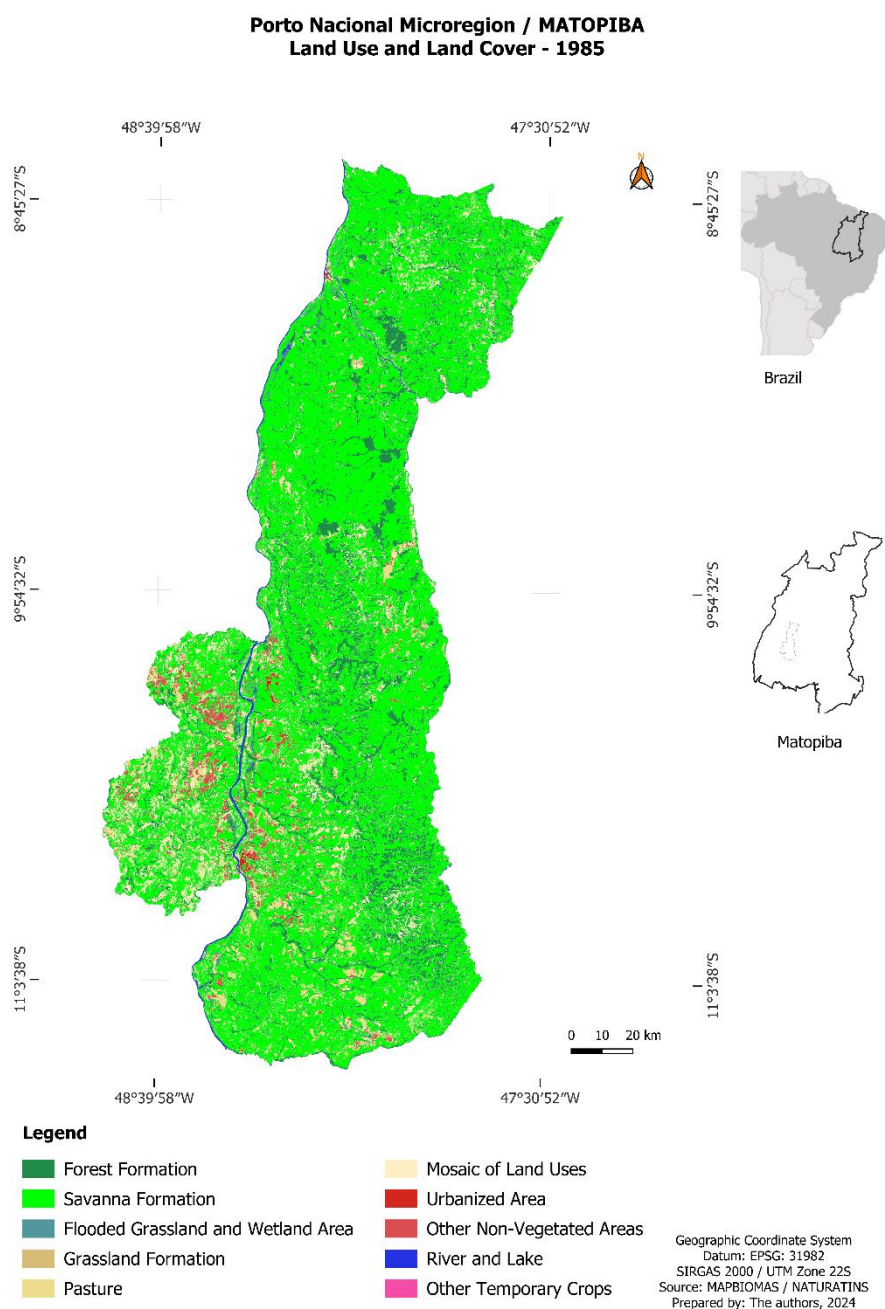


Figure 3. Spatial distribution of land use and vegetation cover in the Porto Nacional/Matopiba micro-region in 1985. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

Significant territorial and socioeconomic changes in the state of Tocantins characterized the 1980s and 1990s. These changes were largely driven by the state's creation in 1988 and the establishment of its capital, Palmas, in 1990. As a result, migration increased, and investments rose, especially in the agricultural sector [16]. In this context, a reduction in native land cover was observed in the Porto Nacional micro-region between 1985 and 1995. The categories of savanna, forest, grassland, rivers, lakes, wetlands, and marshes totaled approximately 17,086.42 km² in 1995, a decrease of 859.38 km² from 1985, highlighting the encroachment of human activities on native vegetation (Figure 4).

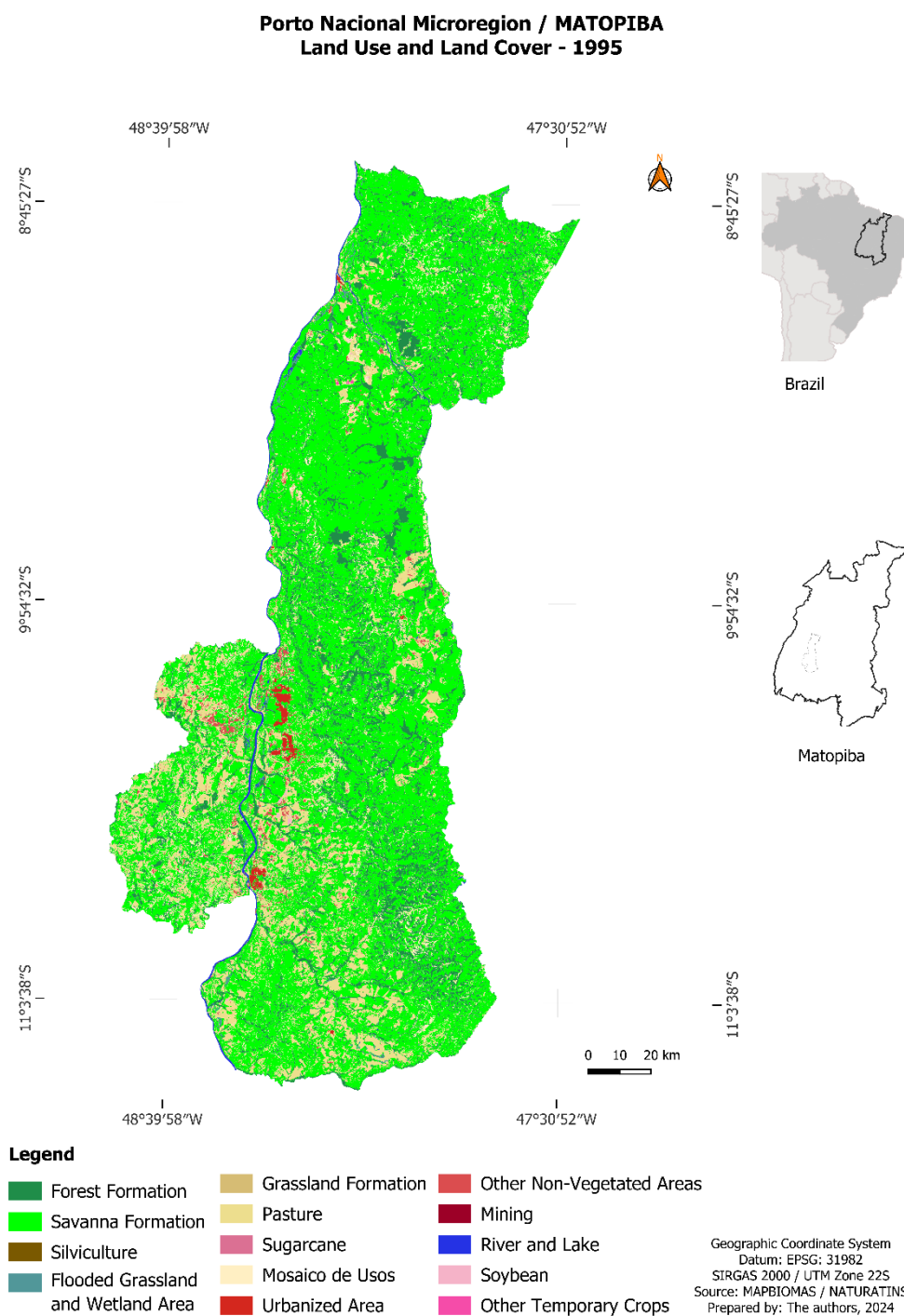


Figure 4. Spatial distribution of land use and vegetation cover in the Porto Nacional/Matopiba micro-region in 1995. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

In 1995, the spatial distribution of land use in the study area revealed a significant concentration of various land uses in the southern and southwestern parts of the Porto Nacional micro-region. This distribution was greatly influenced by the proximity to the largest cities in the micro-region, as well as by the accessibility and transportation options provided by BR 153 and TO 050 (now BR 010), which connect to other regions (Figure 5).

Table 1 shows the reduction in native forest due to the expansion of human activities during the period 1985–1995. It should be noted that, among the categories presented, the urbanized area

category grew by ~183%, as in 1985 it occupied ~35 km² and, within 10 years, the area had grown to ~99 km².

Table 1. Decline in natural vegetation cover and increase in agricultural expansion over a 10-year period (1985–1995).

Soil Cover/Use	1985 Area (km ²)	1995 Area (km ²)	Change from the previous period
Forest Land	3,481.2	3,249.7	-231.4
Savanna Land	14,065.8	13,488.7	-577.1
Wetlands and Swamp Areas	166.6	136.2	-30.4
Grassland	87.9	68.6	-19.4
Rivers, Lakes, and Oceans	144.4	143.2	-1.2
Total	17,945.8	17,086.4	-859.4
Forestry	0.0	1.8	1.8
Pasture	684.4	2,685.2	2,000.8
Sugarcane	0.0	0.3	0.3
Mixed-Use Land	2,005.4	1,025.3	-980.1
Urban Areas	35.1	99.5	64.4
Other Non-Forested Areas	526.20	282.72	-243.48
Mining	0.0	0.4	0.4
Soybeans	0.0	11.5	11.5
Other Temporary Crops	0.8	4.5	3.7
Total	3,251.9	4,111.3	859.3

In 2005, land use in the Porto Nacional micro-region began to show new categories, notably the expansion of soybean cultivation and a significant change in the rivers and lakes category. The area occupied by rivers and lakes increased from approximately 143.2 km² in 1995 to 626.3 km² in 2005, as a result of the construction of the Luís Eduardo Magalhães Hydroelectric Power Plant, whose operation between 2001 and 2002 led to the impoundment of water and flooding of areas upstream of the Tocantins River [17].

In 2005, the native land cover, which includes wetlands and marshes, grasslands, savannas, forests, and rivers and lakes, made up ~74.1% of the micro-region's total area. However, notable growth was observed in areas related to human activities, particularly urban development and soybean cultivation, which were driven by migration trends and the expansion of regional agriculture. Soybeans showed the largest increase during the period analyzed, rising from 0.054% of the micro-region's total area in 1995 to 3.7% in 2005. In absolute terms, the cultivated area expanded from 11.5 km² to 782.7 km², becoming about 68 times larger than in the previous period (Table 2).

Overall, land use in the Porto Nacional micro-region increased significantly across all categories analyzed, totaling ~5,485.8 km² in 2005. This growth was directly linked to the expansion of the agricultural frontier in the MATOPIBA region, which intensified from the 2000s onward. In this context, the Ribeirão Lajeado sub-basin (part of Porto Nacional) began to show the first signs of conversion of areas previously used for grazing to soybean production, highlighting the reorganization of land use driven by regional agricultural expansion (Figure 6).

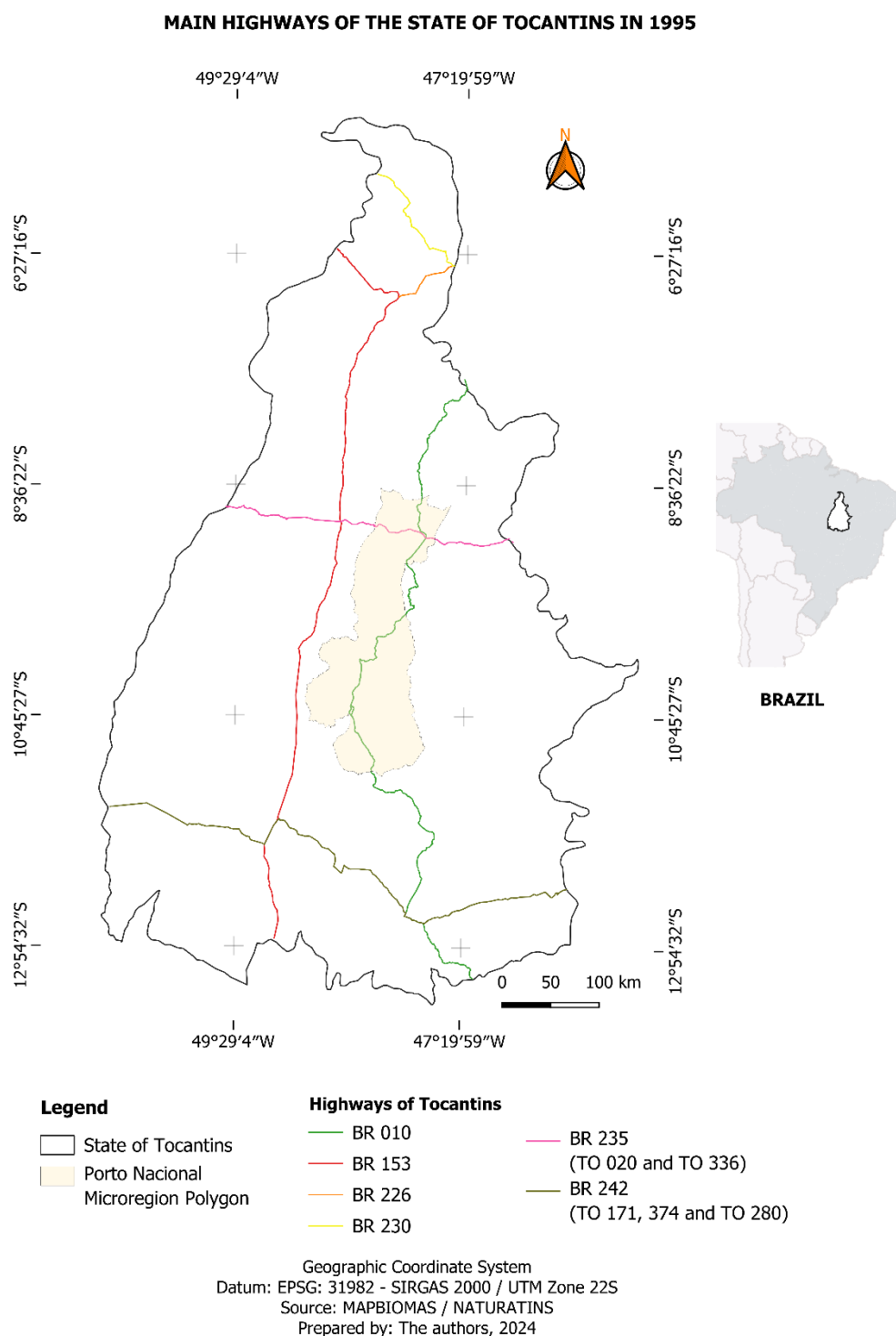


Figure 5. Main access and distribution routes for production in the Porto Nacional/MATOPIBA micro-region in 1995. Prepared based on information from the National Department of Transportation Infrastructure (DNIT) and Naturatins [26].

By 2015, forest, savanna, grassland, wetland, and marshland areas had lost ~1,568.8 km² compared to previous periods. In contrast, agricultural expansion during the same year covered ~7,044.5 km². Given that the total area of the Porto Nacional micro-region is ~21,197 km², it was noted that 33.2% or more of the area was occupied by various land-use categories in 2015. These categories included forestry, pasture, sugarcane, mixed-use areas, urbanized regions, other non-vegetated areas, mining, soybeans, and other temporary crops (Table 3).

Table 2. Decline in natural vegetation cover and increase in agricultural expansion over a 10-year period (1995–2005).

Soil Cover/Use	1995 Area (km ²)	2005 Area (km ²)	Change from the previous period
Forest Land	3,249.7	3,232.3	-0.5
Savanna Land	13,488.7	11,646.2	-13.7
Wetlands and Swamp Areas	136.2	136.4	0.9
Grassland	68.6	70.6	2.9
Rivers, Lakes, and Oceans	143.2	626.3	337.3
Total	17,086.42	15,711.90	-8.04
Forestry	1.8	5.3	188.9
Pasture	2,685.2	3,636.6	35.4
Sugarcane	0.32	0.16	-47.9
Mixed-Use Land	1,025.3	683.3	-33.4
Urban Areas	99.5	126.3	26.9
Other Non-Forested Areas	282.7	223.5	-20.9
Mining	0.44	0.54	22.3
Soybeans	11.5	782.8	6,702.2
Other Temporary Crops	4.5	27.3	503.2
Total	4,111.3	5,485.8	33.4

In 2022, agricultural land covered an area of ~7,955.9 km², representing an increase of ~6,581.4 km² compared to 1985, corresponding to a rise of ~500% (Figure 7).

3.2. Projections for Land Use and Land Cover Through 2055

A temporal analysis of land use and land cover from 1985 to 2015 revealed a loss of approximately 3,792.6 km² of native vegetation, which includes forest, savanna, and grassland ecosystems. A predictive model based on historical, socioeconomic, technological, and environmental conditions observed through 2015 indicates that this trend will continue and accelerate through 2055. It is estimated that an additional loss of 5,069.74 km² will occur, which would amount to 35.8% of the remaining cover as of 2015 (Figure 8).

By 2025, native forest cover is projected to decrease to approximately 12,941.3 km², representing an 8.6% decline over the 2015–2025 period (~1,211.8 km²), corresponding to an average rate of 0.34 km²/day, with the model exhibiting high statistical fit ($R^2 = 0.98$), indicating high reliability of the projections. The projections also indicate an expansion of the agricultural area from 7,044 km² (2015) to 8,256 km² (2025), and a potential reach of 12,114 km² by 2055, equivalent to approximately 57% of the micro-region's area (Figure 9). This projection, based on linear adjustment, demonstrated a high degree of agreement between observed and estimated data ($R^2 = 0.99$) [18].

Given the total area of the micro-region (21,197 km²), approximately 3,697 km² consists of Conservation Areas and Indigenous Lands. Projections indicate that agricultural expansion could reach up to 69% of the total area by 2055, including pressure on protected areas. There is also evidence of the agricultural frontier encroaching on conservation units, such as the Serra do Lajeado Environmental Protection Area (Figure 10), where 1,002 hectares of agricultural occupation were identified beyond the limits established for sustainable use, indicating occupation approximately 15 times greater than what is legally permitted [19].

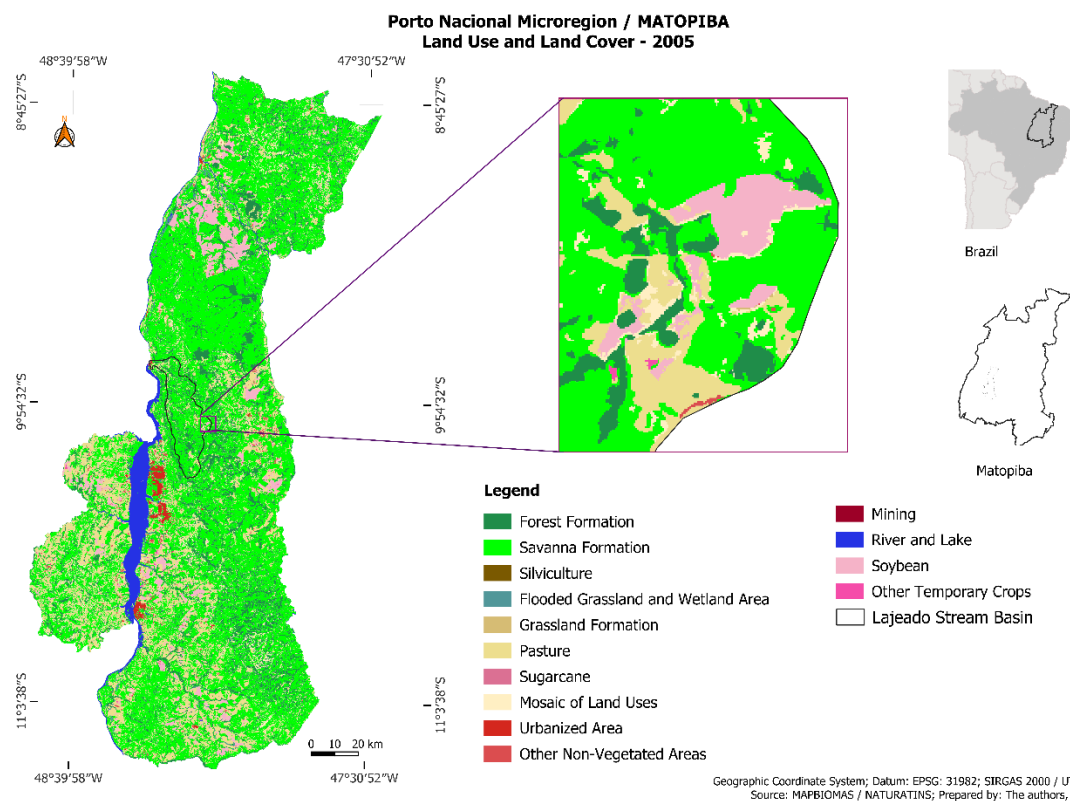


Figure 6. Spatial distribution of agricultural expansion over native vegetation in the Porto Nacional/MATOPIBA micro-region, with a focus on the eastern part of the Ribeirão Lajeado/Tocantins sub-basin in 2005. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

4. Discussion

The data obtained in our study indicate that, between 1985 and 2015, the Porto Nacional micro-region lost approximately 3,792 km² of native vegetation cover, including savanna, forest, and grassland formations. This pattern is directly associated with agricultural expansion and confirms the intensification of land-use change as the agricultural frontier consolidates in MATOPIBA [4,20]. These results are consistent with studies that identify the region as one of the main deforestation hotspots in the Cerrado in Brazil today [9,21].

The concentration of deforestation in areas with gentle topography and high agricultural suitability highlights the targeted nature of agricultural expansion. Urgilez-Clavijo et al. [22] demonstrate that land slope, in conjunction with soil type, facilitates land-use conversion, emphasizing the interaction between biophysical and economic factors in determining areas suitable for agricultural growth. Additionally, our findings reveal that native vegetation conversion occurs even within protected areas, indicating shortcomings in environmental governance [23]. Strassburg et al. [24] previously emphasized the ongoing deforestation in key conservation regions of the Cerrado, underscoring the limitations of land-use planning instruments.

Table 3. Decline in natural vegetation cover and increase in agricultural expansion over a 10-year period (2005–2015).

Soil Cover/Use	2005 Area (km ²)	2015 Area (km ²)	Change from the previous period
Forest Land	3,232.4	3,041.9	-190.4
Savanna Land	11,646.2	10,280.9	-1,365.4

Wetlands and Swamp Areas	136.4	140.0	3.6
Grassland	70.6	65.6	-5.2
Rivers, Lakes, and Oceans	626.3	625.0	-1.3
Total	15,711.9	14,153.2	-1,558.7
Forestry	5.3	14.5	9.2
Pasture	3,636.6	4,308.9	672.2
Sugarcane	0.16	76.0	75.9
Mixed-Use Land	683.3	584.7	-98.7
Urban Areas	126.3	165.8	39.5
Other Non-Forested Areas	223.5	260.8	37.4
Mining	0.54	0.63	0.08
Soybeans	782.8	1,403.66	620.87
Other Temporary Crops	27.33	229.5	202.1
Total	5,485.8	7,044.5	1,558.7

Landscape fragmentation is another significant consequence of this process, with impacts on ecological connectivity and ecosystem resilience, as discussed by Magioli et al. [25]. In the Serra do Lajeado Environmental Protection Area (Figure 10), land use exceeding the permitted limit (1,002 ha versus 80 ha) highlights the low effectiveness of environmental management, corroborating data from Naturatins [26]. The expansion of agriculture into environmental protection areas has a direct impact on fauna and flora, often posing a risk of extinction for species that require specific habitats to survive, as occurs in biomes such as the Brazilian Cerrado [27].

The expansion of the agricultural frontier in MATOPIBA is one of the main drivers of these changes. Soybean production has grown dramatically, increasing from 11.5 km² in 1995 to 782.8 km² in 2005, underscoring its role in replacing native vegetation. This trend aligns with findings from Rausch et al. [28], Song et al. [29], and Rocha et al. [30], who emphasize the increasing conversion of natural forests into agricultural land in the Brazilian Cerrado. In the Ribeirão Lajeado sub-basin (Figure 6), there is also growing pressure on natural areas, indicating the likelihood of further soybean cultivation expansion into new natural regions [31].

Territorial reconfiguration is also linked to public policies and market dynamics. Soybean expansion was driven by federal incentives and the shift in production following the soybean moratorium, which transferred part of production from the Amazon to the Cerrado [32,33], accelerating land-use conversion in this important Brazilian biome. Transportation infrastructure played a decisive role in this process (Figure 5). The presence of the BR-153 and BR-010 highways facilitated logistical integration and accelerated agricultural expansion in the region. Soliani [34] demonstrates that proximity to transportation corridors is directly associated with the development of agribusiness in Brazil.

ESCALATION OF AGRICULTURAL EXPANSION IN THE PORTO NACIONAL MICROREGION / MATOPIBA BETWEEN 1985 AND 2022

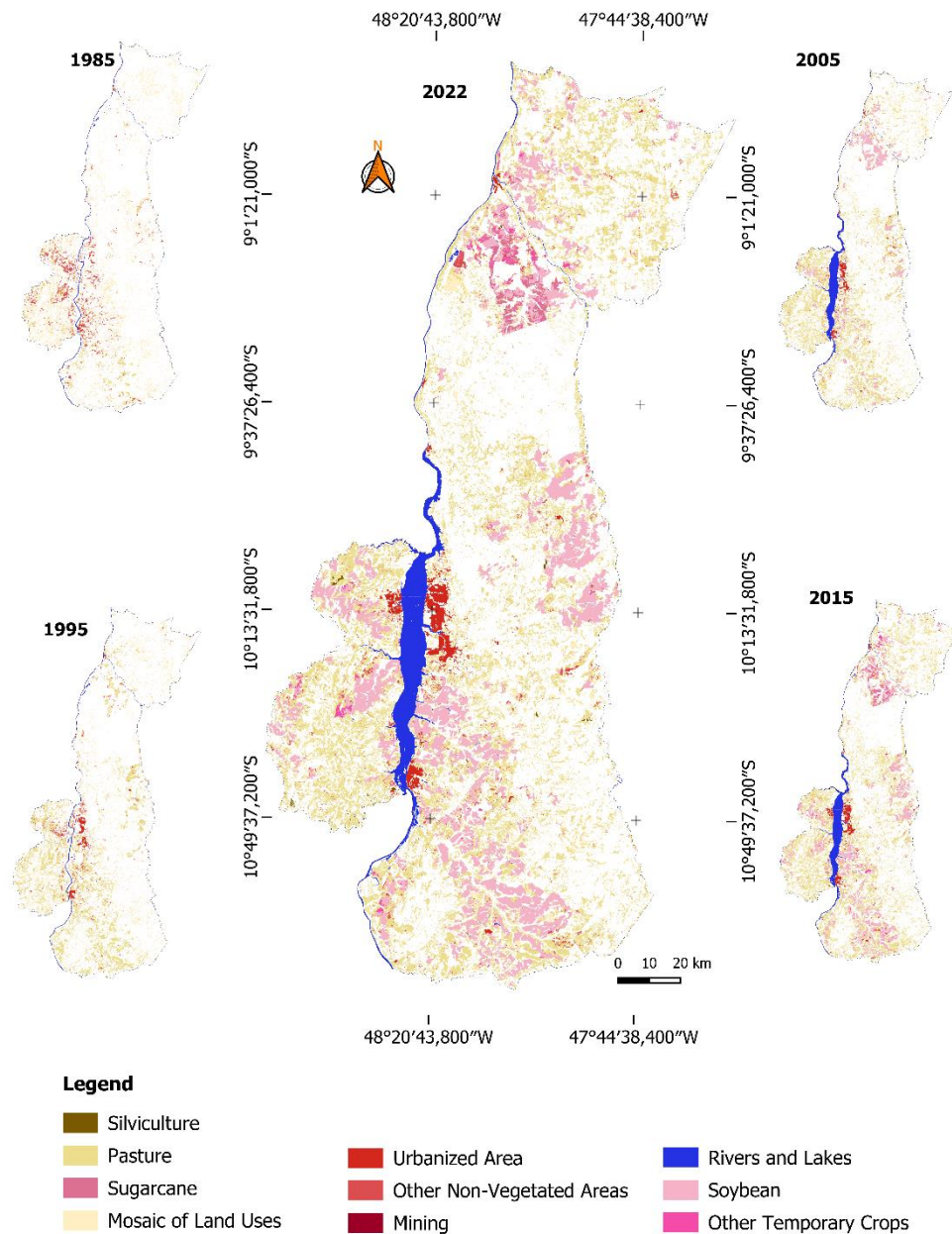


Figure 7. Changes in the conversion of native forest cover to agricultural land in the Porto Nacional/Matopiba micro-region from 1985 to 2022. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

Our study's projections suggest that by 2055, agribusiness could occupy around 57% of the Porto Nacional micro-region (Figure 9). This scenario supports the hypothesis of ongoing conversion of native vegetation (Figure 8) and aligns with the findings of Soares-Filho et al. [35], provided that the current institutional and economic conditions remain unchanged. Additionally, the expansion of agricultural areas into environmentally protected regions, such as the Serra do Lajeado Environmental Protection Area, highlights weaknesses in institutions and limitations in environmental enforcement. This situation resembles discussions about environmental governance

that took place during COP-27 [36] and reinforces the conclusions of Bonelli et al. [37] regarding the impact of institutional fragility on deforestation.

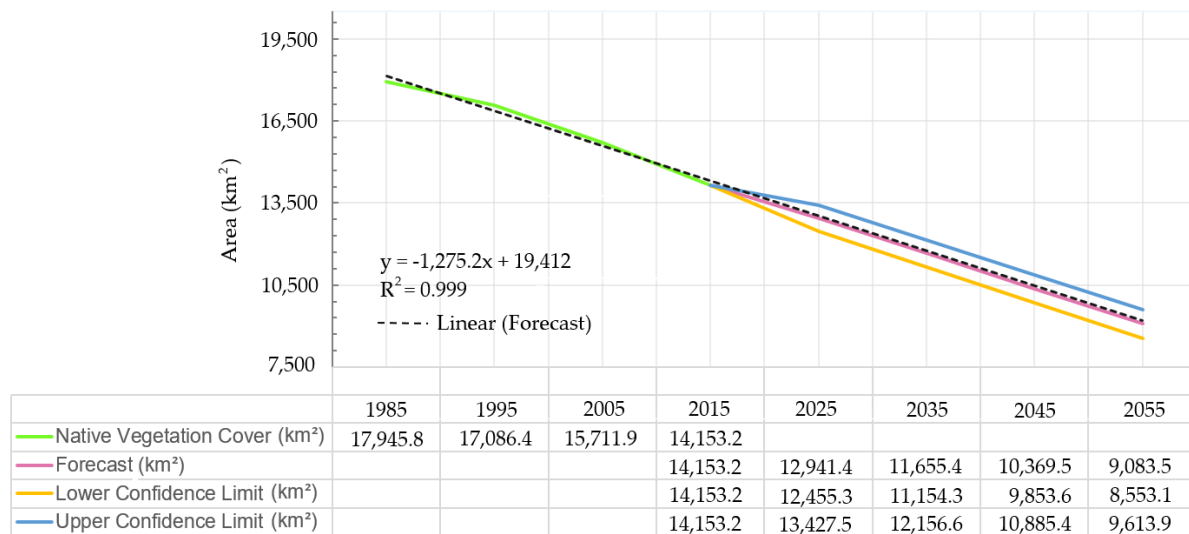


Figure 8. Projected loss of native vegetation cover in the Porto Nacional/MATOPIBA micro-region. Prepared based on MapBioma (Collection 8, 2023).

One notable observation from our study, although not directly analyzed, is the increase in burned areas in MATOPIBA, especially in Maranhão and Tocantins, indicating a rise in fire use. The practice of burning native forests to convert the land for agriculture and livestock farming remains prevalent in certain regions of Brazil [38]. Silva et al. [3] link this trend to the interaction between climate variability and agricultural expansion, which encourages such practices. However, it is important to highlight that these practices significantly contribute to carbon emissions, polluting the atmosphere with particulate matter and greenhouse gases [23,39].

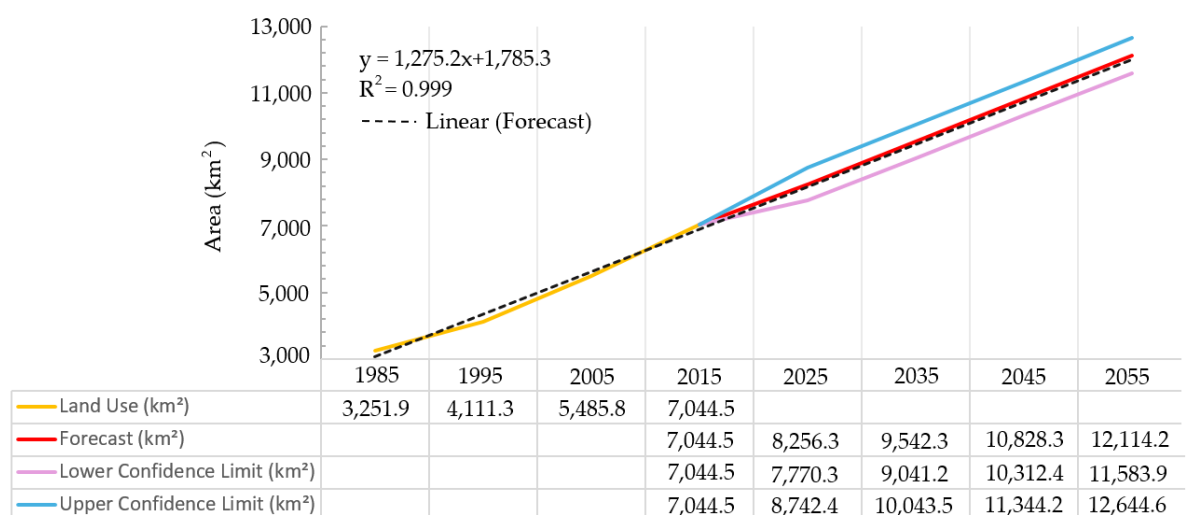


Figure 9. Predictive modeling of land use in the Porto Nacional/MATOPIBA micro-region from 1985 to 2055. Prepared based on MapBioma (Collection 8, 2023).

In this scenario, potential solutions for advancing agriculture in fragile biomes like the Cerrado include integrated land management strategies such as agroforestry, low-carbon agriculture, ecological corridors, institutional strengthening, and payments for environmental services. By coordinating these measures with public policies and local stakeholders, we can reduce pressure on

the Cerrado and promote a better balance between production and conservation, thereby leading to a more sustainable use of natural resources.

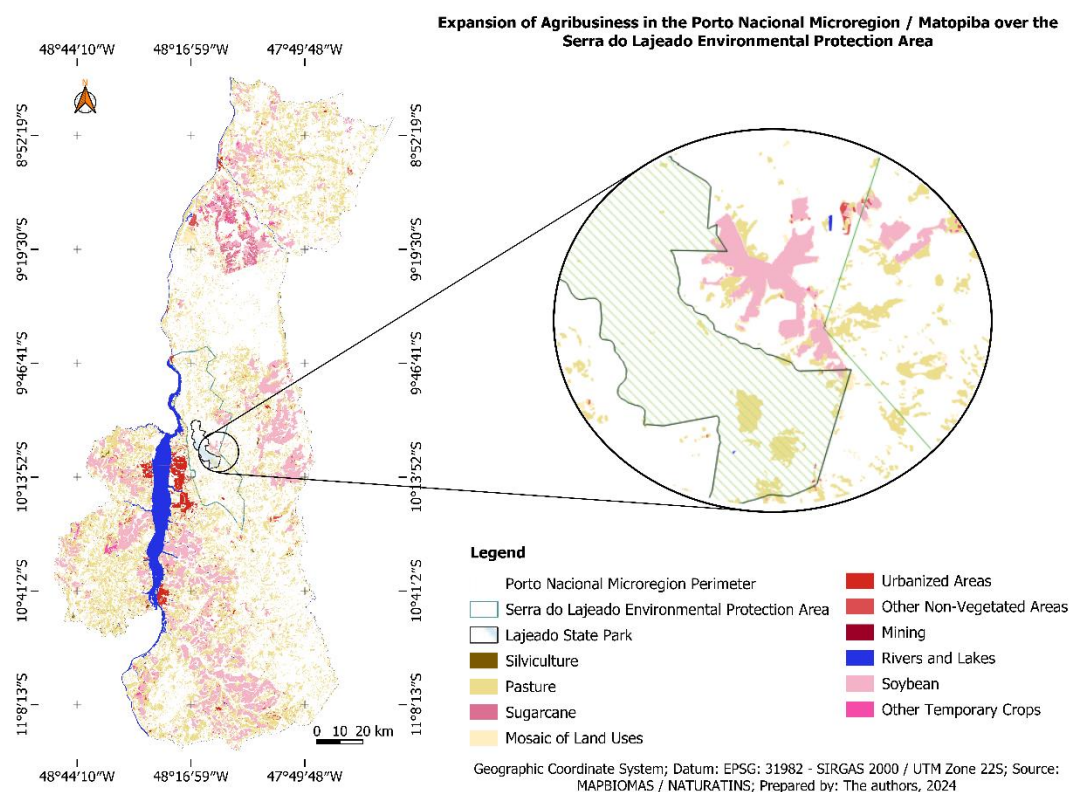


Figure 10. Expansion of the agricultural frontier into the Serra do Lajeado Environmental Protection Area, located in the MATOPIBA region. Prepared based on MapBioma (Collection 8, 2023) and Naturatins [26].

5. Conclusions

The spatio-temporal analysis of land use and land cover in the Porto Nacional microregion, located within the MATOPIBA agricultural frontier, revealed significant landscape changes from 1985 to 2022. These changes were primarily driven by the expansion of soybean cultivation and pastureland, which replaced native Cerrado vegetation. The use of geotechnologies, such as Google Earth Engine, QGIS, and MapBiomas Collection 8 data, proved highly effective for long-term environmental monitoring. This approach provided reliable spatial analyses with strong statistical support. Our findings confirm the rapid expansion of agricultural activities encroaching on natural ecosystems and underscore the growing anthropogenic pressure on the Cerrado biome.

The observed land-use dynamics have significant implications for environmental sustainability, particularly regarding soil degradation risks, habitat fragmentation, hydrological imbalance, and reduced ecosystem services. The expansion of agricultural activities near environmentally sensitive areas, such as the Serra do Lajeado Environmental Protection Area, suggests limitations in current territorial planning and environmental governance mechanisms. In this context, the results reinforce the urgent need for integrated land management strategies that reconcile agricultural production with biodiversity conservation, sustainable soil use, and long-term ecosystem resilience.

Methodologically, this study highlights the effectiveness of combining remote sensing, GIS, and statistical modeling to analyze historical land-use changes and support predictive environmental assessments at the regional scale. Projected trends through 2055 indicate that anthropogenic land use will continue to expand without effective regulatory interventions. This underscores the necessity for ongoing environmental monitoring and the development of evidence-based public policies. The

proposed approach in this study offers a replicable framework to support sustainable land-use planning and climate-resilient agricultural management in vulnerable tropical biomes, such as the Brazilian Cerrado.

Author Contributions: All authors have contributed substantially to this manuscript. Conceptualization, S.E.F., M.L.C. and L.F.P.; methodology, S.E.F.; formal analysis, S.E.F.; investigation, S.E.F.; resources, S.E.F., M.L.C. and L.F.P.; data curation, S.E.F.; writing—original draft preparation, S.E.F., M.L.C. and L.F.P.; writing—review and editing, S.E.F., M.L.C. and L.F.P.; supervision, M.L.C. and L.F.P.; project administration, S.E.F., M.L.C. and L.F.P.; funding acquisition, M.L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in this study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Acknowledgments: Luiz F. Pires would like to thank the “Conselho Nacional de Desenvolvimento Científico e Tecnológico” (CNPQ) for the productive research grant (303950/2023-4) and project financial support (400136/2025-2). In preparing this work, the authors utilized Grammarly, an AI-assisted tool, to enhance the manuscript’s overall readability. Following the use of this tool, the authors reviewed and edited the content as needed.

Conflicts of Interest: The authors declare no conflicts of interest.

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