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Soybean expansion and land use dynamics in the Chapadinha microregion Maranhão, Brazil

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A B S T R A C T

The Chapadinha microregion stands out in soybean cultivation, accounting for 78% of production in eastern Maranhão. The replacement of natural vegetation with soybean farming has impacted biodiversity, regional water cycles, and ecological balance. Therefore, the aim this study was to comprehend the land use and land cover using geoprocessing techniques and multivariate analysis, in a soybean cultivation region situated at the Maranhão state, Brazil. The methodology integrated the use of two approaches for spatiotemporal analysis. The first approach utilizes a database from the Annual Land Use and Land Cover Mapping Project in Brazil (MAPBIOMAS) applied to Chapadinha, Anapurus, and Mata Roma on the 1985, 2009, and 2021 years. The second consisted in multivariate analysis for to understand the dynamics of land use classes. The results revealed that the area dedicated to soybean cultivation significantly increased, reaching 6,442 hectares in Chapadinha, 8,200 hectares in Mata Roma, and 10,825 hectares in Anapurus on the 2021. The multivariate analysis highlighted a substantial increase in soybean-cultivated lands in Anapurus and Mata Roma on the 2009 and 2021 years. It contrasted for the forest and savanna vegetations reductions. This study provides insight into the advancement of soybean cultivation in the Chapadinha microregion, highlighting the need for greater oversight and policies aimed at the sustainable use of natural resources, especially in the face of growing global food demand and the development of emerging economies.

Keywords: Multivariate Analysis. Cerrado Biome. Geotechnologies. Land Use Change.

Dinâmica do Uso e Ocupação da Terra em Áreas de Expansão da Soja na Microrregião de Chapadinha, Maranhão

R E S U M O

A microrregião de Chapadinha se destaca no cultivo de soja, respondendo por 78% da produção do leste maranhense. A substituição da vegetação natural por produção sojícola tem impactado a biodiversidade, os ciclos hídricos regionais e o equilíbrio ecossistêmico. Assim, objetivou-se avaliar a dinâmica do uso e cobertura da terra em áreas de expansão da cultura da soja em três municípios da microrregião de Chapadinha via Sistema de Informação Geográfica (SIG), técnicas de geoprocessamento e análise multivariada. A metodologia integra duas abordagens para análise espaço-temporal. A primeira abordagem utiliza uma base de dados obtida pelo Projeto de Mapeamento Anual de Uso e Cobertura da Terra no Brasil (MAPBIOMAS) para os municípios de Chapadinha, Anapurus e Mata Roma, referente aos anos de 1985, 2009 e 2021, enquanto a segunda consiste na análise multivariada para compreender a dinâmica das classes de uso da terra. Os resultados obtidos revelaram que a área destinada ao cultivo de soja cresceu consideravelmente, alcançando em 2021, 6.442, 8.200 e 10.825 hectares em Chapadinha, Mata Roma e Anapurus, respectivamente. A análise multivariada destacou em Anapurus e Mata Roma, nos anos de 2009 e 2021, o substancial aumento de terras cultivadas com soja em contraste com a redução de áreas de formações florestais e savânicas. Este estudo fornece um avanço da expansão da cultura da soja na microrregião de Chapadinha, evidenciando a necessidade maior fiscalização e políticas voltadas ao uso sustentável

dos recursos naturais, especialmente diante do aumento da demanda global de alimentos e o desenvolvimento das economias emergentes.
Palavras-chave: Análise Multivariada. Bioma Cerrado. Geotecnologias. Mudança do uso da terra.

Introduction

Brazil stands out as one of the world's leading producers and exporters of food, with vast territorial extensions dedicated to agriculture (Aguiar & Balogh, 2022; Mores et al., 2022). In recent years, there has been a significant increase in the area under agricultural activities, rising from 74.5 million hectares in 2021/22 to 78.3 million hectares in 2022/2023, of this, 44.1 million hectares are cultivated with soybeans (Glycine max (L.) Merrill), the main agricultural crop produced in Brazil. Currently, Mato Grosso state is the largest producer of soybeans in Brazil, with production reaching 45.6 million tons in the 2022/2023 crop season.

The replacement of native vegetation by other land use types is directly related to the impact on essential ecosystem services, including, among others, climate regulation (Lima et al., 2019; Carvalho et al., 2023). This affects the preservation of vegetation and animal life, as well as soil organic carbon and the water cycle. Therefore, it contributes to the loss of ecosystem resilience to climate change, while also amplifying the effects of these global changes. In this context, it hinders progress toward achieving the goals of the 2030 Agenda established by the United Nations (UN), particularly to 17 Sustainable Development Goals (SDGs). Especially on SDG 15 (Life on Land), which addresses the protection of terrestrial ecosystems, and the fight against desertification and land degradation (BRASIL, 2020; Sims et al., 2021; Lui et al., 2024; Sousa et al., 2025).

The soybean fields expansion has been intense in the brazilian Cerrado biome, particularly at the Maranhão, Tocantins, Piauí, and Bahia states, known as the MATOPIBA region, recognized as one of the world's major agricultural frontiers (Lima et al., 2016; Ferraz-Almeida & Mota, 2021; Bachi et al., 2023). This agricultural expansion accounts for 40% of brazilian annual agricultural crop production and is one of the most impactful human activities in the Cerrado biome (Matricardi et al., 2020; Silva-Junior et al., 2021). The Cerrado biome lost over 20,000 km^2 of its native vegetation between 2017 and 2019 (Assis et al., 2019; Trigueiro et al., 2020), thus becoming one of the most threatened biomes on the planet (Trigueiro et al., 2020).

Therefore, the conversion of native areas for various agricultural uses has implications for biodiversity, as well as alters regional and global biogeochemical cycles, influences climate change, and disrupts ecosystem balance (Lapola et al., 2023). For example, Silva et al. (2021), Costa et al., (2022) and Aragão et al. (2023) report that in recent decades, the brazilian Cerrado has experienced an intensification of forest fires, largely due to increased agricultural production and urbanization, significantly amplifying environmental impacts across various scales. Furthermore, Medeiros et al. (2022) found that the conversion of vegetation to conventional agricultural systems results in a loss of 10% of soil organic carbon stocks in the Cerrado.

In this context, the Maranhão, which has 64% of its territory within the Cerrado biome, was the second-largest soybean producer in the MATOPIBA region, with a production of 3.90 million tons in the 2022/2023 harvest (CONAB, 2023). In that state, the Chapadinha microregion stands out in soybean production, accounting for 78% of the production in eastern Maranhão. Among the nine municipalities, four are prominent in soybean cultivation: Anapurus, Brejo, Buriti, and Mata Roma, collectively responsible for 91% of the entire cultivated area (Soares et al., 2021; Sousa et al., 2025). Therefore, conducting studies that investigate the land use and land cover in agricultural expansion regions is crucial to contribute to environmental planning, aiming to promote sustainability in agriculture.

The geoprocessing techniques and unsupervised machine learning algorithms has emerged as robust and effective tools for analyzing spatial-temporal variability, allowing for mapping and monitoring landscape changes over time (Souza Jr et al., 2020; Silva et al., 2022). In this regard, Geographic Information Systems (GIS) emerge as an important tool enabling to collection and understanding of land use and land cover database. It can be crucial for the public policies development such as agricultural sustainable programs (Patel et al., 2024; Marieye e al., 2024).

Given this scenario, Garcia et al. (2023) analyzed land use and land cover using geoprocessing techniques in the southern region of Macapá and Amapá state, Brazil, from 1985 to 2022. They concluded that there was an increase in the "Urban Area" class from 2% to 19%, along with a reduction in the "Vegetation" class from 58% to 47%. Similarly, Sousa et al. (2025) found that human activities are the main causes of deforestation and reduction of water bodies, which consequently led to the expansion of agriculture and livestock farming in the Amazon-Cerrado region.

Therefore, these studies are very important and urgent for understanding sustainable development levels in different regions of the world. Given this, it is important to note that this study type is still in its early stages in Maranhão, known as the last agricultural frontier of the brazilian Cerrado. So, the aim this study was to comprehend the land use and land cover using geoprocessing techniques and multivariate analysis, in a soybean cultivation region situated at the Maranhão state, Brazil.

Materials and methods

Description of the study area

The study area corresponds to the Chapadinha microregion, Maranhão, Brazil, with a total territorial extension of 4,404.836 km² (Figure 1), encompassing the municipalities of Chapadinha (Latitude: 3° 44' 26" S, Longitude: 43° 21' 33" W - 3,247.385 km²), Anapurus (Latitude: 3° 40' 18" S, Longitude: 43° 6' 57" W - 608.903 km²), and Mata Roma (Latitude: 3° 37' 15" S, Longitude: 43° 6' 33" W - 548.548 km²). This microregion is located within the Cerrado biome, specifically in the geographical extension that partially covers the Maranhão, Tocantins, Piauí, and Bahia states, known as MATOPIBA (Bachi et al., 2023).

The Chapadinha microregion is characterized by an Aw' climate classification according to the Köppen system, with an average annual precipitation of 1673 mm and average air temperature ranging between 26 and 29 °C (Alvares et al., 2013; Corrêa et al., 2023). Additionally, it holds significant socioeconomic relevance for the state of Maranhão, owing to its agricultural hubs.

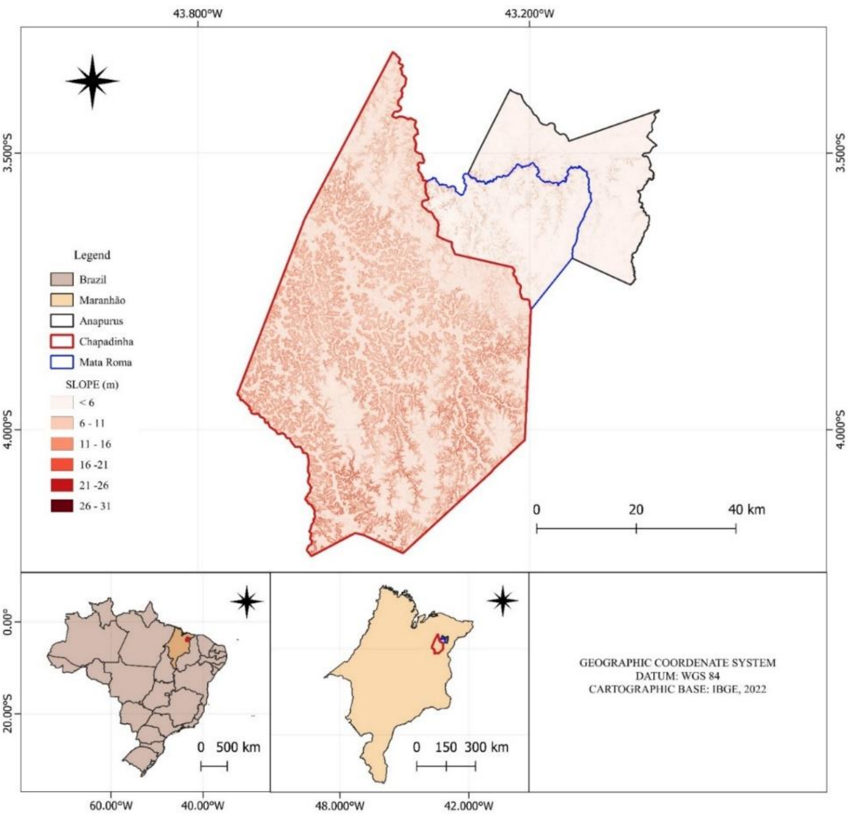

Figure 1. Location of the Chapadinha microregion, Maranhão, Brazil.

Data collection

The database used for the spatial-temporal analysis was obtained from Collection 7 of the Annual Land Use and Land Cover Mapping Project in Brazil (MAPBIOMAS), using the Google Earth Engine (GEE) platform. We used satellite images of Maranhão state for 1985, 2009, and 2021 yearsm in TIFF format with a spatial resolution of 30 meters, using a JavaScript algorithm in GEE provided by MapBiomas. This allowed for the download of raster data related to land use and land cover for each year.

Next, the Quantum GIS (QGIS) software, version 3.22.4, was used to reproject the database and perform clipping using a mask based on shapefiles of Anapurus, Chapadinha, and Mata Roma, provided by the Brazilian Institute of Geography and Statistics (IBGE, 2021) (Figure 2).

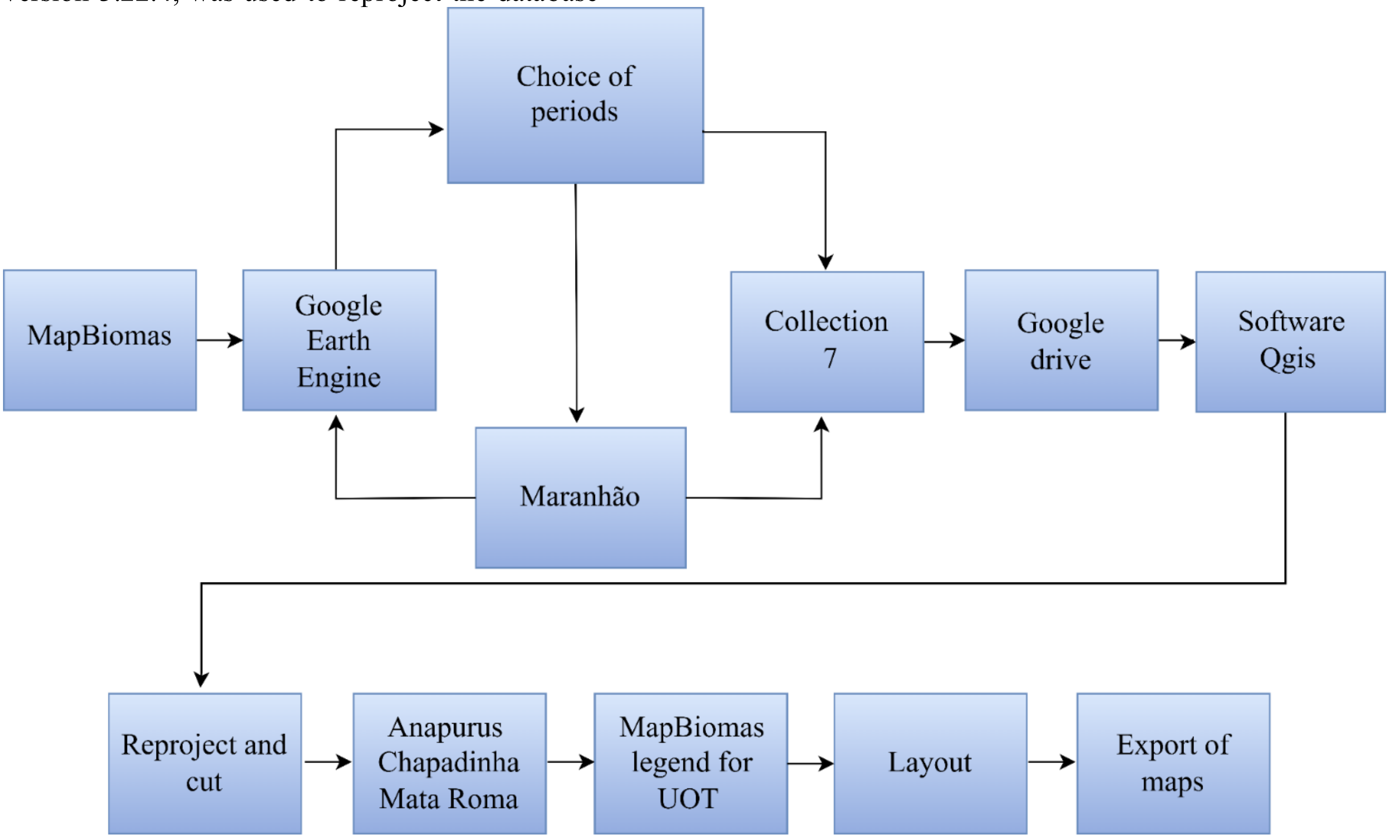

Figure 2. Flowchart of the methodological procedure for land use and land cover data in the Chapadinha microregion, Maranhão, Brazil.

Land Use and Land Cover

The land use and land cover (LULC) categories adopted by MapBiomas, which served as the basis for the thematic map creation, align with classifications proposed by Anderson et al., (1979), Ribeiro and Walter (1998), and the Technical Manual of Land Use by IBGE (2013). These classifications include categories such as forest formation, savanna formation, grassland formation, agriculture, pasture, non-vegetated areas, and water bodies, among others. In the present study, the focus of the analysis was on the Land Use and Land Cover classes: Forest Formation, Savanna Formation, Pasture, Soybean, Non-vegetated Area, and Urbanized Area. The absolute values of Land Use and Land Cover were exported and subsequently manipulated in a spreadsheet, where comparisons were made between the total area of the municipality and the land use classes.

Statistical analyses

Multivariate statistical analysis was used to determine the relationships between land use classes in Anapurus, Chapadinha, and Mata Roma. Principal Component Analysis (PCA) was employed on the database to reduce the dimensionality of attributes into a smaller number of new independent and interpretable variables (orthogonal principal components - PCs). The Kaiser-Guttman method was used to retain principal components that could be interpreted. This method retains components with eigenvalues >1 (Kaiser, 1958). Only the first of two principal components are presented because they capture the majority of the variance. All statistical analyses were performed using Statistical Analysis System® (SAS Institute Inc., 2012).

Results and discussion

The analysis of land use and land cover database in Mata Roma and Anapurus from 1985 to 2021 revealed significant changes in the landscape, particularly related to agricultural expansion and urban development (Table 1). During this period, the area dedicated to soybean cultivation in the three municipalities increased significantly, reaching 6.442 hectares in Chapadinha, 8.200 hectares in Mata Roma, and 10.825 hectares in Anapurus by the year 2021.

Table 1. Variation of Land Use and Land Cover Classes in the Maranhão Municipalities of Chapadinha, Mata Roma, and Anapurus (1985-2021), Maranhão, Brazil.

Municipalities	Classes	Total area in hectares		
		1985	**2009**	**2021**
Chapadinha	Florest Formation	274,488	271,580	271.580
	Savanna Formation	45,982	41,722	37,479
	Pasture	769	5,629	5,724
	Soybean	0.00	2,277	6,442
	Non-vegetated Area	678	1,135	1,509
	Urbanized Area	668	1,051	1,467
Mata Roma	Florest Formation	46,204	44,561	43,485
	Savanna Formation	6,834	5,583	4,033
	Pasture	47	112	159
	Soybean	0.00	3,506	8,200
	Non-vegetated Area	87	200	241
	Urbanized Area	86	177	233
Anapurus	Florest Formation	29,773	28,409	27,402
	Savanna Formation	26,142	23,751	15,574
	Pasture	284	64	200
	Soybean	0.0	5,340	10,825
	Non-vegetated Area	151	299	330
	Urbanized Area	134	238	314

In 1985, there was no soybean cultivation in Anapurus, Chapadinha, and Mata Roma (Figure 3). Overall, soybean production was concentrated in the Southern mesoregion of Maranhão, expanding to other mesoregions of Maranhão from the 1990's years (Jardim, 2021).

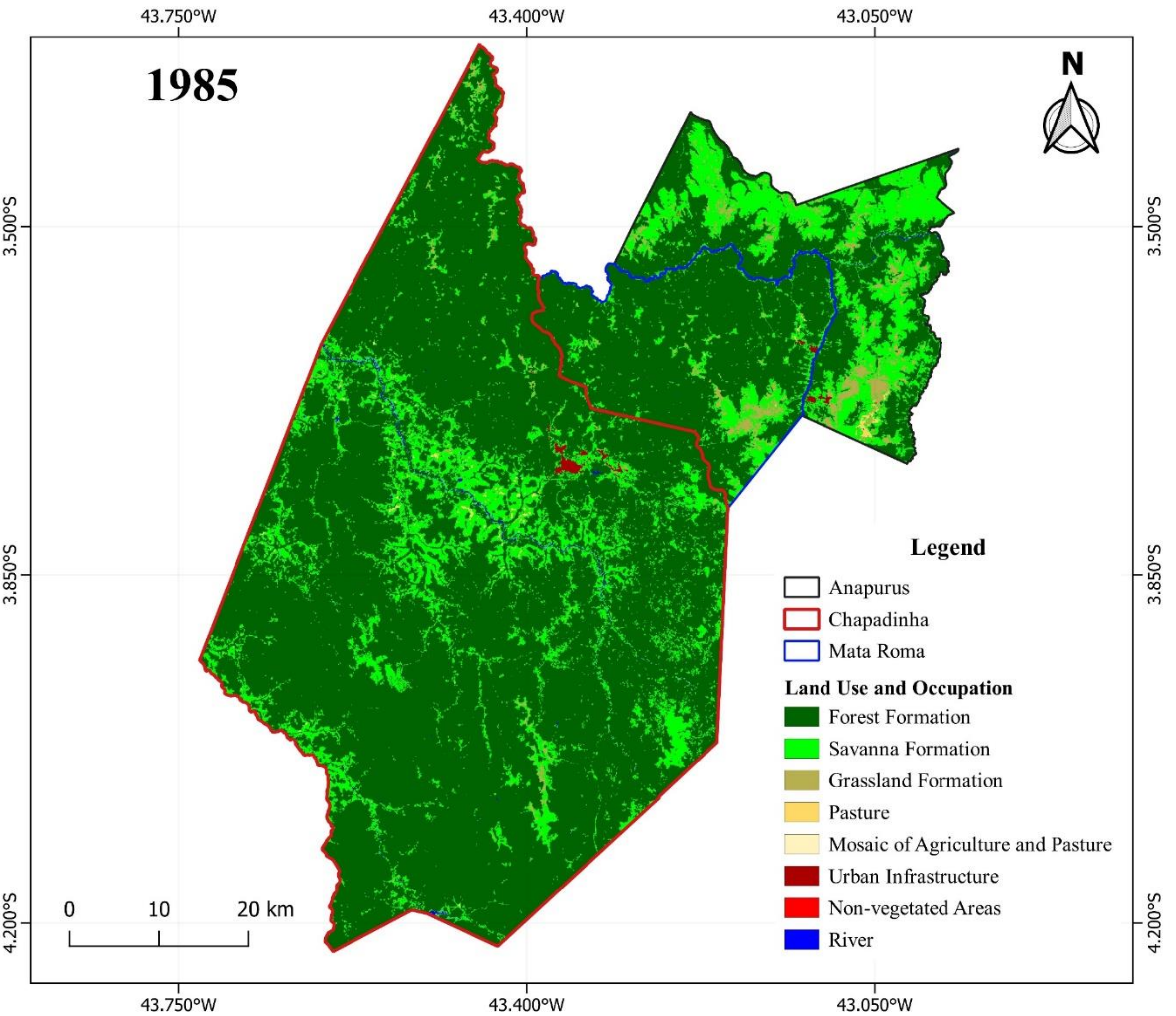

Figure 3. Thematic Map of Land Use and Land Cover Classes in the Maranhão Municipalities of Chapadinha, Mata Roma, and Anapurus (1985).

In 2009 year, the soybean cultivation was predominantly observed in regions previously occupied by savanna formations (Figure 4). Therefore, these results suggest a trend of conversion from savanna formations to soybean fields, specifically in Anapurus and Chapadinha. It was observed that the forest formation area remained relatively stable, but there was a significant reduction of 2,391 and 4,260 hectares in the savanna formation of these municipalities, respectively (Table 1). Polizel et al., (2021) study confirms that in the MATOPIBA region, between 1990 and 2017, approximately 31% of savanna formation areas were converted to agricultural fields.

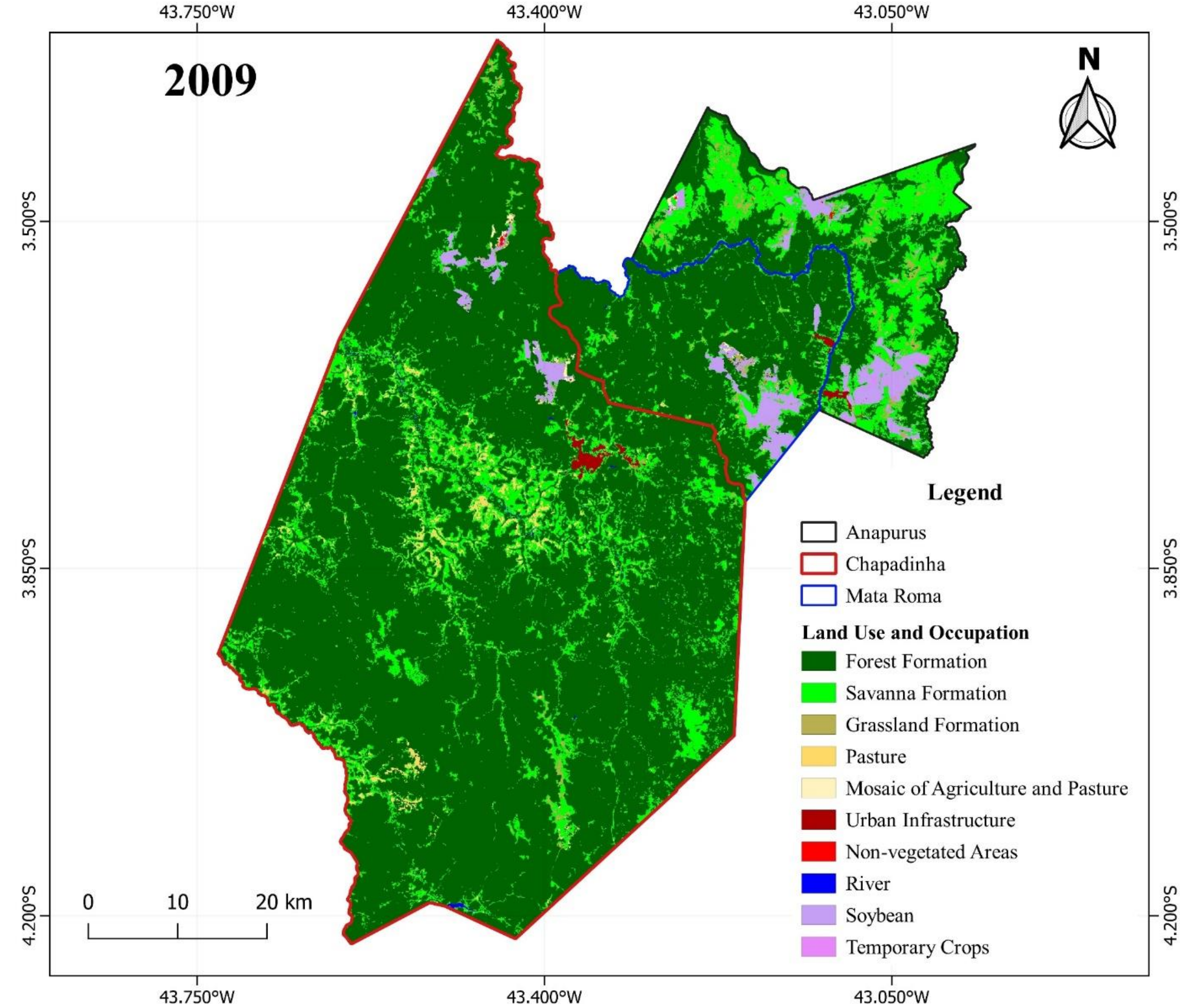

Figure 4. Thematic Map of Land Use and Land Cover Classes in the Maranhão Municipalities of Chapadinha, Mata Roma, and Anapurus (2009).

The soybean expansion was also observed in 2021 (Figure 5), surpassing the levels of the 2009, at the Anapurus, Chapadinha, and Mata Roma. Which increases of 5,485 hectares, 4,165 hectares, and 4,694 hectares, respectively. These results are consistent with Pires et al. (2021), whose Anapurus presented the highest percentage of deforestation between 2004 and 2020.

Additionally, were observed some reductions of 34.4%, 10.2%, and 27.7% in the savanna formation class. MapBiomas data highlights that between 1985 and 2022, savanna formation lost 29 million hectares, representing 22% of the area present in 1985. In each five hectares deforested, four (83%) were cleared in the Cerrado biome. This alarming deforestation rate in the Brazilian savanna is concentrated in the MATOPIBA region, where these vegetations are converted to agricultural fields (MAPBIOMAS, 2022).

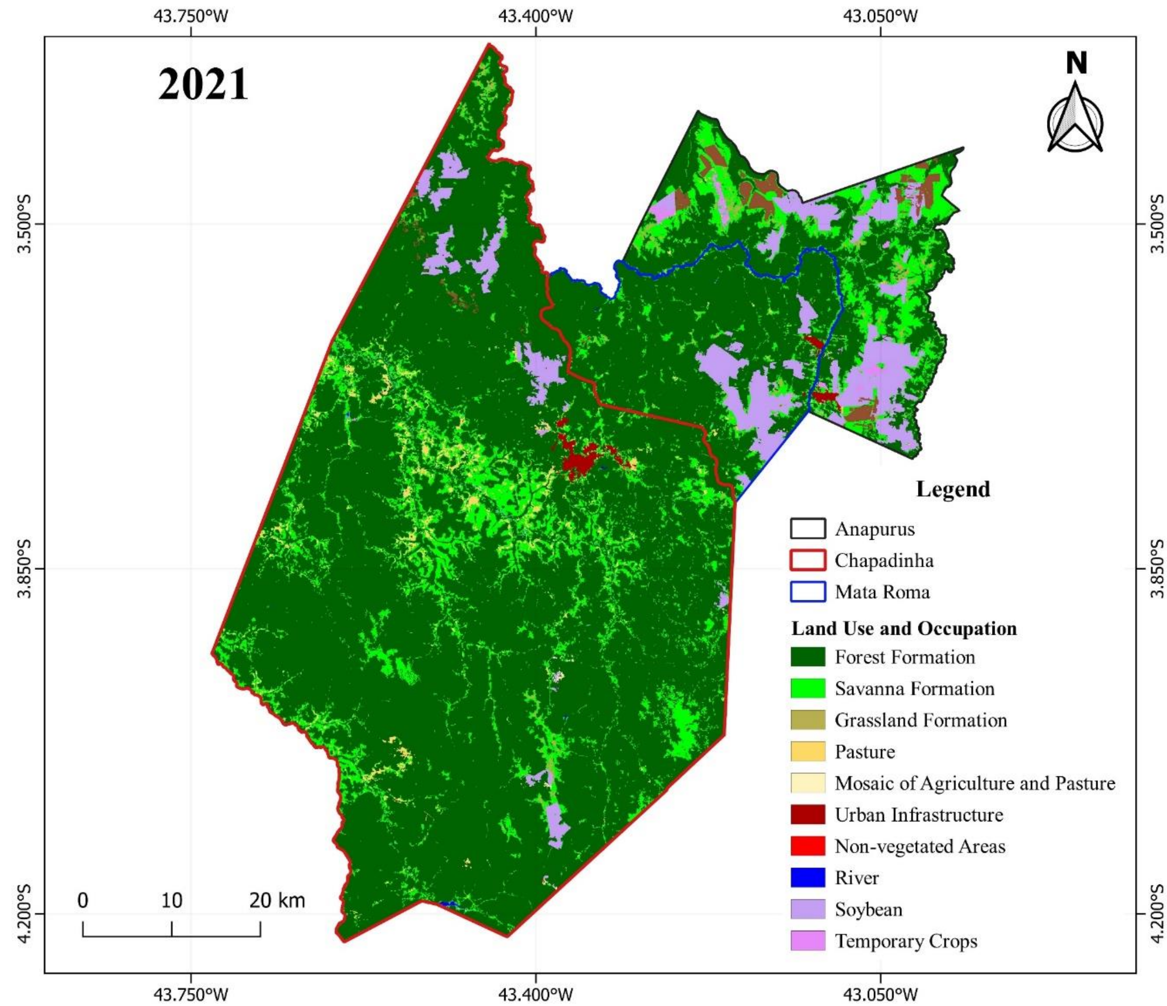

Figure 5. Thematic Map of Land Use and Land Cover Classes in the Maranhão Municipalities of Chapadinha, Mata Roma, and Anapurus (2021).

From 1985 to 2021, there was a significant decrease of 2,719 hectares in forested areas, along with a reduction of 2,801 hectares in savanna extent in Mata Roma (Table 1), with a trend of soybean expansion advancing mainly southwestward across its territory (Figure 4). In Anapurus, over the same time, soybean expansion was widely spread, significantly concentrating in savanna formation areas (Figure 5). In this transitions, the forest formation decreased 2,371 hectares, while the savanna, 10,568 hectares in Anapurus.

It is important to highlight that in 2023, the Cerrado biome exhibited the highest deforestation rate among brazilian biomes, with a deforested increase of 448,140 hectares (67%), particularly in the MATOPIBA region, where the states of Maranhão, Bahia, and Tocantins have the highest deforestation rates in Brazil. Increases in deforestation were observed at rates of 18.1%, 15.9%, and 12.6%, respectively, in these states (MapBiomas, 2023).

In 1985, the Chapadinha microregion showed few impacts from anthropogenic activities in land use, including no recorded soybean cultivation (Figure 3). These results corroborate with Cunha & Espíndola (2019), Castillo et al., (2021) e Jardim (2021), those which described the migration of producers from the brazilian southern region and large agricultural companies to Eastern Maranhão starting in the 1990s.

According to Almeida & Mattos Júnior (2016), the first records of soybean production in the Chapadinha microregion were in Anapurus, by the 2000s. Over time, soybean production expanded to other cities in the Chapadinha microregion, driven by the proximity to the Port of Itaqui and the possibility of grain transporting via the BR 222 highway. (Gaspar, 2013).

Between 2009 and 2021 there was a soybean expansion in Anapurus and Mata Roma

(Figura 3). These results are consistent with those found by Soares et al. (2021), who stated that the Chapadinha microregion accounts for 78% of the soybean production in the Eastern Maranhão mesoregion. In addition, it is important to point out that among the nine municipalities in the microregion, Anapurus and Mata Roma stand out in soybean cultivation throughout the entire Eastern mesoregion. Another highly relevant piece of information is that agricultural production, especially soybean cultivation, contributes directly to the Gross Domestic Product (GDP) these cities, accounting for 19% and 23%, respectively (Pires et al., 2021).

Despite Chapadinha having the largest territorial extent among the studied municipalities, the area dedicated to soybean production is the smallest. This can be attributed to the correlation between soil suitability and the higher slope in Chapadinha compared to Anapurus and Mata Roma (Figure 1). According to Zoneamento Ecológico-Econômico (IMESC, 2021), Chapadinha city has only 29.6% of its total area classified as suitable for agriculture, while 68.01% is considered suitable for livestock production. Meanwhile, Anapurus and Mata Roma have a total area classified as suitable for agriculture of 60.94% and 43.74%, respectively. Pijl et al. (2019) and Rabia et al. (2022) highlighted that slope is one of the main causes, because it affects agricultural mechanization and soil properties, facilitating erosion and consequently impacting agricultural production.

Although Chapadinha city does not have a large soybean production, stands out for the significant growth of pasture areas, with approximately 6,000 hectares recorded in 2021 (Table 1, Figure 3). According to Pires et al. (2021), approximately 25% of the pasture area in the Chapadinha microregion is concentrated in the Chapadinha city. Furthermore, Brejo and Chapadinha together hold 61% of the cattle herd, explaining the significant growth of pasture areas. These results are consistent with Sousa et al. (2025), who identified an pasture expansion areas in Chapadinha from 1986 to 2023. Based on the future projection model presented in this study by Sousa and collaborators (2025), an increase of 25.5% in the extent of pasture areas is estimated in the municipality of Chapadinha by the 2034 year.

According to the database presented in Table 2 and Figure 4, principal component analysis (PCA) explained 92.72% of the total variation, with the first principal component (PC1) explaining 73.08% and the second component (PC2) explaining 19.64%, in the temporal changes of land use and land cover in Anapurus, Chapadinha, and Mata Roma from 1985 to 2021. PC1 is related to the variability of land cover classes such as forest formation, savanna, pasture, non-vegetated areas, and urbanized areas. On the other hand, PC2 is strongly associated with soybean expansion.

Table 2. Eigenvalues, Differences, Proportions, and Cumulative Variances of Land Use and Land Cover Classes in the Chapadinha microregion, Maranhão, Brazil.

Principal Component (PC)	Eigenvalue	Difference	Proportion	Accumulative
PC1	3.4845	3.2062	0.7308	0.7308
PC2	1.1784	0.8723	0.1964	0.9271
PC3	0.3060	0.1981	0.0510	0.9782
PC4	0.1080	0.0836	0.0180	0.9961
PC5	0.0226	0.0222	0.0038	0.9999
PC6	0.0005	0.0000	0.0001	1.0000

LULC	PC1	PC2

Principal Component (PC)	Eigenvalue	Difference	Proportion	Accumulative
Florest Formation		0.4525*		-0.1828
Savanna Formation		0.4023*		-0.2886
Pasture		0.4435*		0.1366
Soybean		-0.0189		0.8997*
Non-vegetated Area		0.4677*		0.1669
Urbanized Area		0.4669*		0.1653

*Relevant coefficients in the formation of the PC. weight > 0.4

Figure 6 displays the biplot resulting from PCA, demonstrating the multidimensional trends of transformations in the landscape dynamics of the Chapadinha microregion. In the biplot, the configuration of vectors corresponding to different land use classes, along with the spatial arrangement of treatments representing municipalities over the years, reveals significant changes and transformation patterns in land use and land cover.

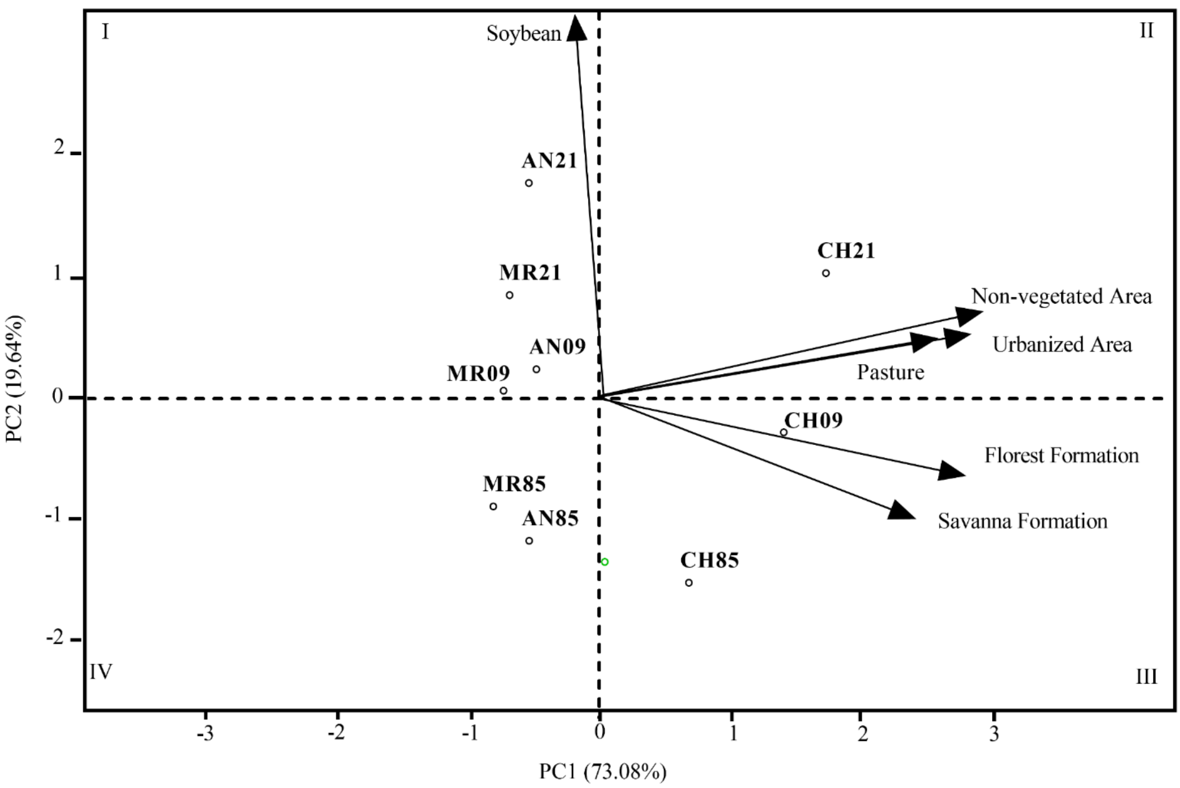

Figure 6. Biplot Analysis of the Principal Components Highlighting Temporal Land Use Changes in Anapurus, Chapadinha, and Mata Roma (1985-2021). Legend: AN85, AN09, AN21 = Anapurus 1985, 2009 and 2021, respectively; CH85, CH09, CH21 = Chapadinha 1985, 2009 and 2021, respectively; MR85, MR09, MR21 = Mata Roma 1985, 2009 and 2021, respectively.

The biplot places Anapurus and Mata Roma in the years 2009 and 2021 firmly in quadrant I, highlighting as the main characteristic the increase in land cultivated with soybeans contrasted with the deforestation of forest and savanna formations. In contrast, Chapadinha in the year 2021 is represented in quadrant II, notable for the increase in areas of pasture, non-vegetated areas, and urbanization. This divergence is pronounced when compared to the years 2009 and 1985, where extensive areas of forest and savanna formations predominated, with less prominence given to soybean fields during those periods. On the other hand, in 1985, Anapurus and Mata Roma were situated in quadrant IV, characterized by sparse presence of pasture and urbanization, reflecting a land use scenario significantly different from the present day.

The PCA results reveal that soybean cultivation exhibits a strong positive association with PC2 (Table 2). Thus, in the Biplot, an increase in soybean cultivation area is observed from 2009 onwards, with the exception of Chapadinha, which shows this trend only in 2021 (Figure 6). In the biplot, treatments positioned above the value of 0 on the PC2 axis demonstrate this increase in soybean cultivation. This expansion is particularly notable in the municipality of Anapurus in the year 2021, which stands out on the vertical axis, indicating a significant increase in soybean area compared to other periods and municipalities analyzed.

There has been a significant increase in soybean production in the Chapadinha microregion, particularly in the municipalities of Anapurus and Mata Roma. Similar findings were reported by Feitosa et al. (2023), who in a temporal analysis of soybean expansion in the state of Maranhão, found that currently 62% of municipalities in Maranhão are agricultural producers.

The database from the present study demonstrates the advance of anthropogenic actions focused on agricultural production in the Chapadinha microregion. Despite Maranhão presenting the highest percentage of deforested area in Brazil, the state adheres to Brazilian environmental legislation, such as the Forest Code (Lei n° 12.651/2012), which mandates that every rural property within the Cerrado biome maintain 35% of its area covered by native vegetation, designated as Legal Reserve (Brasil, 2012).

Understanding the most anthropized areas with a higher propensity for loss of natural vegetation cover in agricultural fields can assist in better environmental planning, aiming for sustainable use of natural resources in balance with global food production demands.

Conclusions

1. Multivariate analysis proved to be an efficient method for analyzing the land use and land cover dynamics.
2. The soybean production in the Chapadinha microregion showed significant growth from 1985 to 2021, especially in Anapurus and Mata Roma, with an increase of 5,485 and 4,694 hectares, respectively.
3. This expansion of soybean cultivation is causing deforestation of Cerrado biome in Maranhão state, predominantly in Anapurus and Mata Roma cities.
4. The soybean expansion in the brazilian Cerrado, especially in the Maranhão state, requires greater supervision and policies aimed at the sustainable use of natural resources, in line with the increase in global demand for food and emerging economies development.

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