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Land Use and Cover Changes in Brazilian Biomes between 1985 and 2018

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ABSTRACT

In the last decades, there have been changes in land use and cover in the Brazilian territory, many resulting from anthropic activities. However, these changes impact the environmental system, compromising biodiversity and ecological services. In this context, integrative geographic information about environmental changes in the Biomes allows the identification of the main Spatio-temporal changes in land use and cover and can contribute to efficient environment planning. Thus, this paper proposes to describe and synthesize the Spatio-temporal changes in Brazilian Biomes between 1985-2018 using spatial statistics techniques and Principal Component Analysis with data from the MapBiomas project. It has employed the Google Earth Engine and QGIS for the analysis, with emphasis on spatial statistics and Principal Components Analysis which enabled the identification of the main changes in land use and cover. From the Principal Components Analysis, it was possible to reduce the data set with 34 images to two Principal Components that represent significant percentages of the variance of the original database. The results showed that the Brazilian Biomes had undergone significant changes over 34 years. The main vectors that drove these transformations were anthropic activities, such as urban growth, the advancement of agriculture, and cattle ranching in the countryside. Amazon and Cerrado present the largest area altered in square kilometers. And the fastest changes occurred on Amazon, Cerrado, and Pantanal. This work presents a synthesis of the main patterns and spatial-temporal changes in the use and cover of Brazilian Biomes, which can assist in the national environmental planning.

Keywords: Google Earth Engine, MapBiomas, Principal Components Analysis.

Mudanças no Uso e Cobertura da Terra nos Biomas Brasileiros entre 1985 e 2018

RESUMO

Nas últimas décadas, houve mudanças no uso e cobertura da terra no território brasileiro, muitas resultantes de atividades antrópicas. Porém, estas mudanças afetam o sistema ambiental, comprometendo a biodiversidade e os serviços ecológicos. Neste contexto, a informação geográfica integradora sobre alterações ambientais nos Biomas permite a identificação das principais mudanças espaço-temporais no uso e cobertura da terra e pode contribuir para um planejamento ambiental eficiente. Assim, este trabalho objetiva descrever e sintetizar as mudanças espaço-temporais nos Biomas brasileiros entre 1985-2018 utilizando técnicas de estatística espacial e Análise de Componentes Principais com dados do projeto MapBiomas. Utilizou o Google Earth Engine e QGIS para a análise, com ênfase nas estatísticas espaciais e Análise de Componentes Principais que permitiram a identificação das principais mudanças no uso e cobertura da terra. A partir da Análise de Componentes Principais, foi possível reduzir o conjunto de dados com 34 imagens para duas Componentes Principais que representam percentagens significativas da variância da base de dados original. Os resultados mostraram que os Biomas Brasileiros sofreram alterações significativas ao longo de 34 anos. Os principais vetores que impulsionaram estas transformações foram atividades antrópicas, tais como o crescimento urbano, o avanço da agricultura, e a prática pecuária. A Amazônia e o Cerrado apresentaram a maior área alterada em quilômetros quadrados. E as mudanças mais rápidas ocorreram na Amazônia, Cerrado e Pantanal. Este trabalho apresenta uma síntese dos principais padrões e mudanças espaço-temporais no uso e cobertura da terra dos Biomas brasileiros, que podem ajudar no planejamento ambiental nacional. Palavras-chaves: Google Earth Engine, MapBiomas, Análise de Componentes Principais.

Introduction

Over the past three decades, Brazil has experienced various productive processes, predominantly in the agricultural and pastoral sectors. These processes have facilitated the expansion of agriculture into the Biomes of the low latitudes and the continental interior, while the East

Coast has become the most densely populated region in the country (IBGE, 2018; Vieira, 2016). This has resulted in significant changes and adaptations of the biomes to new ecological processes, including urbanization and farming. As a result, the preservation of the environmental

system has become a complex task for environmental planning, particularly in a large country like Brazil where geographic information is fragmented at larger cartographic scales.

In Brazil, the predominant source of greenhouse gas emissions stems from the continuous expansion of agricultural areas and pastures (Salmona et al., 2023). While these land uses play a crucial role in fostering economic growth, particularly within the realm of food production, it is imperative that their expansion is strategically orchestrated to align with sustainable practices (Silveira et al., 2022).

The term environmental planning emerged on the global stage as a reflection of the increasing demand for natural resources, which necessitates the orderly use of land and its resources, accompanied by the protection of endangered areas and an improvement in the quality of life for the population. Therefore, the primary goal of environmental planning is to balance the socioeconomic development of a region with the preservation of the natural environment, considering the potential and limitations of the area's use. The discussion on land use and coverage plays a crucial role in environmental planning since it provides insight into the pressure that anthropogenic activities may exert on the environment. To plan effectively, current data on land use and coverage, as well as any changes that have occurred in the environment, should be included (Santos, 2004).

Brazilian biomes have undergone notable changes in land use and cover, particularly intensifying in recent decades. Research by Rosan et al. (2021) has pinpointed a peak in land use and cover changes in Brazil, specifically between 2003 and 2005, with the Amazon emerging as the primary contributor to the overall carbon dioxide emissions resulting from land changes in the country. This contributes to climate change on both national and global scales.

Nonetheless, it is not solely the Amazon biome undergoing shifts in its spatial configuration. According to Silva et al. (2023), the Caatinga biome is grappling with a pronounced degradation process, characterized by an expansion of agricultural areas. Similarly, the Cerrado biome, crucial for conserving biodiversity and ecosystem services such as water and carbon, faces a looming threat due to the deforestation of its native vegetation (Matosak et al., 2022). Despite the implementation of numerous public and private conservation policies for the Atlantic Forest, as highlighted by Ramos et al. (2022), these efforts are insufficient when compared to the persistent degradation and deforestation of the biome.

The Pampa and Pantanal biomes also confront significant transformations in land cover, primarily attributed to the degradation and conversion of native grasslands (Correa et al., 2022; Gomes et al., 2022). Consequently, all Brazilian biomes are undergoing alterations, though in distinct rates and magnitudes.

Numerous projects are dedicated to monitoring and mapping land use and coverage in Brazil, such as TerraClass, PRODES, and MapBiomas. Among these, the MapBiomas project stands out for its extensive historical monitoring series, which utilizes automatic processing techniques on Landsat images. As a result, it has become one of the most comprehensive sources of land use and coverage maps of the Brazilian territory, spanning over 30 years of observation and emphasizing the unique characteristics of the Brazilian biomes in the mapping process (MapBiomas, 2020; Souza et al., 2020).

The MapBiomas database has been extensively utilized in studies investigating environmental change, natural resource utilization, and discussions on environmental conservation systems (Costa et al., 2019; Frey et al., 2018; Mas et al., 2019). However, there is a need for research covering the entire national territory and producing integrative analyses. Furthermore, computational and statistical techniques, such as Principal Component Analysis (PCA), allow for factor analysis, minimizing data redundancy and creating spatial models that represent the highest indices of variance in the database.

Many studies have utilized Principal Component Analysis (PCA) for change detection in remote sensing images, resulting in satisfactory outcomes. For example, Bustos et al. (2011) employed linear PCA to detect changes in an urban area of Argentina using multi-temporal data from CBERS-2B. Li et al. (2022) combined PCA and K-Means clustering to detect changes in hyperspectral images, with PCA reducing data dimensions and K-Means clustering identifying non-changed areas from changed areas. Wu et al. (2021) applied KPCA (Kernel Principal Component Analysis) convolution to multi-temporal, very high-resolution images to extract features for multi-class change detection, producing favourable results.

The purpose of this paper is to describe and synthesize the spatio-temporal changes in Brazilian biomes between 1985 and 2018 using spatial statistical techniques and Principal Component Analysis with data from the MapBiomas project. Given that the PCA statistical technique reduces redundancy and makes it possible to generate spatio-temporal models of the LUCC that caused the greatest covariance in the database. Therefore,

this work hypothesizes that these models should represent anthropogenic and natural changes in Brazilian biomes. Then, the study aims to comprehend changes in land use and coverage in biomes, with a focus on interpreting spatial models derived from Principal Component Analysis. This methodology facilitates spatio-temporal analysis of land use and cover changes (LUCC) at a national scale over a 34-year period, contributing to the comprehension of change processes at a small cartographic scale to support integrative

environmental planning actions. Additionally, this information can stimulate discussions about the preservation and appropriate ways to manage Brazilian biomes, enabling sustainable development.

Material and methods

Study Area

The study area is the Brazilian Biomes, these being: The Amazon, Cerrado, Pantanal, Caatinga, Atlantic Forest, and Pampa (Figure 1).

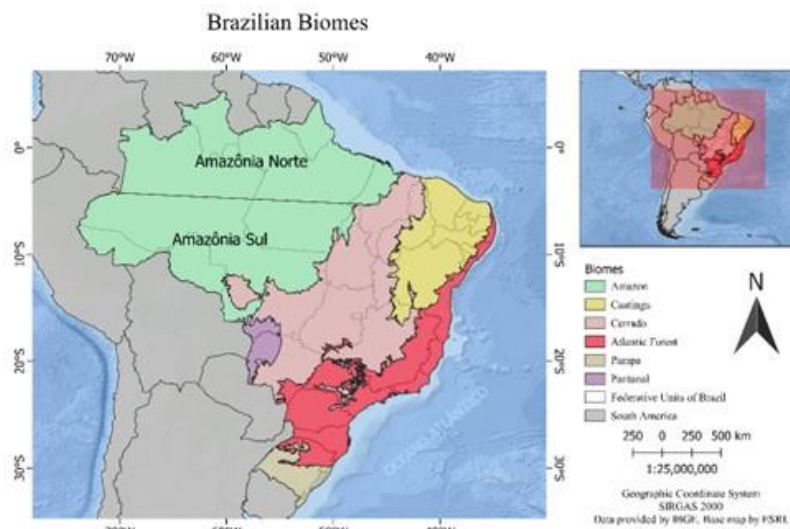


Figure 1. Study Area.

Data and Materials

In this study, data from the MapBiomias project collection 4.1 was utilized, which has a spatial resolution of 30 meters and a temporal resolution of one year between 1985 and 2018. The raster files consisted of 20 classes representing different land use and cover types. These classes are quantified in numerical values between 3 and 33. Information regarding the MapBiomias project can be found in MapBiomias (2020).

In addition, shapefiles of Brazilian biomes, made available by the Brazilian Institute of Geography and Statistics (IBGE), were used. The MapBiomias dataset was processed in Google Earth Engine, and subsequently, the data were integrated and processed in QGIS software version 3.10. The script used was adapted from Google Earth Engine (2020).

Data processing

The analysis was conducted at the Biome level using the GEE platform, except for the Amazon Biome, which was divided into North and South due to its extensive territorial coverage and processing limitations (see Figure 1). Given the substantial amount of data analyzed and the limitations of the GEE platform, it was necessary

to reduce the spatial resolution of the land use and cover maps. As such, the pixels were aggregated by mode to form a new pixel with a resolution of 300 meters, using the `ee.reduceResolution` and `ee.Reducer.mode()` functions. The new pixel value corresponds to the value with the highest frequency in the original set, with a resolution of 30 meters. Although this process results in some loss of detail, it is acceptable given the scale of the analysis.

To conduct the exploratory analysis, the MapBiomias dataset was used, and two metrics were measured over time: (1) the number of classes per pixel (`States`, `ee.Reducer.countDistinct()`) and (2) the number of changes of classes per pixel (`Incidents`, `ee.Reducer.countRuns()`). This approach was proposed by Pontius et al. (2017) and provides insight into the Spatio-temporal behavior of the pixels. These metrics aid in the interpretation of the Principal Components (PC) by identifying regions with higher rates of change and class intercalation over the observed period.

Principal Components Analysis (PCA) is a technique chosen for its ability to reduce the dimensionality of a dataset while preserving important information. Thus, PCA can be applied in big data in machine learning to achieve a dimension-reducing step. It accomplishes this by

reducing the dimensionality while maintaining a significant portion of the variability in the original data. This process facilitates the interpretation of large datasets (Jolliffe & Cadima, 2016; Manly, 2008). The PCA produces new variables, known as Principal Components (PCs), which result from a linear combination of the original data and are uncorrelated with one another. The linear functions are chosen with the aim to maximise the variance of the new variables (Jolliffe, 2022; Jolliffe & Cadima, 2016; Mingoti, 2005). The PCs are ordered in terms of importance, with the first PC explaining the maximum possible variance. The second PC explains the maximum variance that has not yet been explained, and the final PC has the smallest contribution to explaining the total variance of the original dataset (Manly, 2008; Reis, 2001). Each PC has an eigenvalue and an eigenvector, with the eigenvalue indicating the percentage of variance explained by the component and the eigenvector determining the direction/coefficient of each PC (Jolliffe, 2022; Zanotta et al., 2019).

PCA is a technique originally proposed for continuous data. However, according to Jolliffe (2002), PCA can be applied to any type of data with minor adjustments. Because the goal of describing the data and synthesizing information is achieved with any type of data. In the case of categorical data, such as the MapBiomass data used in this study, quantification is required before applying PCA (Mori et al., 2016).

In GEE, the PCA was implemented by following a four-step process for each Biome: 1) Transforming the three-dimensional matrix into a two-dimensional (`ee.toArray()`), 2) Measurement of covariance (`ee.Reducer.covariance()`), 3) Obtaining PCs from orthogonal functions (`ee.eigen()`), and 4) Evaluation of the representation of the PCs. The covariance coefficient reveals how the variables alter together (Zanotta et al., 2019). Based on the eigenvalues, the percentage of variance for each component was determined. That resulted in the selection of the first two PCs, causing a reduction in the data set from 34 to two images that explained considerable percentages of the original variability.

Another important aspect of PCA is that the first PC captures the essential information that is shared among the bands, and thus represents the underlying pattern of the data. On the other hand, the second PC reflects the changes, which is particularly relevant for LUCC analysis (Antunes, 2012; Maldonado, 1999). In this study, the Pearson correlation (`ee.Reducer.pearsonsCorrelation()`), between the first two PCs and the 34 input images was calculated. This coefficient measures the

degree of the relationship between two variables, indicating whether the relationship is strong (coefficient close to ± 1) or weak (coefficient close to 0), and whether the variables have a positive or negative linear correlation (Taylor, 1990).

Therefore, high correlation values (positive indicating similarity and negative indicating divergence) indicate the temporal occurrence of spatial models (PCs). Higher or lower correlations demonstrate similarities or divergences between the statistical model and the input data, making it possible to identify the occurrence over time of principal LUCC. Graphics were generated to interpret this metric. The graph analysis enables the identification of years of initial conditions (before the changes, negative values) and final ones (after the changes, positive values), and to analyze the temporal behavior of changes in land use and cover. The identification of the highest and lowest correlation indices allows for the selection of land use and cover maps from MapBiomass that are closest (highest correlation) and furthest (lowest correlation) from the statistical model of the second PC, enabling the analysis of spatial-temporal patterns of change identified by the PC.

After the results were obtained in GEE, they were exported and reprojected into the SIRGAS 2000 data projection system using QGIS software. The first and second PCs were then reclassified into land use and cover patterns (1st PC) and changes in land use and cover (2nd PC) to enhance their interpretability. The reclassification was carried out using samples that were selected in a supervised approach and through visual interpretation. The area of each change category was measured, and the cartographic products were also produced using QGIS.

Results and discussions

This section presents the results for each Biome, and a summary is provided at the end to highlight changes in the Brazilian Biomes. The results for each Biome are presented in a sequence of maps in a figure, as follows: (A) Number of Classes, (B) Number of Changes, (C) Reclassified PC 1, (D) Reclassified PC 2, (E) Map of MapBiomass of the year with the lowest correlation with the 2nd PC, and (F) Map of MapBiomass of the year with the highest correlation with the 2nd PC.

Amazon

Nobre et al. (2014) have reported that over two million square kilometers of forest have been deforested or degraded until 2013. Besides, the Amazon rainforest assumes a meaningful role in regional climate patterns, biodiversity, and the

global carbon cycle that might be risked due to deforestation (Boulton et al., 2022). The largest devastated area is concentrated in the "Arc of Deforestation," which is situated on the southern and eastern edges of the Biome. This region coincides with areas where human occupation began in the 1970s and where the agricultural frontier has been expanding. As a result, this practice has a direct impact on biodiversity through habitat fragmentation and contributes to climate change (Matos, 2016; Souza-Filho et al., 2016). Therefore, it is imperative to have a spatio-temporal understanding of these changes for efficient environmental planning.

Observing Figures 2A and 2B, it is notable that the interior of the Amazon Forest (in gray) is preserved because it presented only one class in 34 years. Otherwise, the region of the "Arc of Deforestation" (Rondônia, Mato Grosso, Pará States, Tocantins, and Maranhão) has a concentration of 2–4 values of changes (in purple), with a predominance of two alterations (Figure 2B). The same region also registers two classes over time equivalent to its original natural cover and the anthropic installed permanently. This information indicates intercalation between the classes in some periods.

Another fascinating aspect is the Amazon River, which exhibits more than 10 changes and 2–3 classes over time. This indicates that the region has a high turnover between some classes, and this process can be caused by natural actions that result in intercalation between them. Furthermore, it is observed that the values on the banks of the Amazon River are lower than in the river course, which can be attributed to anthropic occupations established in these areas (Fernandes, 2016).

In the PCA analysis, the Amazon Biome was divided into two parts, namely the North and South regions. Each region exhibits a different percentage of variance explained for each principal component. The South Amazon shows 75.05% of the variance explained by the first principal component and 11.43% by the second principal component. Together, the first two components explain 86.45% of the variance in the original data set. In contrast, the North Amazon displays 87.94% of the variance explained by the first principal component and only 3.59% of the variance explained by the second principal component. The first two components in this case explain a combined 91.54% of the original variance. These results demonstrate the efficacy of the PCA technique in reducing the dimension from 34 images to two principal components, which explain a significant proportion of the variance in the data set.

Based on the values of variance explained, it is possible to make several inferences about LUUC in the Amazon Biome. Considering the association of the first principal component with the pattern and the second with the changes, a high value explained by the second PC indicates the occurrence of significant changes, and conversely, a low value indicates fewer changes. Comparing the values for the first principal component, it is noteworthy that the North Amazon has a higher value than the South, suggesting that the region is closer to the pattern and has undergone fewer changes. In contrast, for the second principal component, the South Amazon (11.43%) has a higher percentage of the variance explained than the North (3.59%). This situation can be attributed to the fact that the southern boundary of the Biome exhibited the most significant changes, deviating from the standard (PC 1) and resulting in higher percentages in PC 2 and lower in PC 1.

The Water Bodies pattern represents areas covered by water bodies such as the Amazon River and its tributaries, which usually exhibit little variation in land use and cover, except when natural processes alter the river bed morphology. The pattern of Forest and Savanna Formations is distributed throughout the Biome, representing areas that are still preserved and can be considered native vegetation.

The Recent Pasture and Grassland pattern is concentrated in areas of recent deforestation and pasture installation in the "Arc of Deforestation," with areas of grassland in the north of Roraima. In deforested areas, there is a formation and enlargement of a "fishbone" pattern in recent pasture areas, which is characteristic of Amazon deforestation (Santos & Lingnau, 2017). The Consolidated Pasture pattern corresponds to areas of ancient pastures, and it is also found in deforested areas before 1985. This pattern is usually associated with the first areas of pasture and openings for access, which form the "fishbone" of deforestation, and from which newly deforested areas arise due to ease of access (Santos & Lingnau, 2017). Finally, the Consolidated Agriculture and Urban Areas pattern represents urban centers and cultivated areas.

The PC2 (Figure 2D) is related to LUCC over time, making it possible to interpret and identify the main changes in the Biome. This PC is classified into five classes: Water Loss (red), Natural Processes and Forestry (yellow), Redundancy (gray), Conversion of Natural Areas into Urban or Farming Areas (pink), and Dams or Flooded Areas (blue). The Water Loss change coincides with the replacement of areas covered by water (rivers, lakes, etc.) with other classes. This

kind of change corresponds to an area of 3,483.99 km², which is 0.08 % of the Biome. Water Loss is more evident in the surroundings of the Amazon River, where changes can be caused by natural factors such as the shifting position of the Amazon River bed (IBGE, 2020). Dams or Flooded Areas changes are associated with dam construction and a consequent widening of the riverbed, the creation of artificial lakes, or areas where water has accumulated by natural processes. Occurring in the surroundings of the Amazon River. This class of

change presents an area of 4,151.25 km² (0.097%). Natural Processes and Forestry represent areas where transitions were found between classes of farming systems to Forest Formation, Savanna Formation, Grassland, and Planted Forest (Forestry). This kind of change corresponds to an area of 22,974.3 km², which is 0.53 % of the Biome. And can be considered a type of secondary vegetation (except Forestry).

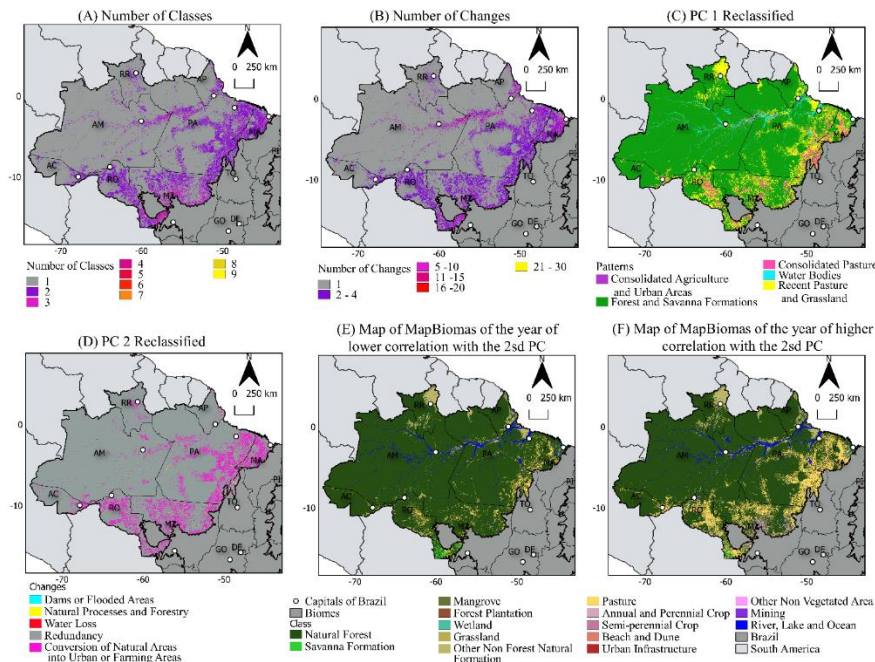


Figure 2. Results for Amazon.

The Redundancy class represents areas with little or no change, which cannot be detected using only two PCs. This class covers a vast proportion of the Amazon Biome, approximately 3,790,281.87 km² (88.8%). It is important to note that this percentage does not solely comprise preserved natural formations, as there have been several changes in land use and cover that have persisted over time, dating back to before 1985.

The most significant change within the Amazon Biome is the Conversion of Natural Areas into Urban or Farming Areas class, which spans 444,025.89 km² (10.4% of the Biome) and is heavily concentrated in the Arc of Deforestation. This conversion is particularly prevalent in the states of Rondônia, Mato Grosso, Pará, Maranhão, and Tocantins, where the agricultural frontier has advanced at a rapid pace, resulting in a high rate of deforestation (Matos, 2016). The "fishbone" shape of Amazon deforestation, which is generated by deforestation around roads or rivers (Santos & Lingnau, 2017), can be observed through the conversion of the Forest Formation class to that of

Pasture. While the expansion of urban areas is not visible on this scale, it is associated with the advancement of the agricultural frontier. As agropastoral economic activities were introduced, there was a subsequent attraction and migration of populations, leading to urban growth in the municipalities of the interior (Moura et al., 2018).

The correlation coefficients between each principal component (PC) and the input data are illustrated in Figure 3.

Figure 3A-B presents the coefficients for the 1st PC, all of which have negative values. This behavior indicates an association between this PC and the land use and cover pattern. In the North Amazon (Figure 3A), the coefficients form a straight line, indicating a stabilization of the classes over time. However, the South Amazon (Figure 3B) exhibits higher values during the 1980s and 1990s, which subsequently decrease from the 2000s onwards. This weaker correlation in the initial years can be attributed to changes in land use and cover that occurred in the region during this

period and are distant from the distribution patterns of the classes.

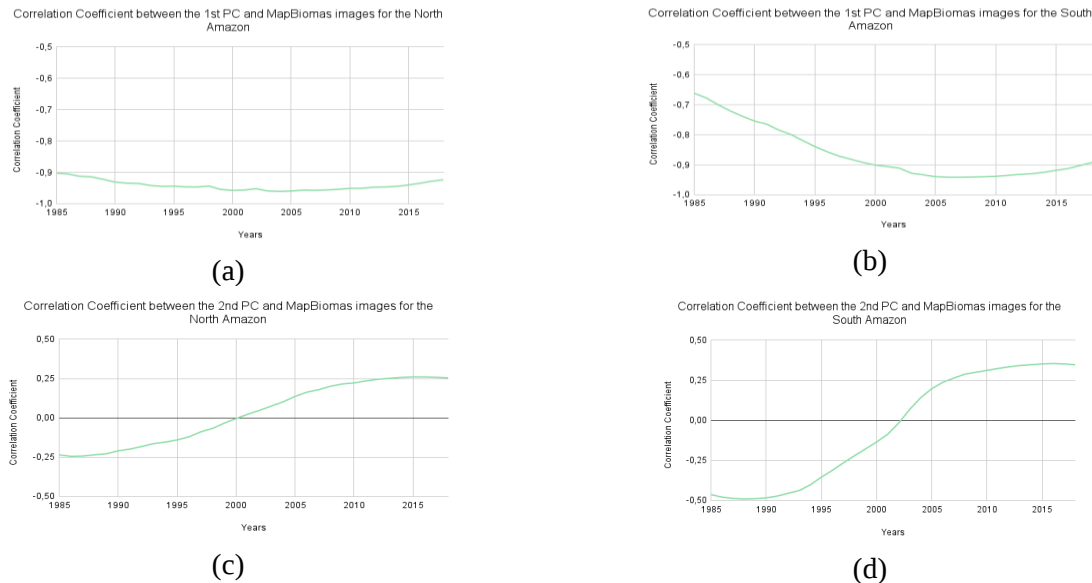


Figure 3. (a) Correlation with PC 1 for North Amazon; (b) Correlation with PC 1 for South Amazon; (c) Correlation with PC 2 for North Amazon; (d) Correlation with PC 2 for South Amazon.

In the 2nd PC (Figure 3C-D), the correlation values form an "S" shape, ranging from negative values (before changes) to positive values (after changes). The curve for the North Amazon (Figure 3C) is milder, indicating smooth changes without rapid transformations. Conversely, the South Amazon (Figure 3D) shows the steepest curve between 1990 and 2005, with a significant increase after 2000. This characteristic suggests the occurrence of the fastest and most intense LUC during the analyzed period. Silveira et al. (2022) similarly observed a reduction in the native forest in the Amazon, mainly in the 1991–2005 years. Led by the pasture expansion in the entire biome, mostly in the Arc of Deforestation, differently, agriculture is more evident in the borders with the Cerrado biome. Notably, in alignment with the present findings, the authors highlight a deceleration in deforestation rates after the year 2005.

Between 1990 and 2005, the Amazon Deforestation Calculation Program (PRODES) of the National Institute for Space Research (INPE) reported high annual deforestation rates in the Legal Amazon. The highest rate was observed in 2004, with approximately 27,772 square kilometers of deforested native forest.

Subsequently, the implementation of programs, such as the Action Plan for the Prevention and Control of Deforestation in the Legal Amazon (PPCDAM), led to a reduction in deforestation values in the region (Matos, 2016).

Figures 2E and 2F present the MapBiomass maps of the years with the lowest (divergence) and highest (similarity) correlation coefficients with Sartorio, L.F.; Maier, E.L.B.

the statistical model of the second Principal Component. The maps selected for the North Amazon were from 1986 (-0.2443) and 2015 (0.2603), while for the South Amazon, the maps from 1988 (-0.4899) and 2016 (0.355) were chosen. A comparison between these maps reveals the expansion of the agricultural frontier towards the Amazon, particularly in the region of the Arc of Deforestation, with a strong emphasis on the expansion of pasture areas. Unfortunately, such expansion often results from illegal deforestation (Guimarães, 2016). Notably, there has been a growth in the pasture class along the Amazon River's banks, which is related to the values found in Figures 2A and 2B. These changes in the spatial configuration of economic activities, such as farming, have been accompanied by population migrations, which intensified after the 1980s and resulted in significant changes in the Brazilian agrarian space (EMBRAPA, 2018). Despite this trend, we can also observe a large area of preservation in the interior of the Amazon Forest.

Cerrado

According to Brazil (2014), the Cerrado Biome has already undergone significant devastation with 47% of its natural areas being affected by deforestation and anthropic fires in 2010. This situation has led to the classification of the Biome as one of the most degraded in the country. The primary cause of deforestation in this area is attributed to agricultural and cattle ranching activities, which have intensified over the past few decades (Rocha, 2012). These actions have had direct negative impacts on the local biodiversity,

causing habitat fragmentation, pollution of aquifers, an increase in fires, and regional climate change (Klink & Machado, 2005).

Figure 4A shows that the number of classes for the Cerrado is predominantly between two and five. There are only a few areas with a single class over time (in Tocantins, Piauí, and Maranhão states), highlighting the crucial transformations occurring in this biome. The number of changes (Figure 4B) is also high, with a significant presence in the range of two to ten. These conditions may be associated with the intercalation and expansion of agricultural activities in the states of Mato Grosso, Mato Grosso do Sul, Goiás, and the MATOPIBA frontier agricultural region (Maranhão, Tocantins, Piauí, and Bahia) (Guimarães, 2016; IBGE, 2020), accompanied by the expansion of infrastructure and urban areas.

In the PCA analysis, PC 1 explains 75.37% of the variance and PC 2 explains 9.97% of the variance in the original data set. Together, the first two components represent 85.34% of the original variance. Given these values, significant changes in the biomes are expected to be represented by PC 2, as it explains almost 10% of the variance in the data set.

PC1 (Figure 4C) is classified into five classes: Consolidated Agriculture and Urban Areas

(purple), Forest and Savanna Formations (green), Consolidated Pasture (pink), Water Bodies (blue), and Grassland (yellow). This PC represents the spatiotemporal patterns of land use and cover in the Cerrado. Water Bodies represent watery surfaces and are most visible in the Minas Gerais State. Forest and Savanna Formations denote natural areas that have been preserved, with a higher presence in the north, east, and west boundaries of the biome, particularly in Maranhão and Piauí States. Consolidated Agriculture and Urban Areas are distributed in Goiás, Mato Grosso do Sul, Mato Grosso, and the MATOPIBA (a recent agricultural frontier). These areas have a high concentration of consolidated agriculture activities, such as soybean and sugarcane monocultures (Guimarães, 2016; IBGE, 2020). Consolidated Pasture has a significant presence in the states of Minas Gerais, Goiás, and Mato Grosso do Sul, particularly in the south of the Cerrado, representing older pasture areas. In contrast, Grassland has its principal distribution in the states of Mato Grosso, Tocantins, Bahia, and Maranhão, primarily in the north of the biome, representing natural areas that are still preserved.

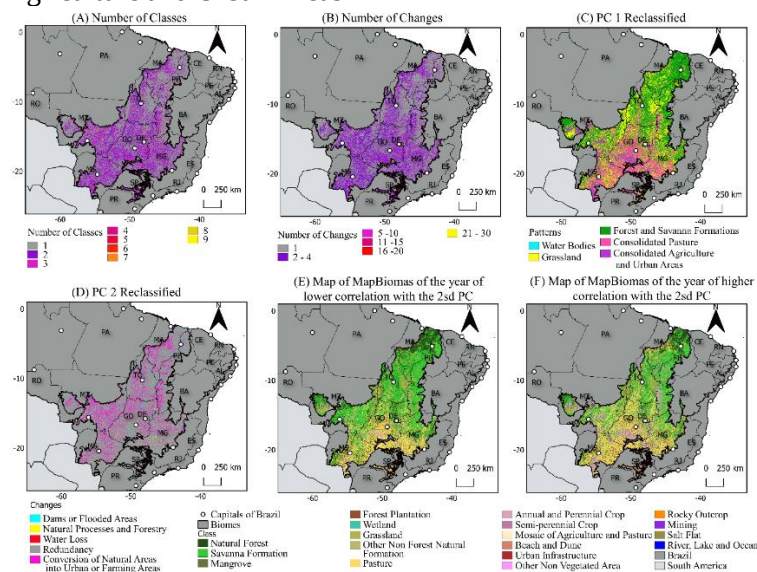


Figure 4. Results for Cerrado.

PC 2 (Figure 4D) is associated with alterations in land use and covers over time, enabling interpretation and identification of the main changes in the Biome. This PC is classified into five categories: Water Loss (red), Natural Processes and Forestry (yellow), Redundancy (gray), Conversion of Natural Areas to Urban or Agricultural Land (pink), and Dams or Flooded Areas (blue). Water Loss affected 0.04% (926.19

km²) of the Biome. The Redundancy class corresponds to 80.51% (1,663,789.59 km²) of the Biome and may indicate areas that maintain their class over time (such as natural areas preserved or a stable class) or are not represented by only two PCs. Natural Processes and Forestry occurs in 2.10% (43,457.67 km²) of the Biome, mostly in Minas Gerais and Goiás. This change represents the conversion of agricultural areas into natural

formations or forestry. The former case can be considered a type of vegetation regeneration.

The conversion of natural areas into farming or urban areas in the Cerrado Biome is a crucial change that has occurred over the past few decades. This change represents 17.1% (352,810.44 km²) of the Biome and is distributed across almost all of it. The conversion is related to the advance of the agricultural frontier over the Brazilian Midwest, particularly in the MATOPIBA region. In this region, agriculture and ranching have occupied natural areas (Vieira, 2016). The growth of urban areas is associated with the implementation of farming activities, which attract the population to the interior of the country (Moura et al., 2018). It is important to note that the region's economy is driven by agriculture and cattle ranching, especially soybeans, corn, and the livestock sector, which supply the demand of national and international markets. This is due to the Biome's favorable characteristics for mechanized agriculture, such as its smooth topography and the use of fertilizers to improve soil productivity (Fernandes et al., 2016).

The last change is the Dam or Flooded Areas which occupied an area of 3,366.9 km² (0.16%) of the Biome. Then, the increase in the surface water is higher than the loss (Water Loss). In Cerrado, this change is more present in the Goiás and Tocantins States. In North of Goiás is the artificial lake named Lago da Serra da Mesa, from the Serra da Mesa power plant. Further, up in the map (Figure 4D), we have the Cana Brava Lake, the artificial lake of the Cana Brava Plant, and other hydroelectric plants installed on the Tocantins River (Fernandes, 2010). The installation of hydroelectric power plants and their artificial lakes causes the flooding of areas and produces social and environmental impacts in the locality. Among the main environmental impacts, there are changes in flora, fauna, fishing, tourism, loss of biodiversity, erosion downstream of the hydroelectric plant, etc. (World Commission on Dams, 1999 apud Souza, 2010).

The correlation coefficients between the principal components and input data are presented in Figure 5. For the 1st PC (Figure 5A), all values are negative, with higher correlation values at the beginning of the time series and decreasing values after 1995. This trend suggests a change in the pattern of land use and land cover between 1985 and 1995. In the 2nd PC (Figure 5B), the correlation values form an "S" shape, with negative values before the changes and positive values after the changes.

The curve generated by the correlation values is steeper, indicating quicker and more

intense changes in the period. This behavior is consistent with the rapid LUCC that occurred in the Cerrado Biome between 1990 and 2005, followed by a period of stabilization.

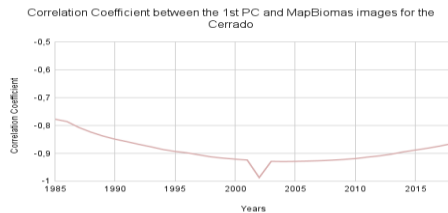
Figures 4E and 4F depict MapBiomias maps representing the years with the lowest (divergence) and highest (similarity) correlation coefficients with the statistical model of the second Principal Component, respectively. The years 1988 (-0.4866) and 2015 (0.2718) were chosen for this analysis. The most prominent changes in the Cerrado Biome are associated with the expansion of Pasture and the replacement of Ancient Pasture with Agricultural Areas. This transformation occurs in an east-to-west direction, towards the interior of the continent. In the MATOPIBA region, there is a notable conversion of natural areas to agricultural land, and in the states of Mato Grosso, Tocantins, and Maranhão, there is a clear expansion of Pasture. These changes indicate the ongoing expansion of the agricultural frontier over the Cerrado Biome.

The Caatinga biome has already lost 46% of its original cover (Brazil, 2020b). The process of deforestation in this biome is primarily related to the exploitation of firewood as fuel by farmers and the clearing of land for pasture and agriculture. Deforestation has a direct impact on the natural resources of the Caatinga, including the reduction of local fauna and flora, a decline in soil fertility, acceleration of the erosion process, and changes in the microclimate. These changes, in turn, accelerate the desertification process (Kill & Porto, 2019; Salazar et al., 2021), rendering the areas unproductive (Gusmão et al., 2016).

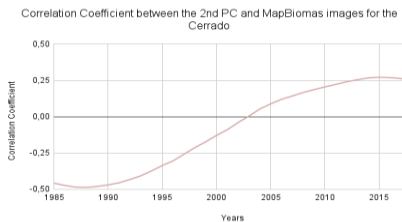
Analyzing the map presented in Figure 6A, it is evident that the two to four land cover classes have predominated over time. The purple color, which represents the conversion of Savanna Formations into Pasture, is prominently visible. On the coast of Caatinga, there are high values of land cover classes, which can be attributed to the expansion of urban areas and economic activities. The distribution of the Number of Changes (Figure 6B) mostly ranges between two to ten, with a concentration of a high number of changes on the coast and lower changes in the interior of the Biome.

The results of the PCA show that PC1 explains 77.2% and PC2 explains 7.08% of the variance in the original dataset. Together, they account for 84.28% of the total variance. These values are lower than those found for the Cerrado and the southern Amazon, suggesting that the Caatinga biome has undergone fewer changes than these other biomes.

The land use and cover pattern in Caatinga between 1985 and 2018 is represented by PC1 (Figure 6C), which is classified into five classes: Consolidated Agriculture and Urban Areas (purple), Forest and Savanna Formations (green), Consolidated Pasture (pink), Water Bodies (blue), and Recent Pasture (yellow). The Consolidated Agriculture and Urban Areas pattern is concentrated in the interior of Bahia State and some parts of the coast. The coast of the Northeast is an area of ancient occupation, characterized by the establishment of monoculture of sugarcane and urban centers (Guimarães, 2016; IBGE, 2020;



(a)



(b)

Figure 5. (a) Correlation with PC 1 for Cerrado; (b) Correlation with PC 2 for Cerrado.

PC 2 (Figure 6D) is associated with land use and cover change over time. This PC is divided into five change classes: Water Loss (red), Natural Processes and Forestry (yellow), Redundancy (gray), Conversion of Natural Areas into Urban or Farming Areas (pink), and Dams or Flooded Areas (blue). The Water Loss only accounts for 0.04% (33.11km²) of the biome. However, it is important to consider that the Caatinga population suffers from water scarcity, and they rely on rainwater storage in cisterns to extend water availability during drought times (Gusmão et al., 2016). Therefore, any reduction in the water surface area must be carefully analyzed. On the other hand, the Dams or Flooded Areas changes occupy only 0.07% (609.48km²), indicating that the growth of flooded areas was higher than the loss. The Redundancy class covers 82.36% (725,274.36 km²), representing land cover that is stable over time and does not show significant changes that can be represented by only two principal components.

The change Conversion of Natural Areas into Urban or Farming Areas occurred over an area of 14.60% (128,571.75km²) and is spread throughout the Biome, with a higher intensity in the Coastal zone, Eastern, and Central parts of the Biome. This type of change is associated with the growth of cities and the expansion of pasture, which replaces the Savanna Formation. On the other hand, Natural Processes and Forestry represent only 2.82% of the changes in the Biome, covering an area of 24,794.91km². This type of change represents the conversion of farming areas into natural formations (secondary vegetation) or

forestry. It is mostly distributed in the Bahia, Piauí, Paraíba, and Rio Grande do Norte states. Monitoring secondary vegetation is crucial for environmental planning as it represents vegetation regeneration after economic activity.

Overall, Figure 7 shows the correlation coefficients between the PCs and the input data, providing insights into the relationships between land use and cover changes and their corresponding PCs. In particular, Figure 7A displays negative correlations for all variables in the 1st PC, with higher values at the beginning of the time series and a decreasing trend after 1995, which suggests changes in the land use and cover pattern during this period.

In contrast, Figure 7B shows an "S" shaped curve for the 2nd PC, ranging from negative values before changes to positive values after changes. Caatinga exhibited smoother curves compared to Cerrado and South Amazon, indicating that land use and cover changes in Caatinga occurred at a slower pace than in other biomes.

The main changes in Caatinga took place between 1995 and 2010. Overall, Figure 7 provides valuable insights into the dynamics of land use and cover changes in Caatinga and their relationship with the corresponding PCs.

The maps presented in Figures 6E and 6F respectively show the MapBiomas maps for the years with the lowest (divergence) and highest (similarity) correlation coefficients with the statistical model of the second Principal Component. The selected maps are from 1989 (-0.3563) and 2015 (0.2991). The most noticeable

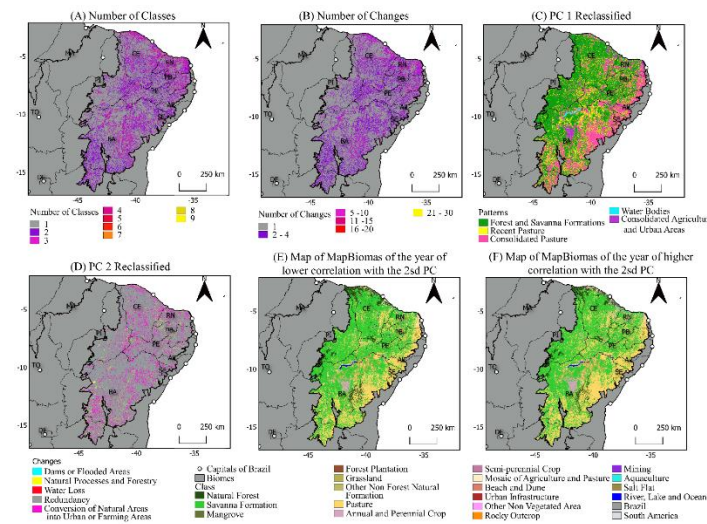
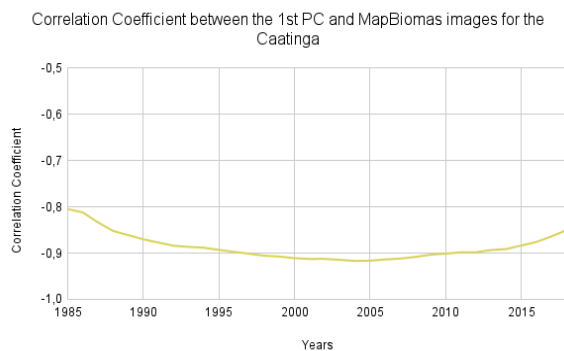


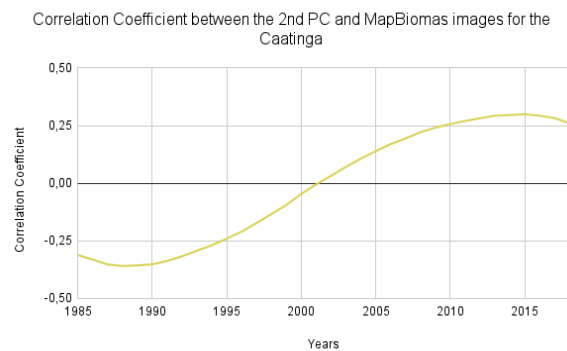
Figure 6. Results for Caatinga.

change between the two maps is the expansion of the Pasture class towards the interior of the Biome. This change transforms Savanna Formations into new areas for livestock rearing. Caatinga presents a unique biodiversity that needs to be conserved

and restored because the fragmentation and loss of connectivity impact negatively species and could modify the functionality of the ecosystem (Salazar et al., 2022).



(a)



(b)

Figure 7. (a) Correlation with PC 1 for Caatinga; (b) Correlation with PC 2 for Caatinga.

Pantanal

Pantanal is the most conserved Brazilian Biome, with more than 80% of its original area preserved (Brazil, 2020a).

Regarding the Number of Classes (Figure 8A), the values range from two to five. At the borders of the biome, there is a concentration of two classes over time, which is associated with the original natural formation and the pasture that was installed. In the center of the Pantanal, higher class values are observed, which may be related to the intercalation between flooded and humid areas (IBGE, 2020). A similar situation is observed in the map of the Number of Changes (Figure 8B), where two to four changes are concentrated at the

boundaries and a higher number of changes are observed in the main area of the Pantanal.

Results point out that PC 1 explains 77.4% and PC 2 8.85% of the variance in the original data set. They together account for 86.25% of the original variance. Then, with the values of percentage explained by each PC, it is possible to infer that the Pantanal Biome could present more changes than the Caatinga Biome. Due to the higher value of variance explained by PC2.

PC1 (Figure 6C) represents the land use and cover patterns in the Pantanal during the observed period and is classified into five classes of patterns: Consolidated Agriculture and Urban Areas (purple), Forest and Savanna Formations (green), Consolidated Pasture (pink), Water Bodies

(blue), and Recent Pasture, Wetland, and Grassland (yellow). The Recent Pasture, Wetland, and Grassland class dominates the biome, with Pasture primarily located at the borders and Wetlands and Grasslands in the center. In the PC2 reclassification, it was not possible to separate these three classes. Forest and Savanna Formations are distributed around the Recent Pasture, Wetland, and Grassland pattern. The Consolidated Pasture class is present in some areas on the boundary of the biome, representing the ancient occupation by this economic activity. Water Bodies are more visible in areas close to the Brazilian border. Consolidated Agriculture and Urban Areas occupy only a few areas in the biome, with the city of Corumbá/MS being a notable highlight.

PC2 (Figure 6D) is associated with land use and cover change and is divided into five change classes: Water Loss (red), Natural Processes and Forestry (yellow), Redundancy (gray), Conversion of Natural Areas into Urban or Farming Areas (pink), and Dams or Flooded Areas (blue). The Redundancy class, covering 82.14% (131,329.17km²) of the Pantanal, represents no change or no representation by only two principal components. Dams or Flooded Areas occur in 0.20% (313.2km²) and represent an increase in water surface area, typically through natural processes. The Water Loss occurred at 0.48% (763.38km²), indicating that the Pantanal experienced more surface water loss than gain. Natural Processes and Forestry are mainly distributed in the north and west of the biome, covering an area of 2357.46km² (1.49%). This change suggests a shift from farming activities to natural formations or forestry.

Lastly, the principal change in the Pantanal is the conversion of natural areas into urban or

farming areas, covering 24,691.86km² or 15.44% of the biome area. There is a high concentration of this change in the borders and center of the biome, representing mainly the expansion of pasture into natural formations. Notably, this transformation occurred within only 34 years.

The correlation coefficients between each PC and the input data are presented in Figure 9. In the 1st PC (Figure 9A), all correlations are negative, which is consistent with the other biomes. The correlation values were higher at the beginning of the time series and decreased after 1995, suggesting a variation from the pattern and a likely occurrence of changes in land use and cover. For the 2nd PC (Figure 9B), the correlation values form an "S" shape, ranging from negative values (before changes) to positive values (after changes). In Pantanal, the curve became steeper between 1995 and 2005, indicating a rapid rate of change in land use and cover during this period.

Figures 8E and 8F respectively present the MapBiomos maps of the years with the lowest (divergence) and highest (similarity) correlation coefficients with the statistical model of the second Principal Component. The maps from 1988 (-0.4121) and 2013 (0.3387) were selected. It is notable that the primary changes in Pantanal were due to the expansion of the Pasture area, particularly in the borders, which resulted in the loss of natural areas and harm to local biodiversity. Correa et al. (2022) also elucidate that the Pantanal biome is undergoing an expansion of pasture, particularly in an east-west direction. This expansion has a significant increase of 51% during the period spanning 2000 to 2019, concurrently leading to a reduction in the coverage of savanna areas within the biome.

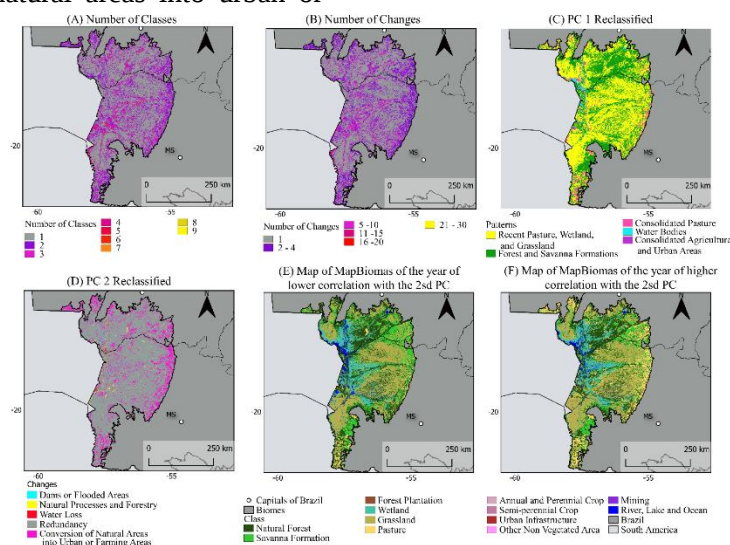


Figure 8. Results for Pantanal.

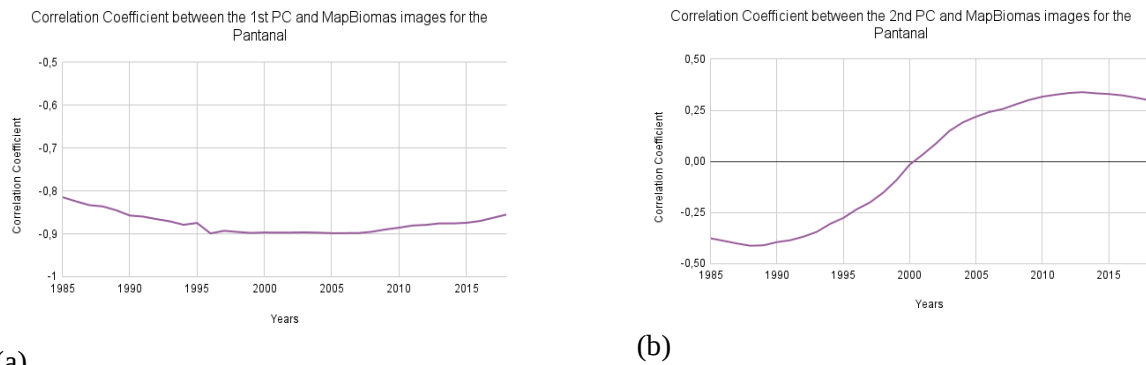


Figure 9. (a) Correlation with PC 1 for Pantanal; (b) Correlation with PC 2 for Pantanal.

Atlantic Forest

The Atlantic Forest is considered the most deforested and threatened biome in Brazil, with remaining areas of original coverage varying from 12.5% to 29% depending on the study or approach used. Additionally, the biome suffers from low connectivity among its remnants, affecting threatened species (Diniz et al., 2022; Viezzer et al., 2019).

For the Atlantic Forest, the map depicting the number of classes (Figure 10A) shows a significant concentration of values between two and four, especially in coastal areas and the states of São Paulo, Paraná, Santa Catarina, and Rio Grande do Sul. These values may be attributed to the expansion of urban and agricultural areas, resulting in a shift in land use classes. Similarly, the map illustrating the number of changes (Figure 10B) displays a comparable pattern, with values ranging between two and ten. This phenomenon may be linked to the intercalation of classes within the biome, primarily driven by agricultural activities. The results of the PCA analysis show that PC1 accounts for 82.7% of the variance in the

data set, while PC2 accounts for 5.74%. Together, these two principal components explain 88.44% of the original variance. Similar to the North Amazon and Caatinga biomes, the Atlantic Forest shows a lower value of variance explained by PC2 when compared to the Cerrado, South Amazon, and Pantanal. This may indicate that the Atlantic Forest has undergone fewer changes over time and has a relatively stable pattern of land use and cover classes.

The first principal component (PC1) of the Atlantic Forest land use and cover patterns (Figure 10C) can be classified into five distinct categories: Consolidated Agriculture and Urban Areas (purple), Forest and Savanna Formations (green), Consolidated Pasture (pink), Water Bodies (blue), and Grassland and Forestry (yellow). The Water Bodies pattern mainly represents the Tiete and Paraná Rivers. The Forest and Savanna Formations pattern is indicative of areas that are still preserved, such as the coast of Bahia, Rio Grande do Sul, and the Serra do Mar region extending from São Paulo to Santa Catarina.

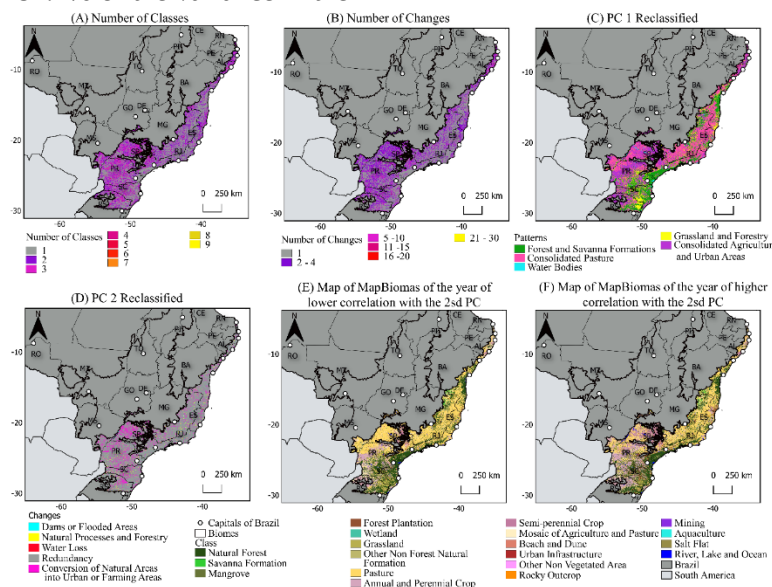


Figure 10. Results for Atlantic Forest.

The Consolidated Agriculture and Urban Areas pattern is primarily present in the north of Rio Grande do Sul, west of Santa Catarina and Paraná, and in the central part of São Paulo State. These areas are major centers of agricultural production, primarily for soybean and sugarcane crops (Guimarães, 2016; IBGE, 2020). Large urban areas are primarily located along Brazil's coastal belt, due to the concentration of inhabitants and large metropolitan areas (Lima, 2016). The Consolidated Pasture pattern has a widespread distribution in the Biome, covering parts of Rio de Janeiro, Espírito Santo, São Paulo, Mato Grosso do Sul, and the northeast coast. The Grassland and Forestry pattern is present in the states of Rio Grande do Sul, Santa Catarina, Paraná, and Bahia.

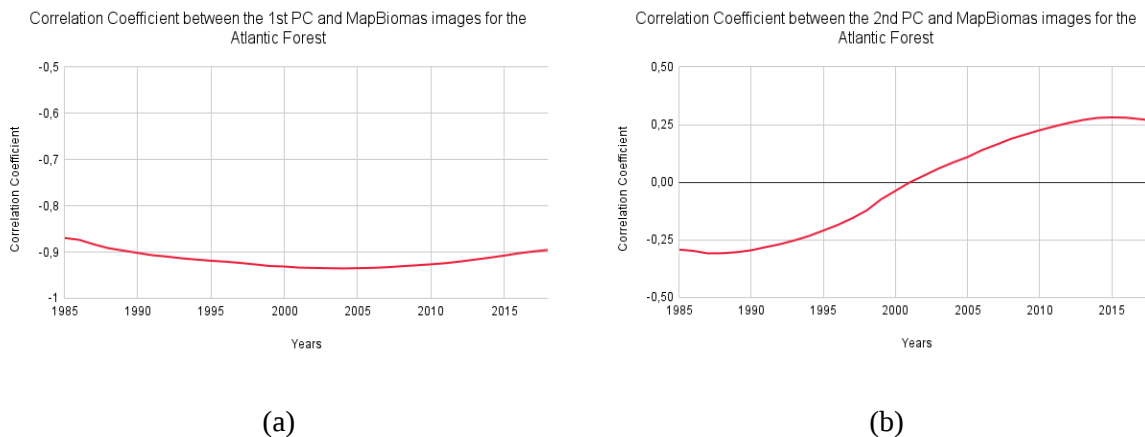
In terms of PC 2 (Figure 10D), it is closely related to LUUC and is divided into five change classes. The first one is Water Loss (red), which only occurred in 0.13% (1,567.08km²) of the Atlantic Forest. The second class is Natural Processes and Forestry (yellow), which covers 2.54% (30,523.32km²) of the changes in the Biome, and it represents the expansion of forestry and the regeneration of farming areas into natural formations.

The third class is Redundancy (gray), which covers 83.4% (989,659.8km²) and is mostly located along the coast (Serra do Mar and Northeast). This class indicates a no-change or a no-representation by only two PCs. The fourth

class is Conversion of Natural Areas into Urban or Farming Areas (pink), which occupies 14.4% (173,486.34km²) of the Biome and is mainly present in the States of São Paulo, Paraná, Santa Catarina, and Rio Grande do Sul. This class indicates the advance of farming in the interior of the Biome, with urban growth being more significant in the big cities.

Finally, the fifth class is Dams or Flooded Areas (blue), which only accounts for 0.15% (1,819.62km²) of the Forest Atlantic and represents areas that have been flooded due to dam construction.

The correlation coefficients for each principal component (PC) with the input data are displayed in Figure 9. In the first PC (Figure 11A), all correlations are negative, and the values form an almost straight line, indicating an approximation to the pattern without intense changes over time. For the second PC (Figure 11B), the values of correlation form an "S" shape, ranging from negative (before changes) to positive (after changes) values. Upon examination of the graph of PC2, we observed that the curve formed is smoother and less steep. This condition suggests the occurrence of softer and slower changes in the period, which is expected due to the variance explained by PC2 for this biome. The principal changes occurred between 1995 and 2010.



Figures 10E and 10F present the MapBiomas maps for the years with the lowest (divergence) and highest (similarity) correlation coefficients with the statistical model of the second principal component. The maps from 1987 (-0.3085) and 2015 (0.2814) were selected for comparison. Upon comparing the maps for these two dates, it is notable that agricultural areas have expanded towards the west, in areas of consolidated pasture (São Paulo, Paraná, and Santa

Catarina States), as well as in Bahia and Espírito Santo. Furthermore, there has been an increase in forestry in Santa Catarina, Paraná, Minas Gerais, Espírito Santos, and Bahia. Finally, significant urban growth has occurred in cities on the coast, particularly in the major metropolises, which attract migrants due to their industrial concentration.

Pampa

The Pampa biome has had over 60% of its original vegetation land modified due to the conversion of native areas into monoculture, mostly for soy and exotic species for forestry, as well as cultivated pastures. As a result, it is currently one of the most endangered biomes in the country (Chomenko, 2016). According to Gomes et al. (2022) the Pampa biome is suitable for livestock development and converting pastureland to crops increases the pressure on water resources, soils, and natural vegetation.

Upon analyzing Figure 12A, it is noteworthy that there is a predominance of values

between two and four classes. Additionally, the East of the biome retains higher values and consequently, more LUCC. This scenario is supported by the map of the number of changes (Figure 12B), which shows a higher presence of values between two and 10 changes. Once again, higher numbers of changes are concentrated in the East of the biome. These changes may be associated with the expansion of planted forests in the region (AGEFLOR, 2020). In the interior of Pampa, changes can be related to the expansion of agricultural areas.

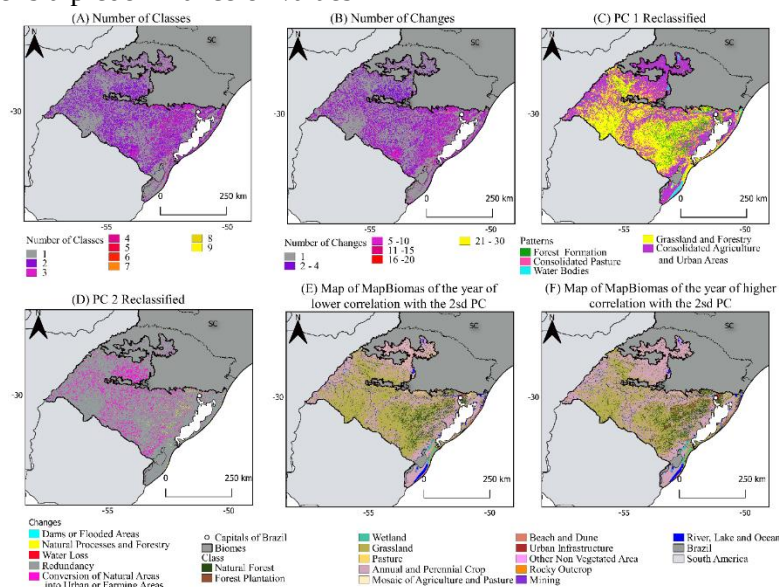


Figure 12. Results for Pampa.

The results of the principal component analysis indicate that PC1 explains 87.89% of the variance in the original dataset, and PC2 explains 3.42%. Together, they represent 91.31% of the original variance, making it the biome with the highest value explained by the first two components. When comparing these values with the Cerrado and South Amazon, it is evident that the Pampa has undergone fewer changes than the other biomes. Due to the high value explained by PC1, it indicates a tendency towards stabilization of land use and land cover.

PC1 (Figure 12C) represents the land use and cover patterns in the Pampa between 1985 and 2018 and is classified into five pattern classes: Consolidated Agriculture and Urban Areas (purple), Forest Formation (green), Consolidated Pasture (pink), Water Bodies (blue), and Grassland and Forestry (yellow). Among the Water Bodies patterns, Mirim Lake, the Ronda Alta Dam, and the Passo Real Hydroelectric Power Plant stand out. The Forest Formation mainly occurs on river

banks, forming the riparian forest. Consolidated Pasture is less prevalent in Pampa when compared to other biomes, likely due to the natural grasslands being utilized for animal husbandry in the region.

The presence of Consolidated Agriculture and Urban Areas is observed in the East, North, West, and near large rivers in the center of the Biome. The North and East regions are dominated by agriculture, with the North of Rio Grande do Sul being a significant grain-producing area, while rice cultivation that uses the water from the Lagoa dos Patos City for irrigation is predominant in the East. However, the Pampa still has a large area covered by natural grasslands that are used as pasture. In recent years, there has been significant growth in Forestry in the East of the Biome, due to favorable climate and soil conditions, availability of land, and proximity to the Port of Rio Grande, which facilitates the export of products (Figueiredo, 2016).

PC 2 (Figure 12D) is related to modifications in land use and covers. This PC is

divided into 5 classes of changes: Water Loss (red), Natural Processes and Forestry (yellow), Redundancy (gray), Conversion of Natural Areas into Urban or Farming Areas (pink), and Dams or Flooded Areas (blue). Water Loss represents only 0.03% (69.21km²) of the changes in the Biome, while Dams or Flooded Areas represent 0.06% (128.34km²). As a result, the Pampa has experienced an increase in surface water. The Redundancy class covers 83% (174,365.1km²) of

the Biome and mainly represents stable areas of Grasslands that have not undergone changes over time or are not represented by this PC.

The Natural Processes and Forestry change occurred in 1.63% (3,423.87km²) of Pampa and mainly represents the expansion of Forestry in the East, which has a significant presence. However, it also represents the substitution of Dunes and Other Non-Vegetated Areas by Forest and Countryside Formation on the coastal plain.

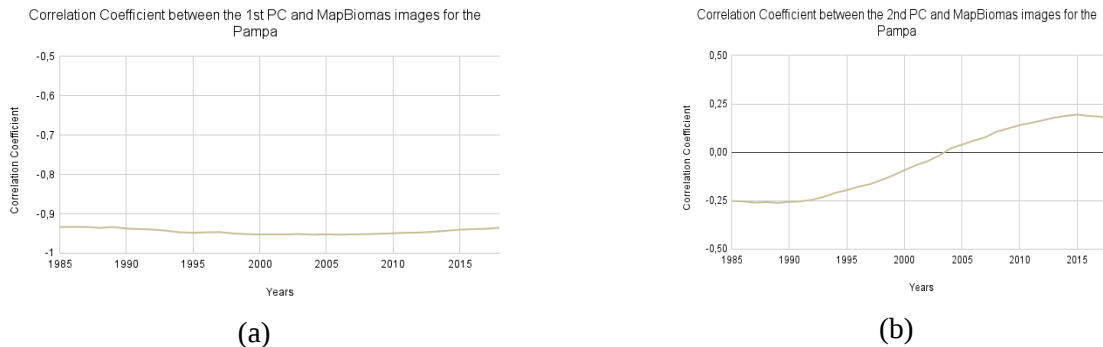


Figure 13. (a) Correlation with PC 1 for Pampa; (b) Correlation with PC 2 for Pampa.

Finally, the Conversion of Natural Areas into Urban or Farming Areas change occurred in 15.12% (31,785.3km²), mainly in the North, West, and center of Pampa, and is related to the advanced production of soybeans in the Biome.

The correlation coefficients for each PC with the input data are presented in Figure 13. In the 1st PC (Figure 13A), all correlations are negative, consistent with the other biomes. The values almost form a straight line, indicating a strong adherence to the pattern without significant changes over time. In the 2nd PC (Figure 13B), the correlation values form an "S" shape, ranging from negative (before changes) to positive (after changes) values. Upon analyzing the PC2 graph, it is evident that the curve formed is the least steep among all biomes, and it does not exhibit significant peaks. This suggests the occurrence of more gradual and slower changes, especially between 1990 and 2010.

Figures 12E and 12F respectively present MapBiomias maps for the years with the lowest (divergence) and highest (similarity) correlation coefficients with the statistical model of the second Principal Component. The maps selected were from 1989 (-0.2613) and 2015 (0.1946). It is noteworthy that for the Pampa, the correlation values do not present such a large amplitude as for the Cerrado and Southern Amazon. This suggests that there have been no major natural transformations in the Pampa as in these biomes. Looking at the maps, it is noticeable that the biggest changes are related to the expansion of

agriculture in the North and West and the growth of Forestry in the East.

Summary

Overall, the Conversion of Natural Areas into Urban or Farming Areas was the primary driver of land use change across all biomes, particularly between 1990 and 2010. The Amazon and Cerrado experienced the most extensive changes in terms of square kilometers, but when considering the percentage of altered area relative to the total biome area, the Cerrado, Pantanal, and Pampa exhibited higher values.

Thus, these biomes underwent significant transformations due to land use change, followed by Caatinga and Atlantic Forest. In contrast, the Amazon had the lowest percentage of altered area due to its vast size. When examining the correlation coefficient of the second Principal Component, the most rapid changes occurred in the Amazon, Cerrado, and Pantanal. In the Amazon and Cerrado, the largest changes were concentrated between 1990 and 2005, spanning 15 years. Meanwhile, the Pantanal experienced the most significant changes within a shorter timeframe of 10 years between 1995 and 2005, indicating a higher rate of change.

Another important aspect to consider is the changes related to water surface, as there have been both losses and gains in different biomes. Cerrado, for instance, has experienced more gains due to the implementation of dams, while Pantanal has suffered more losses in its natural water surface. Furthermore, it is worth mentioning that the changes in natural processes and forestry have occurred with greater significance in the Caatinga

(2.82%), Atlantic Forest (2.54%), Cerrado (2.10%), and Pampa (1.63%) biomes. These changes represent an increase in forestry and secondary vegetation, which requires further studies to understand their impact on the environment.

In summary, changes in land use and cover in the Brazilian biomes between 1985 and 2018 were mainly caused by the expansion of farming and urban growth. At the national level, there has been a movement of farming activities towards remote locations in the countryside. The expansion of pastures and agriculture followed the agricultural frontier, primarily in the Cerrado and Southern Amazon. In some cases, agriculture has even replaced former pasture areas (IBGE, 2020). Meanwhile, migratory movements towards urban environments have led to population concentration in consolidated urban areas, especially along the coast and in the Southeast, where there has been significant growth in urban areas (Lima, 2016). Nevertheless, there are still preserved areas of vegetation formations in the Amazon, along the coast of the Atlantic Forest, and in the interior of the Caatinga bordering the Cerrado. Additionally, some biomes have seen the regeneration of farming areas into vegetation.

Some authors have also found similar results for the Brazilian biomes. According to IBGE (2020), the Amazon and Cerrado biomes have experienced the highest losses of natural areas between 2000 and 2018. In the Amazon, the growth of the pasture class with management was 71.4%, and the agricultural area increased by 288.6%, which supports the findings of PC 2. In their recent study, Boulton et al. (2022) revealed a concerning trend: over 75% of the Amazon Forest has experienced a decline in resilience since the early 2000s. This decreasing resilience is intricately linked to both recurrent drought events and the intensifying extent of human-induced land-use activities. Notably, the magnitude of resilience loss intensifies in proximity to regions characterized by heightened human land use. Rorato et al. (2022) investigated the environmental vulnerability of Indigenous Lands (ILs). Their findings underscore that the ILs facing the highest levels of exposure, sensitivity, and vulnerability are concentrated in the Arc of Deforestation, characterized by consolidated settlements, and within the States of Roraima, Pará, and Maranhão. Furthermore, the research reveals a notable escalation in the sensitivity and exposure of most Amazon ILs to environmental hazards post-2010.

In the Cerrado, the main LUCC occurred with the expansion of agriculture and forestry and the reduction of grassland and forest areas

(Beuchle et al., 2015; IBGE, 2020). The study of Salmona et al. (2023) emphasizes the potential water flow discontinuity in the Cerrado biome. This discontinuity poses substantial risks to water supply, agricultural production, and electric supply. The alterations in water flow and surface water are attributed primarily to changes in land use, notably the expansion of agriculture, coupled with the effects of climate change. Moreover, the study anticipates a worsening of this scenario in the years ahead, potentially leading to water insufficiency in the Cerrado, renowned for its role as a water reservoir.

The Atlantic Forest exhibited a slight reduction in vegetation cover, but the main changes were caused by the growth of agricultural and forestry areas (IBGE, 2020). Silveira et al. (2022) analyzed the Atlantic Forest, yielding results congruent with the present study. Their findings suggest that predominant changes in the biome are primarily driven by advancements in agriculture and planted forests, resulting in a decline in pasture and native forest areas. The transformation of consolidated pasture lands into agricultural areas is particularly concentrated in the southwest region of the biome. Silva et al. (2023) observed that municipalities within the Atlantic Forest exhibiting greater crop diversity and lower average annual precipitation tended to experience higher net gains in natural forest cover, indicating a forest regeneration. Additionally, their findings point to a noteworthy inverse relationship: as crop expansion occurs, there is a corresponding decrease in pasture areas. This process is presented in the Figures 10E and 10F.

According to IBGE (2020), most forested natural areas are concentrated in the Amazon. In the Atlantic Forest, fragmented forest remnants are present along the coast. The Pantanal has a high degree of conservation of its natural areas, while the southern part of the Cerrado and the eastern part of the Caatinga show strong anthropization, and the Pampa exhibits considerable anthropization in the plateau areas (IBGE, 2020). These situations can be observed in the Redundancy class and in maps of lower and higher correlation. The Matopiba region also recorded growth in agricultural areas (IBGE, 2020; Matricardi et al., 2019). Souza et al. (2020) found that the area of agriculture grew in all biomes (172.5%), and the areas of pasture increased by more than 46% between 1985 and 2017.

The reduction of grassland and forest vegetation has been observed in the Caatinga, with an increase in mosaic areas, agricultural areas, and managed pasture (Beuchle et al., 2015; IBGE, 2020). Jardim et al. (2022) report that the

expansion of agricultural areas is trimming the Caatinga biome. The removal of native vegetation for anthropogenic purposes poses a threat, potentially resulting in soil and vegetation degradation. This process may further contribute to alterations in climatic conditions and disrupt essential ecosystem services.

In Pampa, there has been a loss of grassland vegetation (Oliveira et al., 2017), with agricultural and forestry growth being the principal agents of this reduction (IBGE, 2020). Peixoto et al. (2022), in their analysis of the thermal characteristics of various land covers within the Pampa biome, noted a significant temperature disparity. Specifically, cultivated areas exhibited a temperature elevation of 6°C compared to tree-covered areas and a 2.8°C increase in comparison to grassland areas. This underscores the impact of land cover changes on the local and regional microclimate.

In the Pantanal, the main changes were caused by the advancement of pastures over grassland areas (IBGE, 2020). Miranda et al. (2018) also identified the growth of "short vegetation" due to the implementation of pasture between 2000 and 2015. The Pantanal faces an additional threat from recurrent fire events, with the 2020 incident being particularly severe. However, this issue has persisted for the past two decades. Over this period, a substantial portion of the Pantanal, at least 20.8% of the biome's grassland-covered area, has experienced fire-related impacts, as revealed by Correa et al. (2022). Notably, grasslands are the most frequently affected class, although even the humid areas in the Pantanal exhibit susceptibility to fires. In conclusion, there were LUCC in all Brazilian biomes, however, they are distinct in its type and rate.

Conclusions

The analysis of spatial changes in the Brazilian biomes between 1985 and 2018 has enabled the characterization of land use and land cover patterns that either contribute to or threaten the preservation of these biomes. This analysis can provide valuable insights for proactive and efficient environmental planning, leading to more effective management of environmental resources.

The LUCC processes are distinct in the biomes, both in the spatial extension and the rate. The different magnitudes and types of conversion point out processes that occurred in specific temporal and spatial scales in each biome. Additionally, PCA has demonstrated its ability for dimensionality reduction and to describe the database for interpretation of its variability. The

spatial-temporal models generate by PCA represented the LUCC processes in the Brazilian biome and enabled us to identify the main changes.

The results indicate that the Brazilian biomes underwent significant changes over a 34-year period, primarily driven by anthropogenic activities such as urban expansion, agricultural growth, and cattle ranching in rural areas, particularly between 1990 and 2010, with varying rates of change across biomes. These activities have numerous environmental impacts that can affect the quality of life of the population, emphasizing the need for mitigating and compensatory measures to address environmental impacts.

Understanding the main spatial and temporal changes in land use and cover in Brazilian biomes is essential to guide priority areas and practices, as highlighted by Santos (2004). In this study, we provide a synthesis of the primary patterns and spatial-temporal changes in land use and cover of Brazilian biomes, which can assist in national environmental planning. The results demonstrate the significant role of anthropogenic activities in reducing natural areas, particularly through deforestation, agriculture, and cattle ranching in the Cerrado and Amazon biomes. This study contributes to the field of land use and cover studies by providing a broad perspective on the biome scale, which can support future research on a larger cartographic scale or investigating practical solutions to mitigate the impacts of land use and cover changes.

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