Revista Brasileira de Geografia Física v.18, n.05 (2025) 3872-3890.

Revista Brasileira de Geografia Física

ISSN:1984-2295

Homepage: https://periodicos.ufpe.br/revistas/rbgfe

Unveiling Spatiotemporal Patterns in the Pampa Biome Using Principal Component Analysis

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Artigo recebido em 12/10/2024 e aceito em 19/02/2025

A B S T R A C T

The Pampa biome has been transforming its traditional landscape since the 1950s. Comprehending the spatiotemporal dynamics of land use and land cover change (LUCC) in the Pampa and its primary drivers is crucial in formulating territorial planning and environmental management. Therefore, the purpose of this paper is to use the potential of Principal Components Analysis (PCA) to analyze LUCC in the Pampa biome between 1985-2020, based on the synthesis of the MapBiomas project database. The methodology is divided into three stages, the first is in GEE where pre-processing and PCA are carried out, and the second is in Planetary Computer where correlation coefficients are calculated. Finally, in QGIS 3.10.4, reclassification and cartographic production were conducted. The LUCC processes identified in the Pampa biome reveal a significant transformation of its landscape, characterized by a reduction in the extent of grassland formations due to the expansion of anthropogenic activities. The conversion of natural grasslands to agricultural land uses, particularly soy, forestry, and farming, has been a prevalent trend. The results of the analysis highlight that the large-scale conversion of grassland areas is a recent phenomenon in the Pampa, occurring mainly between 1995 and 2010, linked to the replacement of cattle ranching by large-scale agriculture.
Keywords: MapBiomas, Google Earth Engine, Landscape, Changes.

Desvendando Padrões Espaço-temporais no Bioma Pampa Usando Análise de Componentes Principais

R E S U M O

O bioma Pampa vem transformando sua paisagem tradicional desde a década de 1950. Compreender a dinâmica espaço-temporal das mudanças no uso e cobertura da terra (MUCT) no Pampa e seus principais fatores é crucial para a formulação do planejamento territorial e da gestão ambiental. Portanto, o objetivo deste artigo é usar o potencial da Análise de Componentes Principais (ACP) para analisar as MUCT no bioma Pampa entre 1985-2020, com base na síntese do banco de dados do projeto MapBiomas. A metodologia está dividida em três etapas, sendo a primeira no GEE, onde foram realizados o pré-processamento e a ACP, e a segunda no Planetary Computer, onde foram calculados os coeficientes de correlação. Por fim, no QGIS 3.10.4, foram realizadas a reclassificação e a produção cartográfica. Os processos MUCT identificados no Bioma Pampa revelam uma transformação significativa de sua paisagem, caracterizada por uma redução na extensão das formações campestres devido à expansão das atividades antropogênicas. A conversão de campos naturais para usos agrícolas, especialmente soja, silvicultura e agricultura, tem sido uma tendência predominante. Os resultados da análise destacam que a conversão em larga escala de áreas formação campestre é um fenômeno recente no Pampa, ocorrendo principalmente entre 1995 e 2010, associado à substituição da pecuária pela agricultura em larga escala.
Palavras–chave: MapBiomas, Google Earth Engine, Paisagem, Mudanças.

Introduction

Land use and land cover change (LUCC) is a complex phenomenon resulting from several interacting processes acting at varying spatiotemporal scales and intensities (Verburg et al., 2002; He et al., 2023). As noted by Briassoulis (2020), LUCC leads to various environmental problems, including climate change, acidification, global warming, and desertification, among others. Furthermore, landscape changes have significant impacts on biodiversity, due to changes in habitats caused by ecosystem modification and fragmentation (Verburg et al., 2015; Aslam et al., 2024).

Reis et al. (2020) explain that the trajectories of LUCC are derived from the analysis of time series of remote sensing images. The concatenation of classifications from different dates forms a LUCC trajectory, which represents a sequence of land use and land cover in a temporally ordered geographic location (Reis et al., 2020; Zioti et al., 2022). Given the rapid and intense LUCC, it becomes crucial to develop a continuous cartographic mapping that represents these transformations (Mas et al., 2017).

The Pampa biome has been transforming its traditional landscape since the 1950s, mainly due to the expansion of agriculture and the implementation of forestry activities. These processes have significantly altered the biome's landscape and have generated a series of environmental and socio-cultural impacts. The shift in the production base is reflected in LUCC, as natural formations are replaced by large-scale monocultures geared toward agribusiness exports. Moreover, this process is closely associated with the biome's low level of environmental protection, with minimal agenda and actions towards conservation, resulting in high rates of conversion and land degradation (Botelho and Cleveládio Júnior, 2016; Chomenko, 2016; Verdum, 2016; Lima et al. 2020).

Andrade et al. (2023) points out that the Pampa occupies just 2% of Brazilian territory but holds 9% of its biodiversity, with at least 12,503 species of plants, animals, fungi and bacteria. The lack of environmental conservation efforts is a clear indication of negligence, and it demands greater attention and effort from the Brazilian government. The Pampa biome plays a vital role in supporting essential ecological services and harbors high biodiversity (Ellwanger et al., 2022). Therefore, comprehending the spatiotemporal dynamics of LUCC in the Pampa and its primary drivers is crucial in formulating territorial planning and environmental management strategies for preserving biodiversity and promoting landscape rational use (Deng et al., 2008).

Projects like the Annual Mapping of Land Cover and Land Use in Brazil (MapBiomas) provide annual land use and land cover maps of Brazilian biomes (+30 years of data), supplying essential information for planning and conservation efforts (Souza et al., 2020; MapBiomas, 2022; Marques, et al., 2025; Pessoa et al., 2025; Tomazoni et al., 2025). However, the challenge remains in extracting spatiotemporal patterns of LUCC from the MapBiomas extensive database. Techniques such as sorting and dimensionality reduction are required to synthesize and describe Big Data effectively.

The Principal Component Analysis (PCA) is a powerful and universally used tool for reducing the dimensionality of a dataset with high levels of correlated information, which is typical of Big Data. However, the technique still retains a significant percentage of the original variance present in the data while eliminate the redundant data (Jolliffe, 2002; Deng et al., 2008; Hasan and Abdulazeez, 2021; Ribeiro et al., 2024). As a multivariate method, PCA employs a set of initial variables to generate the principal components (PC) through linear combination and orthogonal mathematics. It shifts the original attributes to a new space, in which the properties with the greatest variations are used in constructing the new space. The resulting PCs are uncorrelated with each other and capture as much of the original variance as possible. Principal components are ordered in decreasing order according to the amount of variance that each one explains (Jolliffe, 2002; Jolliffe and Cadima, 2016; Zanotta et al., 2019; Dharani and Sreenivasulu, 2021; Greenacre et al., 2022; Jesudhas et al., 2024).

The potential of using PCA for detecting changes from remote sensing images has been highlighted by various studies (Deng et al., 2008; Antunes, 2012; Gupta et al., 2013; Afaq and Manocha, 2021; Thein and Htwe, 2023; Li et al., 2024). This is mainly due to the technique's ability to highlight patterns and differences between images, thus allowing LUCC detection. The first principal component usually contains the common information in all bands or images, while the other components capture the variations and changes in the dataset (Antunes, 2012; Estornell et al., 2013). Martinez-Izquierdo et al. (2019) used PCA to detect spatial changes in satellite imagery by focusing on the second principal component, which contains the changes between the analyzed dates. The study found that PCA was effective in synthesizing the data and detecting changes. Overall, the use of PCA in detecting changes in remote sensing imagery provides a powerful tool for monitoring and managing LUCC.

It is important to note that the PCA technique is designed for quantitative data and is not directly applicable to qualitative data, such as the MapBiomas database (Mori et al., 2016). Jolliffe (2002) highlights that certain types of data, including ordinal and binary data, may require modifications before PCA can be applied. Nevertheless, the author emphasizes that when PCA is used as a descriptive technique, the variables being analyzed do not need to be of any particular type. The main objective of PCA is to reduce the dimensionality of the data while retaining as much of the original variance as possible, irrespective of the type of variables under consideration (Fernando, 2014).

As one of the fundamental methods in data science, as stated by Greenacre et al. (2022), the power of PCA can be utilized to describe and extract spatial-temporal patterns of LUCC from the MapBiomas database. The comprehension of the direction and spatial patterns of LUCC can supply a sense of the potential drivers and impacts. Based on this information, decision-makers and planners can assemble better choices aimed at conservation and sustainable land use.

Therefore, the purpose of this paper is to use the potential of PCA to analyze land use and land cover changes in the Pampa biome between 1985 and 2020, based on the synthesis of the MapBiomas project database. The classic technique was selected for its capacity to reduce extensive datasets and emphasize significant information. By using PCA to synthesize the large MapBiomas database and identify the major trajectories of LUCC in the Pampa biome, this study can contribute to the development of more informed and effective land use policies and strategies. In addition, this article presents a way of using PCA to extract information from Big Data. It introduces an approach that aims to apply the PCA to qualitative data, seeking to achieve its maximum potential for extracting information and reducing large databases.

Methodology

Study Area

The Pampa biome, which covers 2.1% (176,496 km²) of the Brazilian national territory, is located exclusively in the State of Rio Grande do Sul, occupying 63% of its area. This biome extends across the southern half of the state and reaches the Plateau areas to the north (Bencke et al., 2016; Botelho and Cleveláro Júnior, 2016). Figure 1 displays the location of the Pampa biome. Pampa is covered mainly by grasslands with high biological importance (Lima et al. 2020). The Pampa biome presents itself as a heterogeneous landscape mosaic resulting from the combination of distinct physical and ecological characteristics that have structured it, with the addition of humans as agents in the anthropogenization process.

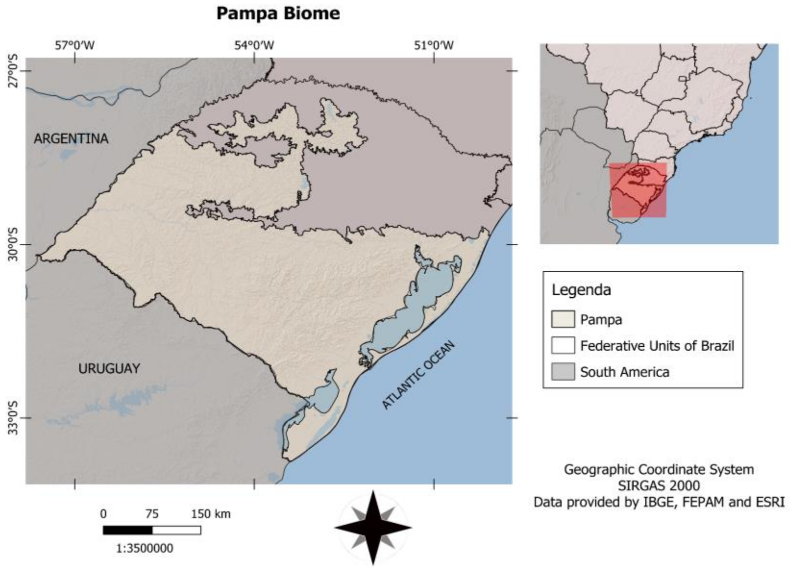

Figure 1. Location of Pampa Biome

Materials and methods

We processed and analyzed the data by using GIS and cloud processing platforms, namely QGIS 3.10.4, Google Earth Engine, and Planetary Computer. Also, we utilized land use and cover maps from MapBiomas collection 6 from 1985 to 2020 at 30-meter resolution (MapBiomas Project, 2022) and the biomes Vector Base at a scale of 1:250,000 (IBGE, 2019).

MapBiomas Collection 6 provides annual land use and land cover maps between 1985 and 2020. The pixel values of this product range from 3 to 33 and represent categorical data, with each value being associated with a specific land use and land cover class. The project uses images from the Landsat satellite series (5, 7, and 8) classified by Random Forest and U-Net. The classification at level three of legend detail shows 87.4% overall accuracy, with 9.2% corresponding to disagreements in allocation and 3.4% to disagreements in terms of area (MapBiomas Project, 2022). Table 1 presents the 15 land use and cover classes that apply to the Pampa biome.

The methodology is divided into three stages, the first is in GEE where pre-processing and PCA are carried out, and the second is in Planetary Computer where correlation coefficients are calculated. Finally, in QGIS 3.10.4, reclassification and cartographic production were conducted. Figure 2 shows a flowchart of the steps taken.

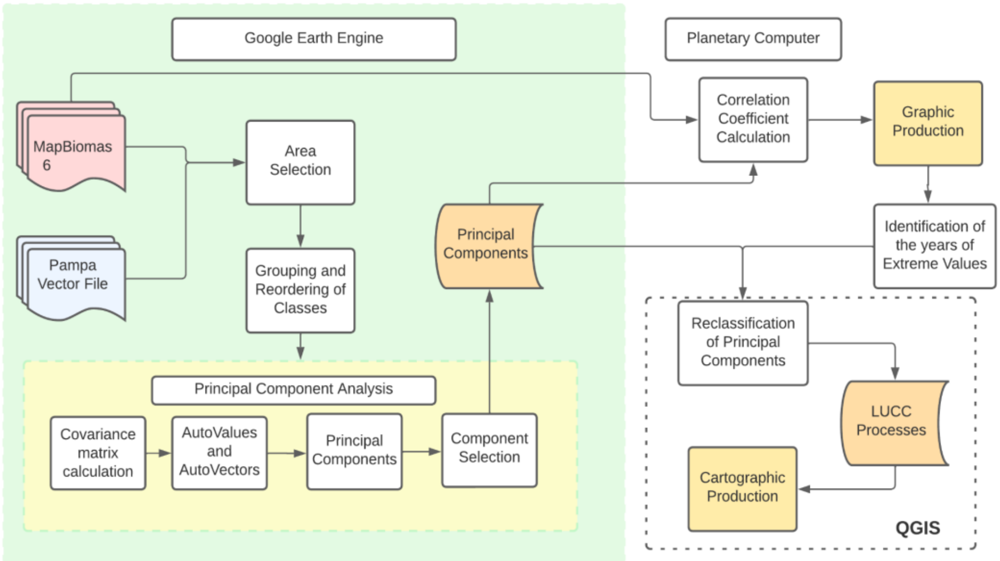

Figure 2. Flowchart of the methodology.

In the GEE platform, the PCA technique was employed to synthesize the MapBiomas data and describe the spatial-temporal changes in land use and cover. The first step involved clipping the maps using the vector file of the Pampa biome made available by IBGE. Subsequently, the land use and land cover classes were grouped into 10 classes, and their values were rearranged using the ee.remap function in GEE to facilitate analysis and interpretation of results. The MapBiomas mapping hierarchy (Mapbiomas, 2022) was considered to group the classes. Due to the original order (3-33) does not follow a logic from natural to anthropic, which can complicate the interpretation of the PCA results, we performed an ordering of the values.

The reordered classes were arranged in a logical order from the most natural to the most anthropic, as shown in Table 1. In its elaboration, the ordering considered the degree of landscape transformation, separating the land cover classes from the land use classes. Notably, there is a significant gap in values associated with the land use classes, aimed at generating large values at the transition between the classes. This measure facilitates the distinction between LUCC processes.

By quantifying and ordering the classes, the data acquired an ordinal character. According to Lu (2021), the methods of quantification of qualitative variables allow the association of numerical values to the categories. This makes it possible to apply techniques designed for quantitative data, such as PCA. However, it is important to consider these characteristics when interpreting the results.

Agresti (2010) explains that an ordinal variable is quantitative because each level on the scale is associated with a greater or lesser magnitude of a specific characteristic relative to another level. To analyze ordinal data with methods of a quantitative nature, ordered scores can be assigned arbitrarily to the categories. The main aspect of this quantification process is the choice of relative distances between pairs of adjacent categories (Agresti, 2010). Additionally, Agresti (2018) notes that the choice of ordered scores has little effect on the results, as long as the relative spacing between scores is the same. Therefore, the process of quantifying, ordering, and defining distances between classes makes it possible to apply PCA to these data.

The subsequent step involved applying the PCA technique in GEE on the preprocessed land use and land cover maps. This was achieved by modifying the algorithm provided by GEE (2024). To generate the principal components, the covariance matrix was computed, and the eigenvalues and eigenvectors were extracted from it, utilizing the ee.eigen function. By analyzing the eigenvalues, the variance percentage explained by each component was evaluated. Based on this analysis, the first three principal components were chosen, which in total explained 76.02% of the original data total variance.

Next, Pearson's correlation coefficient was computed between the three selected PC and the MapBiomas data used as input in the PCA. Pearson's correlation coefficient is a measure of the degree of dependence, whether positive or negative, between two variables (Zanotta et al., 2019). This process generates load factors that reflect the temporal representation of the PC (Maier, 2014), enabling the identification of the temporal occurrence of the elements presented by each principal component. High values (positive or negative) indicate a similarity or divergence between the PC and the input data. This information is critical in identifying changes, as it allows for visualizing the before and after changes that a specific component represents by selecting land use and land cover maps of the years that present extreme values.

Table 1. Grouped classes from MapBiomas collection 6.

Grouped classe	Original Classes	Value
Forest Formation (3)	Forest Formation (3)	1
Non vegetated Area	Beach, Dune and Sand Spot (23); Other non Vegetaded Areas (25)	5
Non Forest Natural Formation	Rocky Outcrop (29); Wetlands (11);	10
Water	. River,Lake and Ocean (33)	15
Grassland (12)	Grassland (12)	20
Forest Plantation (9)	Forest Plantation (9)	70
Farming	Pasture (15); Other temporary Crops (41); Mosaic Agriculture and Pasture (21)	340
Rice (40)	Rice (40)	380
Soybean (39)	Soybean (39)	430

Urban Area e Mining	Urban Area (24); Mining (30)	500

This step was carried out on the Planetary Computer platform using the R programming environment. The three selected PCs and the input data for the PCA were loaded into the environment, and the resulting output was saved in tabular format. A total of 35 coefficients were generated for each principal component. Finally, graphs were produced for each PC to illustrate the evolution of the Pearson correlation coefficient between the years 1985 and 2020. Through the analysis of these graphs, the years with extreme values (positive and negative) for each PC were identified, which can aid in their interpretation.

The following stage involved the interpretation of the principal components using the QGIS 3.10.4 software. To reclassify them into LUCC processes, as proposed by Freitas et al. (2013), to facilitate analysis. This was achieved by visually interpreting and sampling the PC, which allowed the generation of value ranges for each identified class. The input maps from MapBiomas, which exhibited extreme values in the load factor, were used as an auxiliary information to ensure the accurate interpretation of the PC.

The interpretation of the first principal component aimed to identify the stable land use and land cover patterns between 1985 and 2020 since this component typically represents what is common in the database among all maps. On the other hand, the reclassification of the other principal components was intended to identify the LUCC during the observed temporal period. To accomplish this, the load factor information played a crucial role in indicating the land use and land cover maps that are closest to and farthest from the information represented by a certain component. Lastly, the three principal components reclassified into LUCC processes were integrated to produce a synthesis of the main trajectories of LUCC. In the end, each process had its area measured in hectares (ha), and the cartographic products were prepared in QGIS 3.10.4 software.

Results and discussion

The PCA resulted in the selection of the first three principal components. Which accounted for 76.02% of the original variance presented in the MapBiomas database. This reduction in the number of variables from 35 images to three principal components enabled a more efficient description of LUCC. It removed redundancy and facilitated the extraction of LUCC spatial-temporal patterns.

1st Principal Component

The first principal component explained 58.25% of the original data variance and is associated with the land use and cover pattern in the Pampa biome (Antunes, 2012; Estornell et al., 2013). Typically, the first PC is characterized by presenting the most common elements within the original dataset, here being associated with the most stable land uses and covers throughout the time series (1985 - 2020). Figure 3 shows the correlation coefficient graph between the first PC and the input maps used for the PCA.

All the correlation coefficients presented negative values, forming a nearly straight line and ranging between -0.798 and -0.897. The year 2009 had the lowest value (-0.897), while the year 1985 had the highest value (-0.798). These years were used as reference points for interpreting the 1st PC. The load factor values suggest a continuum throughout the time series, linking this component to a pattern of stable or permanent land use and cover classes for much of the observed period.

Seven land use and cover patterns were identified in the Pampa biome, and their spatial distribution is presented in Figure 4. The Areas with LUCC pattern (6,693,300 ha), in gray, indicate areas where a clear pattern was not identified. Rather, a change in land use and cover was observed, proposing the absence of stability in the classes. The Consolidated Urban Areas (90,867 ha) pattern is represented by the red color, highlighting established urban areas in 1985. Such as in the municipalities of Porto Alegre/RS (Figure 4B), Pelotas/RS, Rio Grande/RS, and Bagé/RS. In addition, there are also significant urban infrastructures along the coastal zone.

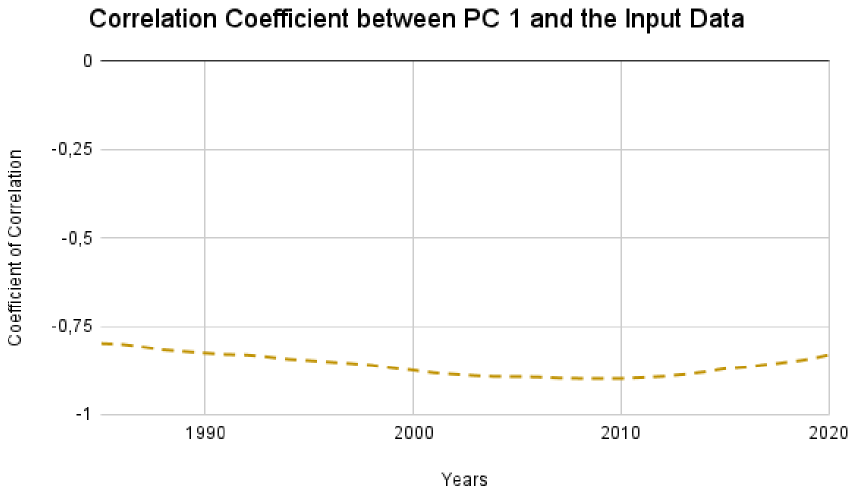

Figure 3. Correlation Coefficient Graph for PC 1.

The Consolidated Farming (4,198,500 ha) pattern is characterized by traditional farming areas with long-standing practices of soybean and rice cultivation. In Figure 4, this pattern is depicted in shades of yellow. The largest concentration of this pattern is in the northern region of the biome, where soybean cultivation predominates; as well on the western border, in the coastal plain, and around water courses (Figure 4C). In the latter areas, farming and rice classes are predominant. These areas are suitable for crop development due to the soils generated from basaltic rocks to the north (Botelho and Clevelário Júnior, 2016), as well as their proximity to water bodies and dams that facilitate irrigation. The Consolidated Farming pattern corresponds to the first areas of implementation and expansion of these practices from the 1950s (Chomenko, 2016; Verdum, 2016).

In shades of brown, we can observe the Consolidated Forest Plantation (122,607 ha) pattern, which is distributed over the eastern portion of the biome, mainly in areas of the Coastal Plain, and Southern Rio-Grandense Plateau. This pattern indicates the first areas of cultivation occupation in Rio Grande do Sul, which expanded from the 1970s (Chomenko, 2016; Hasenack et al., 2019).

The Grassland (4,016,250 ha) pattern, represented in a moss-green tone, indicates areas of natural vegetation that have remained stable for an extended period and are considered preserved areas. However, Pampa's natural grasslands are also used for extensive livestock (Hasenack et al., 2019). The grasslands occupy the central areas of the biome (Figure 4A), separated by the Ibicuí River, and are surrounded by the Consolidated Farming pattern, as illustrated in Figure 4. The Forest Formations (1,557,110 ha) pattern is presented in green and is concentrated around rivers and riparian forests and in areas with greater topographic slopes, such as in the Southern Rio-Grandense Plateau.

The Water Bodies (1,819,810 ha) pattern, represented in blue, highlights the presence of natural and artificial water bodies within the Pampa biome, including the Patos Lagoon, which occupies 5% of the biome's total area. The Coastal Plain features a series of coastal lagoons, while the Mirim Lagoon and Mangueira Lagoon are located to the south. The Jacuí River crosses the biome from west to east, while the Ibicuí River crosses it from north to south (Robaina et al., 2021). Additionally, several small dams can be found in the biome, which are used for water storage and irrigation purposes. Notably, the Ronda Alta Dam and Passo Real Dam are located in the northern part of the biome, as can be observed in Figure 4.

The final pattern, represented by light green shades, is the Non-forested Natural Formation and Non-vegetated Areas (638,099 ha). This pattern is concentrated in the Coastal Plain, and includes dune fields along the coast and wetlands, such as the Taim Marsh that encompasses the Taim Ecological Reserve (Lima et al., 2016). Additionally, this pattern is also present in the northwest of the biome, representing areas of areal.

Overall, the first principal component describes the main land use and cover patterns in the Pampa biome during 1985 and 2020. It highlights classes with a high degree of spatial-temporal stability, while also identifying areas of potential LUCC.

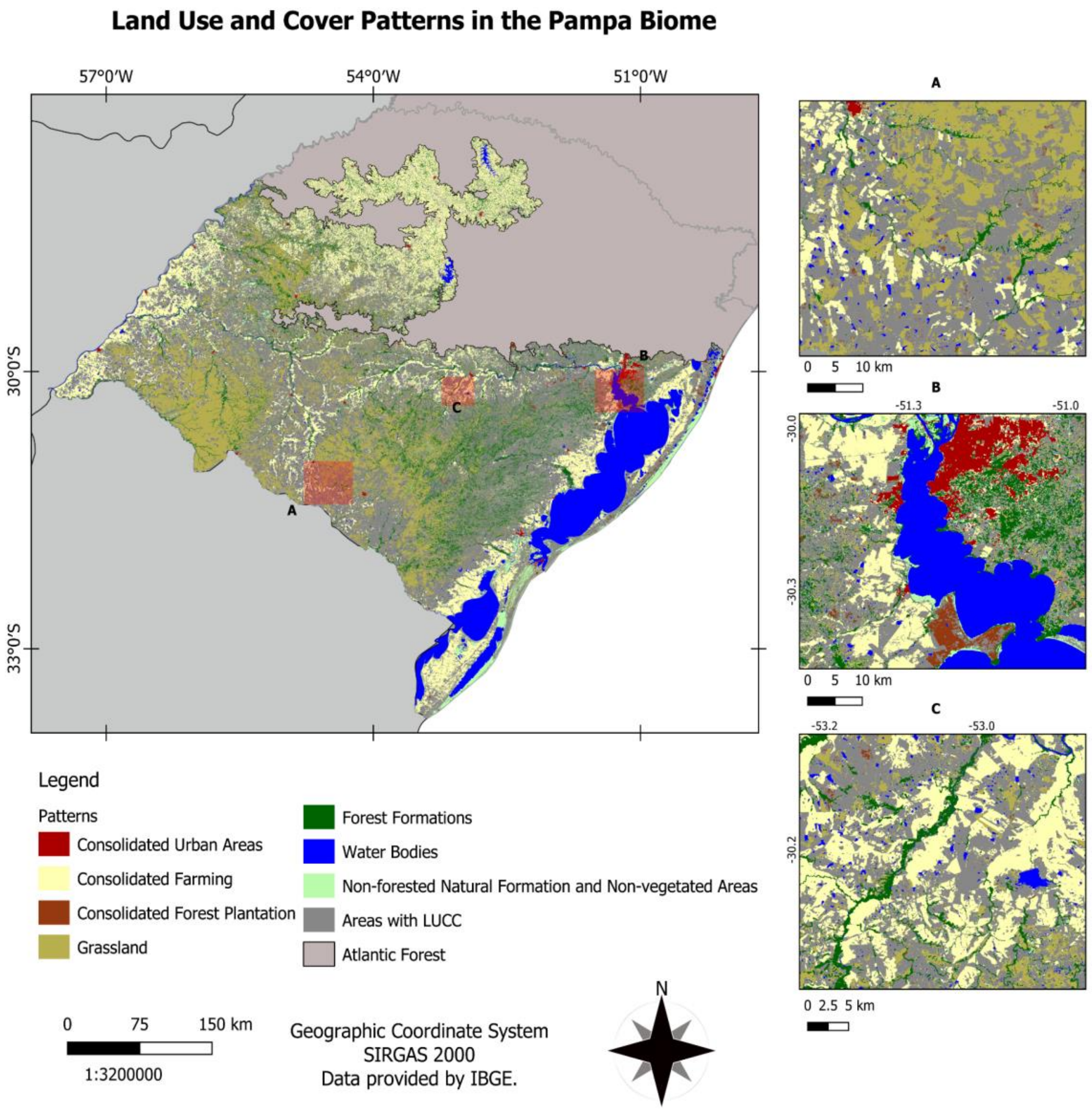

Figure 4. Patterns of Land Use and Cover between 1985 and 2020.

2nd Principal Component

The principal components selected after the first principal component are associated with the variations observed within the original dataset, which in this case refer to LUCC (Antunes, 2012; Estornell et al., 2013). As this study analyzes 35 different dates, the spatiotemporal patterns represented by the second and third components can be interpreted as trajectories of land use and cover. The second principal component explains 11.64% of the variance observed in the input data. Figure 5 presents a graph illustrating the correlation coefficient between the second PC and the maps used as input for the PCA.

Upon examining Figure 5, we can observe that the curve exhibits an "S" shape, with negative values at the beginning of the time series and positive values towards the end. The lowest correlation coefficient between the 2º PC and the input maps was observed in 1990, with a value of -0.445, while the highest correlation coefficient occurred in 2017, reaching a value of +0.302. As a negative correlation indicates an inverse relationship, it can be assumed that the 1990 map diverges from the changes represented by this PC, pointing to a scenario before these changes. Conversely, the map from 2017 displayed a positive correlation, resembling the observed changes and representing a moment after the changes occurred. These specific years played a crucial role in interpreting this PC. Additionally, it is worth noting that the curve became steeper between 1995 and 2010, which possibly indicates a period of more rapid and intense changes, reflecting a transition between two distinct moments.

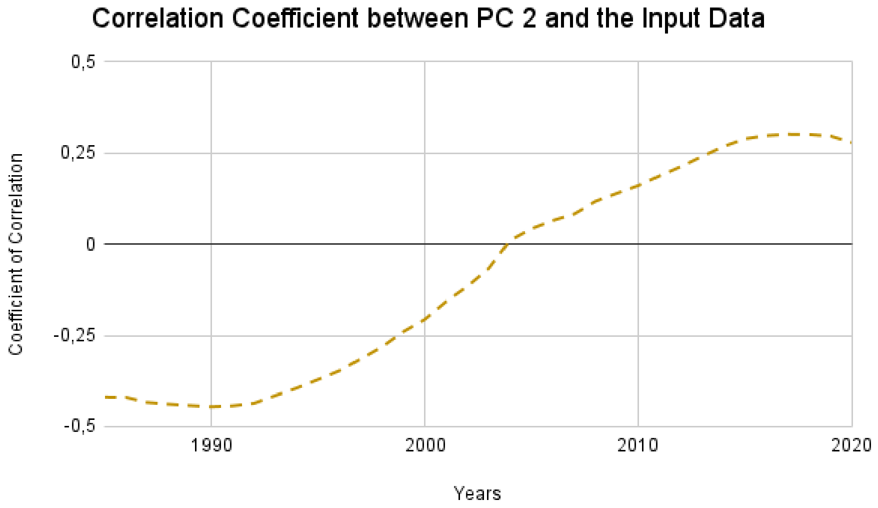

Figure 5. Correlation Coefficient Graph for PC 2.

A total of six processes were identified and are depicted in Figure 6. The process labeled "Expansion" indicates a degradation process in which there is a transition from land cover to land use. It is important to note that the identified processes represent the predominant trajectory of LUCC.

The process of Soybean Expansion (1,456,500 ha) is represented in pink in Figure 6 and is characterized by the degradation caused by the spread of cultivation into natural areas, particularly grassland formations. Soybean cultivation dominates this process, but the expansion of Farming and Rice is also evident, albeit to a lesser extent. Soybean expansion is concentrated in the northern part of the Pampa biome (Figure 6B) and represents the agricultural frontier's forward movement over the Pampa grasslands, spreading from the north to the south (Chomenko, 2016; Verdum, 2016). Additionally, the expansion of soybean cultivation towards the central natural formations of the biome can be observed, resulting in the suppression of remnant grassland areas.

The process of Farming Expansion (838,548 ha) describes the degradation of natural areas, predominantly grassland formations, by the advance of the Farming class. This process is presented in Figure 6 in yellow, and its spatial distribution is observed in practically all the biome, but with a greater concentration in Campanha Gaúcha and Periferic Depression (Figure 6A). The Forest Plantation Expansion (1,136,390 ha) is represented in shades of brown in Figure 6. This type of degradation has occurred mainly in areas of grassland formations, particularly on the Southern Rio-Grandense Plateau, in the area known as the Southeastern Sierra, and there is also an expansion of Silviculture in the coastal belt.

The Farming Intensification (1,527,820 ha) process represents an intensification process characterized by the exchange of Farming classes for Soybean, and intercalation involving the interchange between Farming and Rice classes. This process is displayed in red in Figure 6. It is worth noting that the intensification process is predominant in the northern part of the biome, particularly in the Missions Plateau. This area had the Farming class implemented in the initial years of the time series and was subsequently replaced by the Soybean class. This transition is considered intensification because soybean cultivation is associated with technological advancements, including the use of machinery and pesticides. Conversely, intercalation occurs more frequently in the western and eastern portions of the biome (Coastal Plain), as well as in the floodplain areas of the Periferic Depression (Figure 6C). These regions experienced several exchanges between Farming and Rice classes during the observed period.

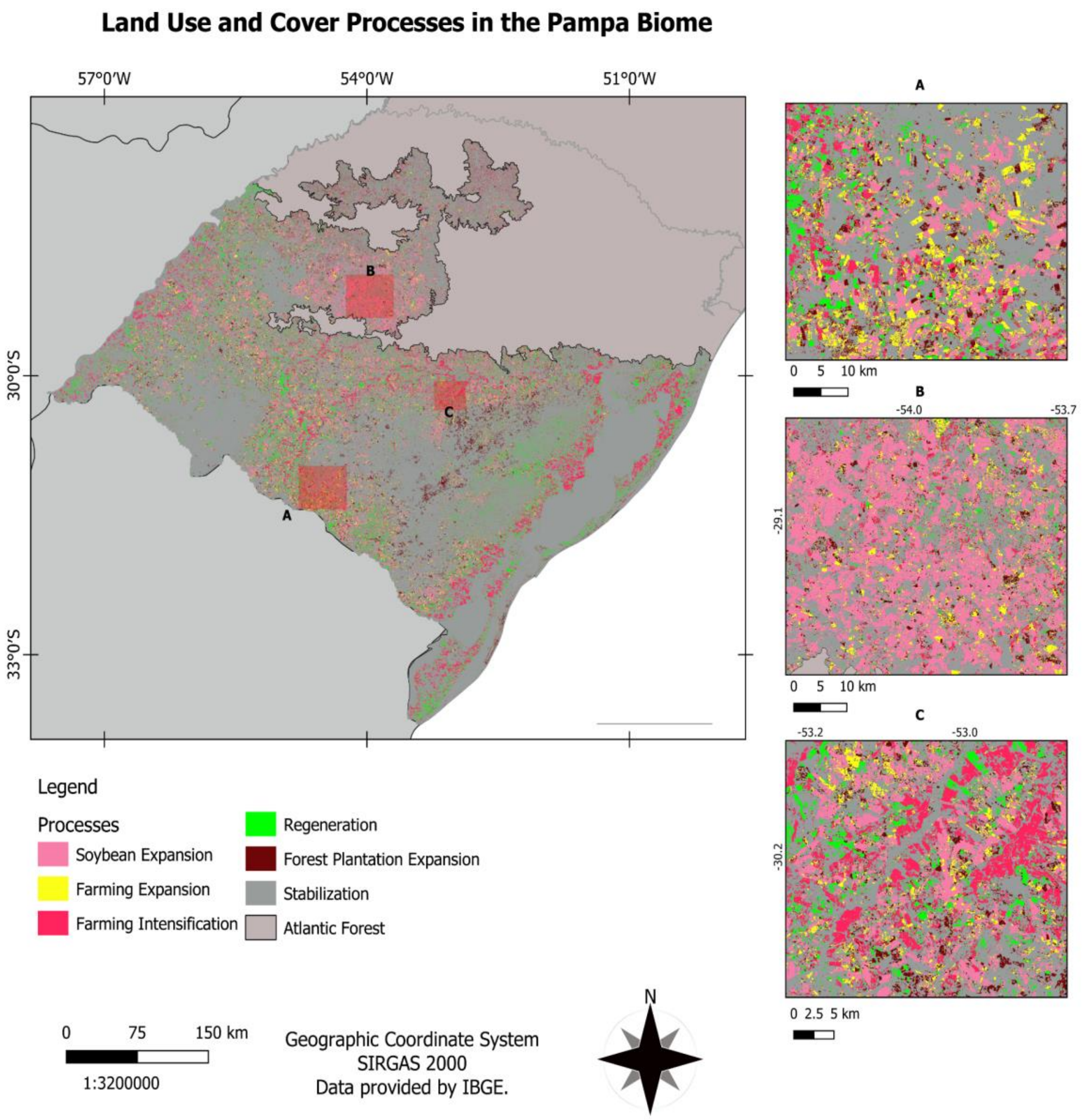

Figure 6. Processes of LUCC.

The Regeneration process (1,033,360 ha), shown in green in Figure 6, was identified as the transition between land use to land cover classes, indicating a recovery of the area with the regeneration of the natural cover. The predominant transition is between Farming classes (Farming, Rice, and Soybean) and natural formation classes (Grassland and Forest Formation). However, small inconsistencies were identified in this process, such as the identification of Regeneration when transitioning from agricultural to forestry classes. When observing the spatial distribution of the Regeneration process, one can notice a concentration on the eastern part of the biome, on the Southern Rio-Grandense Plateau, with a predominance of forested area recovery. Additionally, occurrences were found in the Coastal Plain with the abandonment of farming areas and the regeneration of grassland formations.

The Stabilization (12,982,800 ha) process is represented by the gray color in Figure 6 and indicates areas with no changes in land use and cover, which may indicate preserved areas. Moreover, they may simply not have been represented by this principal component. In terms of spatial distribution, it covers water bodies and grassland formations in the center of the biome, separated by the Ibicuí River. Additionally, there is the stabilization of anthropized areas, such as urban and agricultural areas. In conclusion, the second principal component was able to effectively describe the main LUCC processes in the Pampa region between 1985 and 2020. It explains the primary variations within the original database.

3rd Principal Component

The third Principal Component was responsible for explaining 6.13% of the variance of the input data. Figure 7 presents the graph with the correlation coefficient between the 3rd PC and the maps used as input to the PCA. Upon observing the graph in Figure 7, a "U" shape can be seen with three peaks of values. These three peaks correspond to the load factor values of +0.201 in 1987, -0.289 in 2003, and +0.257 in 2019. The input maps from these three dates were used in the process of interpreting the third PC. This curve format (shown in Figure 7) allows us to divide the analysis of the LUCC processes into two distinct periods: 1987-2003 and 2003-2019.

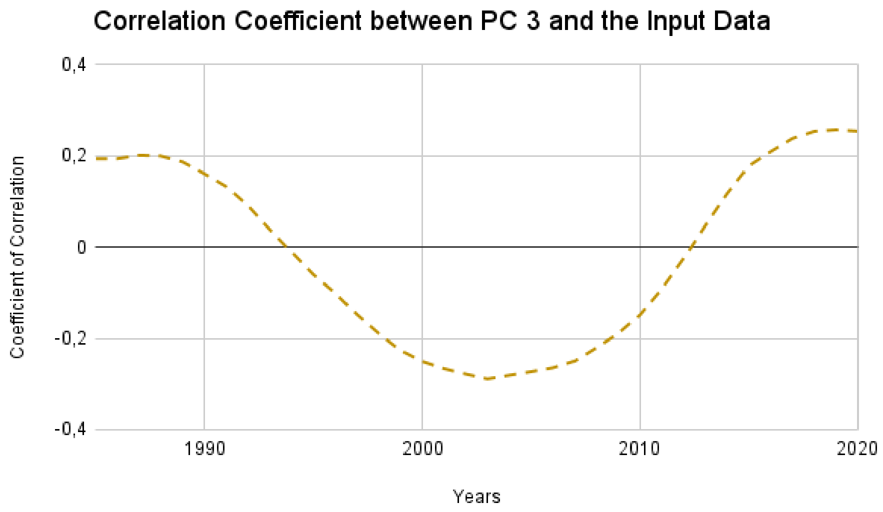

Figure 7. Correlation Coefficient Graph for PC 3.

A total of eight LUCC processes were identified (as shown in Figure 8). As the 2nd PC, these processes are not entirely homogeneous but rather represent the predominant spatial-temporal pattern. It should be noted that the identified processes exhibit temporality, which is indicated by the period determined from the extreme values of the load factors.

The Regeneration (124,373 ha) process is represented by the dark blue color in Figure 8, covering the longest period between 1987 and 2019. This process indicates the regeneration of natural formations such as forest and grassland in areas previously occupied by farming. As the 2nd PC, however, there is also confusion with the transition between farming and forestry classes. This process occurs spatially isolated, which makes it difficult to visualize at the biome scale.

The Farming Expansion process between 1987 and 2003 (1,880,900 ha) is depicted by the color pink in Figure 8. This process indicates the conversion of natural areas, primarily grassland formations, into farming areas such as Soybean, Rice, and Farming classes. It is mainly distributed in the north of the biome, on the Missions Plateau (Figure 8B), expressing the advancement of the agricultural frontier towards rural areas. This action began in the 1950s with the growth of grain production (Chomenko, 2016; Verdum, 2016). It is also noteworthy that this process occurs near the western border of the Pampa, as well as around areas with already consolidated farming.

The light blue color in Figure 8 represents the Farming Expansion between 2003 and 2019 (1,757,600 ha). This process indicates the same conversion as the previous process, with a change in the period. It has a significant occurrence in the biome, distributed throughout the central area. Notably, the advance of farming in the southern part of the Missions Plateau towards the Araucaria Plateau and around areas of consolidated farming (1st CP). This expansion moves towards the remaining grassland formations of the Pampa (Figure 8A), resulting in their suppression.

The process of Farming Expansion in 2019 (206,998 ha), shown in dark green in Figure 8, represents the conversion from grassland formations to farming use that emerged in 2019, indicating recent changes within the analyzed database. However, this process occurs in smaller proportions, making it difficult to visualize on the map in Figure 8. Nonetheless, it is noteworthy that it occurs near existing farming areas. By analyzing these three processes, it is possible to examine the spatial and temporal evolution of farming use in the Pampa biome.

The process of Farming Intensification and Forest Plantation Expansion, which occurred between 1987 and 2003 (848,339 ha), is displayed in shades of yellow in Figure 8. Unfortunately, it was not possible to separate these two processes, as they are grouped in the same temporal period. The intensification of farming is predominantly observed in the northern part of Pampa, particularly in areas of consolidated agriculture. This process involves the conversion of land use from traditional farming practices to soybean production, which has expanded significantly throughout the biome (Mengue et al., 2020). Conversely, the expansion of forestry is predominantly observed in the eastern part of the Pampa, primarily over the Southeastern Sierra and the coastal strip.

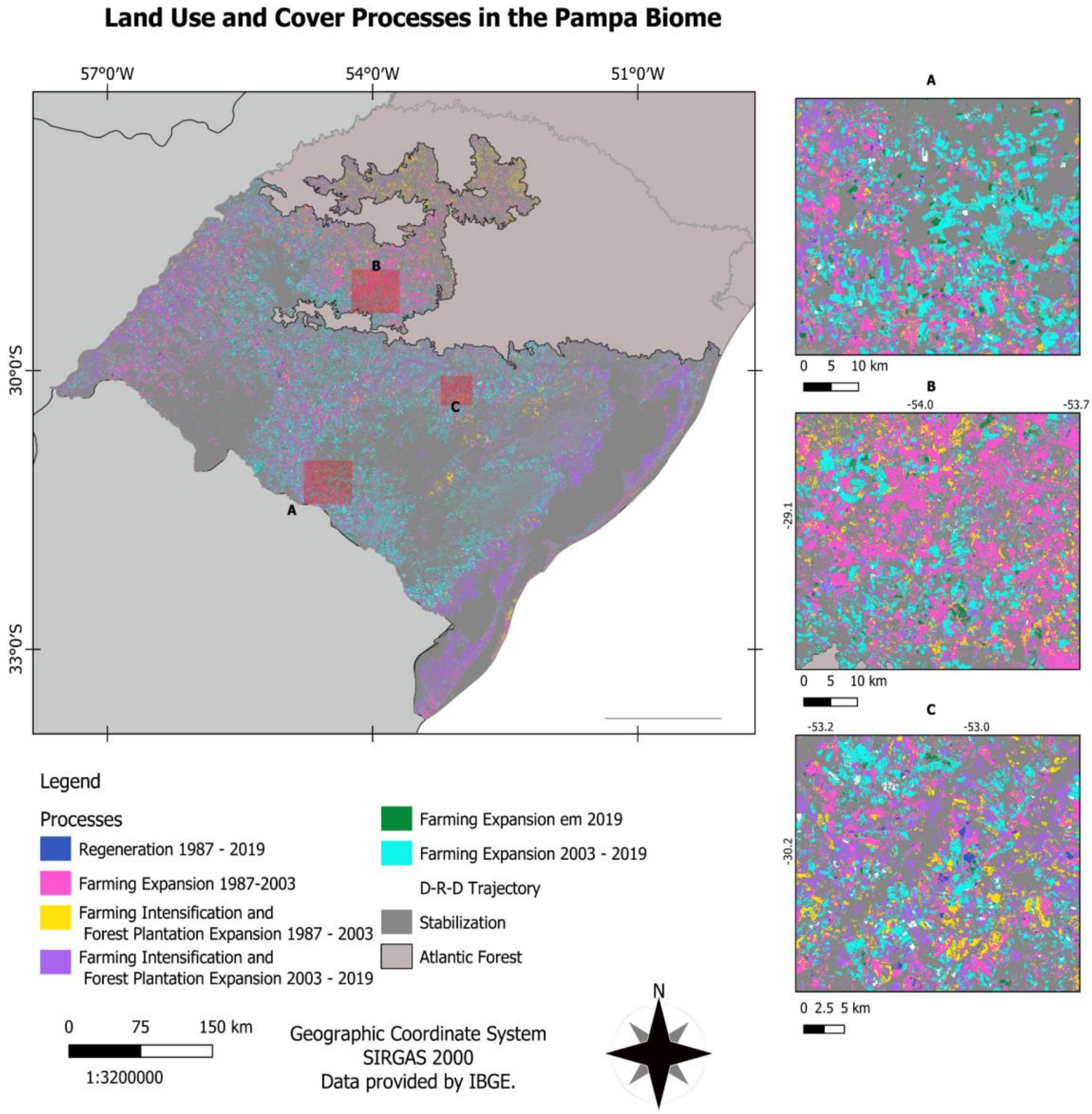

Figure 8. Processes of LUCC.

In Figure 8, the process of Farming Intensification and Forest Planted Expansion between 2003 and 2019 (2,218,840 ha) is presented in purple. This process is similar to the previous one but covers a different period (2003-2019). It is worth noting that this process has a wider spatial distribution, with a predominance in the western border and the Coastal Plain. In these areas, there is an interweaving between the classes of Farming and Rice, where the replacement of farming with rice farming is regarded as a process of intensification of farming practice. This is also observed in the surroundings of Consolidated Farming areas (1st PC) around the Jacuí and

Ibicuí rivers (Figure 8C). The Forest Planted Expansion process between 2003 and 2019 has a greater spatial expression in the Southeastern Sierra areas, particularly in the Southern Rio-Grandense Plateau, near the regions of Forest Planted Expansion between 1987 and 2003. This suggests that the growth of this agricultural practice occurs preferentially in neighboring established areas.

Figure 8 depicts the D-R-D Trajectory (105,491 ha), which portrays the three peak load factor dates: 1987, 2003, and 2019. This trajectory indicates that the pixel was degraded by a land use class in 1987, regenerated to a land cover class in 2003, and degraded again in 2019 with the transition to a land use class. The transitions between farming and grassland are predominant, occurring in a relatively isolated manner in the Pampa, with low spatial expression, making it challenging to visualize on the map. This highlights the potential of PCA to describe these spatial-temporal patterns of a complex nature, thus facilitating the comprehension of the dynamics of LUCC at the scale of the Pampa biome. And finally, we have in gray tone the Stabilization (11,668,800 ha) process in Figure 7. This indicates, similarly to the 2nd PC, the areas with no occurrence of LUCC, and may point to preserved areas.

The third principal component offers crucial temporal information on LUCC processes, enabling a detailed understanding of the landscape dynamics. The division of these processes into time periods provides a trajectory of movement and allows for the identification of the direction of LUCC.

PCs synthesis

To generate a deeper understanding of the LUCC processes taking place in the Pampa biome, we processed a synthesis of the observed processes in the three PCs. These processes were grouped into 14 categories and are presented in Figure 8.

Processes related to the expansion of soybean cultivation are on the map in shades of pink. One of these processes is the Soybean Expansion between 1987 and 2003, represented by dark pink shading, which occurred mainly under the Missions Plateau and marked the first stage of soybean cultivation expansion towards the Pampa fields. Another evident process is the Soybean Expansion between 2003 and 2019, represented by light pink shading, which highlights a second stage where soybean cultivation expanded further, moving beyond the plateau and invading the grasslands in the central area of the Pampa.

In shades of yellow are represented the processes referring to the expansion of farming in two temporal periods. These occur more significantly in Campanha Gaúcha and Periferic Depression. The processes that encompass Farming Intensification are presented in shades of red. The Farming Intensification between 1987 and 2003, in light red, has greater spatial expression in the Missions Plateau, and indicates the exchange of areas devoted to agriculture for soybean cultivation. In dark red is the Farming Intensification between 2003 and 2019, which is distributed around the Jacuí and Ibicuí rivers, and to the north and west of the Pampa. Finally, the Farming Intensification, in an orange tone, occurs in the coastal strip and the vicinity of the Jacuí River.

Forest Planted Expansion processes between 1987 and 2003 and between 2003 and 2019 are both represented in purple shading, with both concentrated under the Southern Rio-Grandense Plateau. Regeneration processes are represented in shades of green and blue, with a temporal distinction between them. There is a higher prevalence of regeneration in the coastal strip, the Southern Rio-Grandense Plateau, and the areas surrounding the Jacuí River.

Discussion

The application of PCA enabled us to describe the main spatial-temporal trajectories of land use and land cover changes in the Pampa, providing insights into its landscape dynamics. We emphasize the importance of the ordering and spacing of values assigned to land use and land cover classes (as presented in Table 1) to interpret PCA results. The spacing between land use and land cover classes facilitated the identification of degradation and regeneration processes. And the larger spacing between land use classes allowed us to identify which class type the degradation was associated with, providing a detailed characterization of the LUCC trajectories. Additionally, the technique revealed transitions or trajectories that might not be discernible in bi-temporal analyses, but which are important spatiotemporal patterns that emerge when analyzing all available years and performing the description with the PCA technique.

However, it was only sometimes possible to distinguish all the LUCC processes in the PC, and there were instances of confusion. This may be attributed to the distance between the value assigned to the Forest Planted class (70 - Table 1) in comparison to the other land uses. This class received the lowest value for land use, making it similar to other land cover classes. Although the proposed approach enabled the identification of the Forest Planted Expansion throughout the time series, it occasionally confused with the Regeneration process.

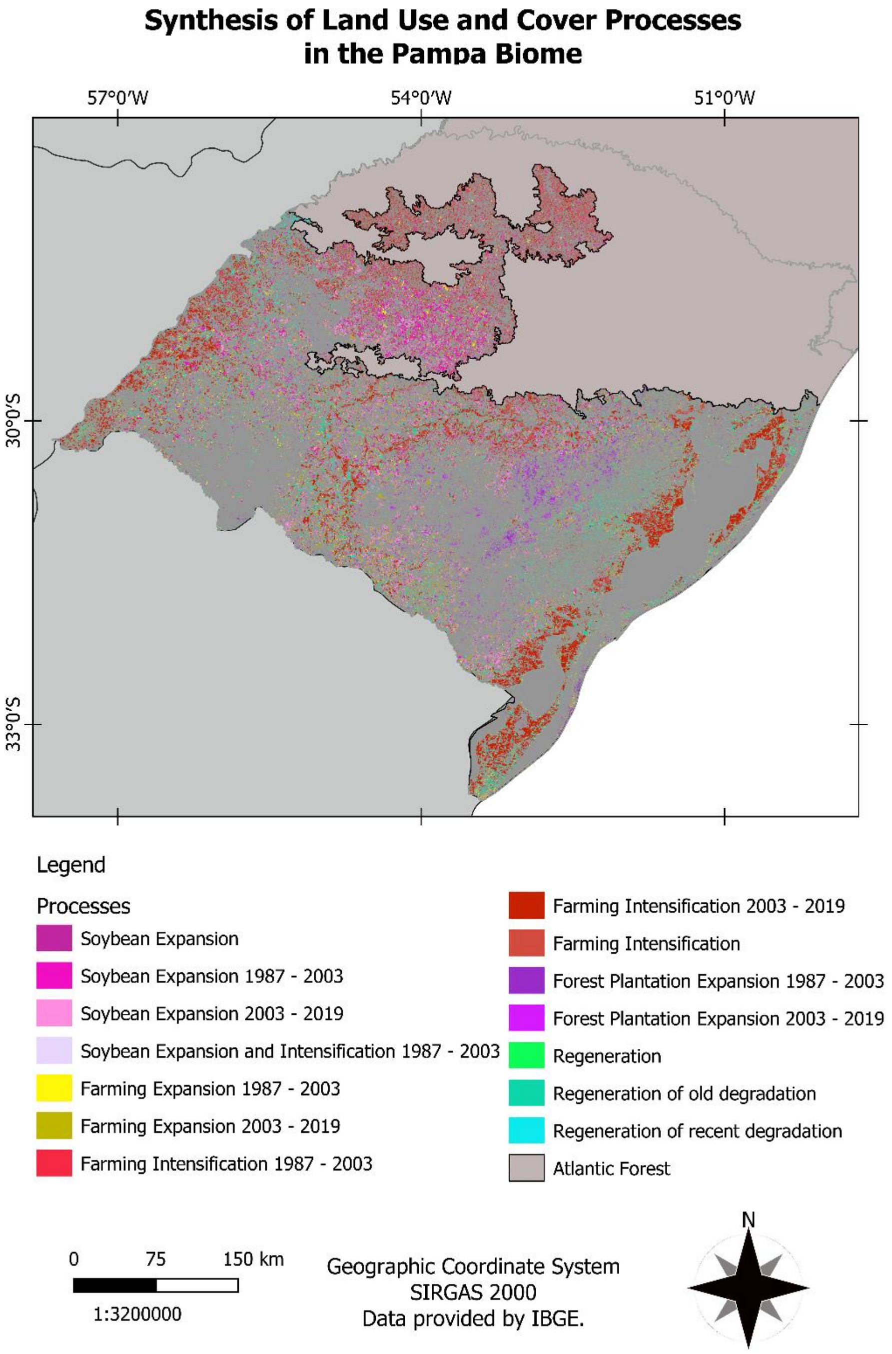

Figure 9. Synthesis of LUCC Processes.

The expansion of soybean cultivation in the Pampa region is a prominent feature, particularly in the neighborhood of consolidated farming areas (as depicted in Figure PC1) and extending towards the central natural formations of the biome, resulting in the displacement of grassland areas. This trend has also been identified by Kuplich et al. (2018) and Mengue et al. (2020). This pattern of expansion can also be observed in Figure 9, which visually represents the growth of soybean farming across the biome. Delgado et al. (2022) argue that the expansion of agricultural production in South America biomes is directly associated with the reduction of biodiversity. The study by Lopes et al. (2024) indicates that the Pampa biome faces medium to high threats to geodiversity, mainly due to land use practices such as agriculture.

Oliveira (2020) showed a reduction in the areas of grassland formations due to the spread of agricultural areas between 1987 and 2017. It also observed the existence of remnants of grassland formations in the Pampa, mainly in the southeast and southwest of the biome, particularly in the southwest is the Environmental Protection Area of Ibirapuitã, which contributes to the preservation of natural areas (Oliveira, 2020). The significant change in the structure of the Pampa landscape was also found in this work, which can be visualized in Figures 6, 8, and 9.

In their study, Mengue et al. (2020) conducted an analysis of LUCC in the Brazilian Pampa region spanning from 2000 to 2014. The findings of the study revealed a significant reduction in grassland formations and simultaneous expansion of agricultural classes, including soy and rice, as well as forestry. Notably, the area covered by Campestral formations experienced a 25% decline over 15 years. In contrast, the area dedicated to soybean cultivation witnessed a substantial increase of 145.56% during the same period, while forestry expanded by 167%, mainly concentrated in the Southeastern Sierra and coastal areas. Furthermore, the study indicates that approximately 98% of the loss of natural grasslands can be attributed to anthropic activities, specifically forestry, and agriculture (Mengue et al., 2020). Peixoto et al. (2022) observed that variations in land use and cover influence surface temperatures in the Pampa biome, with cultivated areas exhibiting higher temperatures compared to forested and grassland areas. The conversion of grassland formations to annual crops also impacts the water balance and river basin flow, as demonstrated by Tretin et al. (2023). These results underscore the significant role played by human actions in the degradation of natural areas within the Pampa region.

According to Moreira et al. (2019), the expansion of soybean cultivation is profoundly transforming the traditional landscape of the Pampa region. Similarly, Beling et al. (2022), in their analysis of the rural transformations in the Pampa, also emphasized the significant agricultural expansion encompassing soy, rice, forestry, viticulture, and olive cultivation. These agricultural activities have brought substantial changes to the traditional landscape of the biome, leading to a reduction in cattle ranching and elements that are intrinsic to the local culture. The authors attribute these transformations to agricultural modernization, which includes the adoption of machinery, agrochemicals, and genetically modified seeds. Additionally, land leasing and the influence of capital have played crucial roles in driving the growth of soybean cultivation in Pampa (Belin et al., 2022; Moreira et al. 2019).

The expansion of forestry activities has also brought significant changes to various regions of the biome, particularly through the establishment of plantations of species such as eucalyptus, pine, and black wattle. It is important to consider that the availability of land plays a crucial role in driving the expansion of soybean cultivation and forestry within the Pampa (Beling et al., 2022; Mengue et al., 2020). The expansion of forestry primarily takes place in grassland areas, resulting in a dramatic transformation of the traditional landscape of the biome. This is particularly concentrated in the Southeastern Sierra region, characterized by its rugged terrain, shallow soils, and lower fertility compared to other areas of the Pampa (Mengue et al., 2020).

Therefore, the degradation of grassland formations in the Pampa is a complex process with multiple contributing factors, leading to various environmental impacts. This process tends to occur in proximity to already degraded areas.

Conclusions

Using Principal Component Analysis to describe the MapBiomas database enabled the analysis of the spatial-temporal dynamics of land use and cover in the Pampa biome. The analysis of only three principal components explained 76.02% of the original data variance, facilitating the identification of the primary spatiotemporal patterns. Additionally, the combination of the first three components provided a condensed representation that summarizes the landscape dynamics of the Pampa in a simplified manner.

The LUCC processes identified in the Pampa biome reveal a significant transformation of its landscape, characterized by a reduction in the extent of grassland formations due to the expansion of anthropogenic activities. The conversion of natural grasslands to agricultural land uses, particularly soy, forestry, and farming, has been a prevalent trend. The results of the analysis highlight that the large-scale conversion of grassland areas is a recent phenomenon in the Pampa, occurring mainly between 1995 and 2010, linked to the replacement of cattle ranching by large-scale agriculture.

Results of this study provide valuable insights into the directions of change and areas experiencing significant anthropic pressure within the Pampa biome. Moreover, the study identifies the primary land uses contributing to the reduction of natural areas, which can greatly contribute to landscape planning strategies. Given these findings, it is crucial to prioritize the conservation of the remaining grasslands and forested areas of the Pampa. These areas possess great potential for establishing environmental protection areas, intending to conserve the ecosystem services offered by the biome and promote sustainable management practices.

It is important to note that the PCA technique has its limitations and requires adaptations for proper application and interpretation of results. However, its potential in describing quantified categorical databases with extensive time series is noteworthy. The technique facilitates the extraction of information and identification of spatiotemporal patterns of changes that may be difficult to detect through bi-temporal analysis. Therefore, while recognizing its limitations, the PCA technique presents a valuable tool for analyzing LUCC dynamics and trajectories in the Pampa biome and other similar regions.

Acknowledgements

The authors thank CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) for providing the doctoral scholarship.

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