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GEOMORPHOLOGICAL CONSTRAINTS AND LAND USE DYNAMICS IN A BRAZILIAN CERRADO PROTECTED AREA: RIO PANDEIROS ENVIRONMENTAL PROTECTION AREA

Wallace Vinicius Martins Ruas
Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Geografia, Belo Horizonte, MG, Brasil
wallaceruas25@gmail.com

Lucas Augusto Pereira da Silva
Universidade Estadual da Paraíba, Departamento de Geografia, Campina Grande, PB, Brasil
lucasaugusto@ufu.br

Aldenice Barbosa Alves
Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre, Belo Horizonte, MG, Brasil
aba@aluno.ifnmg.edu.br

João Paulo Sena-Souza
Universidade Estadual de Montes Claros, Programa de Pós-Graduação em Geografia, Montes Claros, MG, Brasil
joao.souza@unimontes.br

Ana Clara Medeiros de Souza
Universidade Estadual de Montes Claros, Programa de Pós-Graduação em Geografia, Montes Claros, MG, Brasil
anaclaramedeiroz@gmail.com

Marcelo Antonio Nero
Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Análise e Modelagem de Sistemas Ambientais, Belo Horizonte, MG, Brasil
marcelo.nero@gmail.com

Carlos Henrique Jardim
Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Geografia, Belo Horizonte, MG, Brasil
dxhenrique@gmail.com

ABSTRACT

This study aims to analyze the influence of geomorphological units on land use and land cover changes within the Environmental Protection Area of Rio Pandeiros basin, located in northern Minas Gerais, Brazil, in the years 1985, 2000, 2010, and 2024. The present research stems from the need to understand how relief conditions the dynamics of land occupation in protected areas within the Cerrado biome. The methodological approach integrated geomorphological mapping based on morphometric variables derived from the SRTM Digital Elevation Model (DEM) and supervised classification of Landsat imagery using the Random Forest algorithm, and incorporating spectral and topographic covariates. The results indicated high model performance, with strong classification accuracy across all years analyzed. It was observed that anthropogenic transformations were predominantly concentrated in flat relief areas, especially in structural bencheslateau, where pasture emerged as the main anthropogenic class, increasing from 22.99% of the area in 1985 to 26.92% in 2024. In contrast, more dissected compartments showed greater conservation of native vegetation. The findings suggest that geomorphology plays a determining role in the spatial organization of land uses, constituting an essential variable for territorial planning and management in conservation units.

Keywords: Anthropogenic changes. Multitemporal analysis. Relief. Remote sensing. Supervised classification.

Wallace Vinicius Martins Ruas
Lucas Augusto Pereira da Silva
Aldenice Barbosa Alves
João Paulo Sena-Souza
Ana Clara Medeiros de Souza
Marcelo Antonio Nero
Carlos Henrique Jardim

CONDICIONANTES GEOMORFOLÓGICOS E DINÂMICA DO USO DA TERRA EM UNIDADE DE CONSERVAÇÃO DO CERRADO BRASILEIRO: APA DO RIO PANDEIROS

RESUMO

Este estudo visa analisar a influência das unidades geomorfológicas nas mudanças de uso e cobertura da terra na Área de Proteção Ambiental da bacia do Rio Pandeiros, no norte de Minas Gerais, entre 1985, 2000, 2010 e 2024. A pesquisa parte da necessidade de compreender como o relevo condiciona a dinâmica de ocupação em áreas protegidas inseridas no bioma Cerrado. A metodologia integrou mapeamento geomorfológico a partir de variáveis morfométricas derivadas do Modelo Digital de Elevação (MDE) SRTM e classificação supervisionada de imagens Landsat por meio do algoritmo *Random Forest*, utilizando covariáveis espectrais e topográficas. Os resultados indicaram elevada performance do modelo, com elevada acurácia em todos os anos analisados. Observou-se que as transformações antrópicas concentraram-se predominantemente em áreas de relevo plano, especialmente patamares, onde as pastagens se destacaram como a principal classe antrópica, passando de 22,99% da área em 1985 para 26,92% em 2024. Em contrapartida, compartimentos mais dissecados apresentaram maior conservação da vegetação nativa. Conclui-se que a geomorfologia exerce papel determinante na organização espacial dos usos da terra, sendo variável essencial para o planejamento e a gestão territorial em unidades de conservação.

Palavras-chave: Mudanças antrópicas. Análise multitemporal. Relevo. Sensoriamento remoto. Classificação supervisionada.

INTRODUCTION

The increasing anthropogenic transformation of the landscape, associated with the rise of socio-environmental conflicts in Brazil, resulted in efforts by civil society and the scientific community, leading to the creation of the National System of Nature Conservation Units (SNUC) in 2000. This law organized and regulated the already existing conservation units and defined mechanisms for the establishment of new ones. Conservation units were divided into two groups: Sustainable Use and Strict Protection, distributed across 12 distinct categories (BRASIL, 2000). Environmental Protection Areas (EPAs) are among these categories, and they are characterized as territorial management instruments that seek to reconcile the conservation of natural resources with sustainable use, representing a strategic space for understanding the relationships between society and nature in biomes under intense anthropogenic pressure (Campos-Silva *et al*., 2021).

In the Brazilian savanna, referred to as Cerrado, EPAs are established as environmental policy instruments based on the concept of sustainable development. In this context, human activities are carried out responsibly, in an attempt to preserve the quality and integrity of the biome. However, within a scenario of rapid agricultural expansion and territorial transformations, questions have emerged regarding their effectiveness in protecting biodiversity and ecosystem services in the region (Resende *et al*., 2021). In this sense, EPAs have a strategic character, as they are located in areas under intense land-use pressure, restraining the advance of biome transformation.

Considering the period from 1985 to 2017, significant changes in land use and land cover (LULC) were observed, as agricultural areas increased by approximately 176%, particularly in Cerrado, Atlantic Forest, and Pampas biomes (Souza *et al*., 2020). During this interval, substantial transformations occurred in the agricultural suitability of Cerrado soils, reflecting a shift in the way soil was utilized. Due to that, Cerrado soils are no longer regarded solely as a natural resource and became artificially produced capital. As a consequence, the country consolidated its position as one of the world's largest producers and exporters of grains, and Cerrado became one of the world's main agricultural regions (Caballero *et al*., 2023).

Despite the advancement of agriculture, pastures remain the most extensive agricultural activity in Brazil and constitute the most representative land use class in the country. Livestock production originated in Brazil during the colonial period, and its expansion intensified between the 1930s and 1970s, implying a significant increase in deforestation (Dias-Filho, 2014). From the 1970s onward, pasture areas grew by only 4%. This low growth during the period is mainly associated with the expansion of urbanization, mechanized agriculture, silviculture, and bare soil areas, resulting from the degradation of pastures previously destined for extensive livestock production (Landau; Resende; Matos, 2020).

The expansion of anthropogenic activities over natural areas is primarily related to factors that favor the establishment and advancement of such land uses within a given region. These drivers may range from fiscal incentives and public policies to favorable environmental conditions, such as soil, lithological, and relief characteristics (Dupin *et al*., 2018; Espírito-Santo *et al*., 2020; Martins Ruas *et al*., 2025a). With regard to relief, in flat or gently undulating areas, mechanization is favored due to the ease of machinery operation, thereby promoting the expansion of large-scale monocultures (Assis; Couto Júnior; Martins, 2016). In contrast, in more dissected landscapes with high slope gradients, limitations on human occupation are observed, due to erosion risks and, particularly, difficulties related to access and mechanization (Métay *et al*., 2017).

In the northern Minas Gerais Cerrado, the conditioning role of geomorphology on land occupation is especially evident. Flattened surfaces at the tops of plateaus have historically been occupied by large landholdings, where mechanized agriculture and forest formation predominate. Lower areas, which are often more contested, have concentrated smaller properties, characterized by the predominance of pastures and small-scale agricultural practices (Martins Ruas *et al*., 2025b). Thus, the prevailing territorial configuration in northern Minas Gerais tends to restrict the presence of native vegetation predominantly to steeper and more dissected slope areas.

Within this context, Rio Pandeiros Environmental Protection Area (EPA), located in Pandeiros River Basin (PRB), which, although recognized as a protected area under continuous monitoring, has experienced intense anthropogenic processes, as reported by previous studies (Magalhães Filho, 2020; Silva, 2022). Such pressures affect this watershed, which is widely recognized for its high biodiversity, for containing one of the highest densities of *veredas* within the Cerrado biome, and for Pandeiros wetland, responsible for approximately 70% of fish reproduction in the middle São Francisco River basin (Neves, 2011; Borges; Nunes; Leite, 2021). Changes in land use and land cover may also influence infiltration regimes within the watershed, with potential impacts on the discharge of the main river, which constitutes an important tributary of the middle São Francisco River (Leandro; Rocha, 2023).

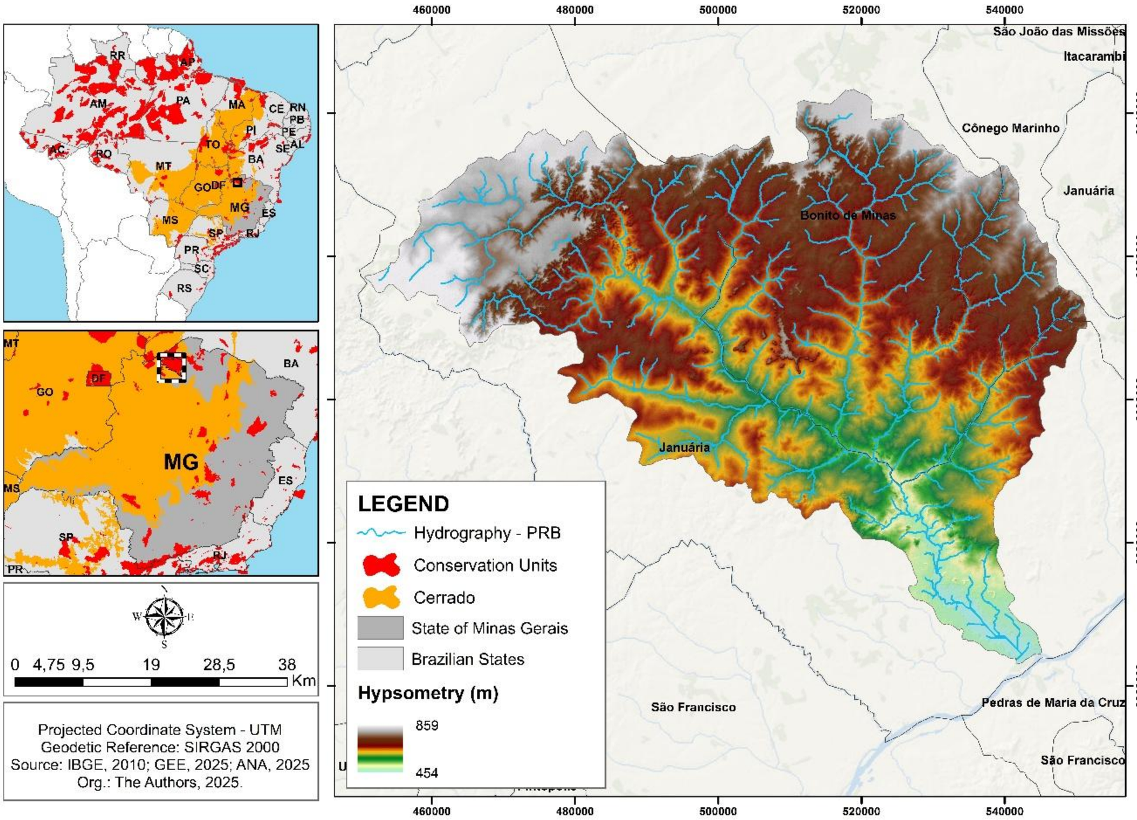
Although studies addressing land use and land cover in the region are available, an important gap remains regarding the influence of geomorphological units on these transformations, which this study seeks to address, particularly within the context of an Environmental Protection Area. The analysis of LULC data available for the watershed reveals occupation patterns associated with relief characteristics, highlighting tensions between ecosystem integrity and anthropogenic activities. In this context, it becomes essential to understand how different geomorphological units condition land-use dynamics over time. Therefore, the objective of this study was to analyze the influence of geomorphology on land use and land cover changes in Rio Pandeiros EPA for the years 1985, 2000, 2010, and 2024.

METHODOLOGY

Study area characterization

The study area is located in the northern region of Minas Gerais, Brazil, comprising the municipalities of Bonito de Minas, Januária, and Cônego Marinho, whose coordinates are 14°57′00″ and 15°35′00″ S latitude and 44°28′00″ and 45°25′00″ W longitude, encompassing Pandeiros River Basin, which covers approximately 3,960 km² (Fig. 1).

Figure 1 - Pandeiros River Basin: Location map, 2025



Source: IBGE 2010; GEE, 2025; ANA, 2025. The authors, 2025.

The geological context of the region is primarily marked by the São Francisco craton and the carbonate rocks of the Bambuí Group, belonging to the São Francisco Supergroup (Chimpliganond, 2013). At higher stratigraphic levels, rocks of the Urucuia Group crop out, consisting of quartz sandstones with reddish and white coloration. Along the floodplains, alluvial deposits composed of unconsolidated sediments are observed, whereas in higher areas there is a predominance of detrital–lateritic covers (Chimpliganond, 2013; Costa *et al*., 2024).

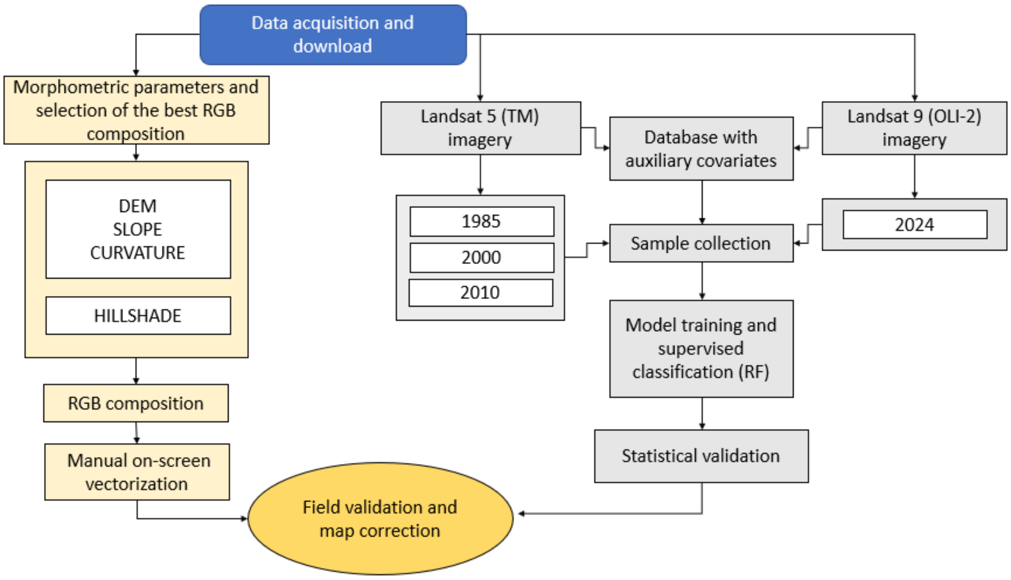
The river basin considered in this study is entirely situated within a semi-humid climate regime, characterized by two well-defined seasons: a hot and rainy summer and a milder and dry winter (IBGE, 2010). According to Jardim and Moura (2018), the mean annual precipitation and temperature correspond to 826.5 mm and 24.4 °C, respectively. The pronounced climatic seasonality plays a fundamental role in the region, shaping the relief through the intensification of weathering cycles, surface runoff, and landscape dissection. As described by Valadão (2009), the landforms within the basin are characterized by the presence of planation surfaces at different stages of conservation and dissection, identified as the South American Surface, South American Surface I, and South American Surface II. In upstream areas, elevations reach up to 847 meters, whereas near the downstream sector, along São Francisco River, elevations decrease to approximately 432 meters (Martins Ruas *et al*., 2025c).

Areas with steeper and more undulating terrain exhibit predominance of native vegetation, mainly cerrado sensu stricto and seasonally dry tropical forest, which are typical phytophysiognomies of the Cerrado biome. In areas of lower elevation and reduced slope, particularly along alluvial plains, wetlands and riparian forests occur (Borges; Rodrigues; Leite, 2019). However, zones with flat to gently undulating topography have historically been occupied by anthropogenic activities, especially pastures and, more recently, mechanized agriculture (Dias; Moschini; Trevisan, 2017). Previous studies have demonstrated, for example, the expansion of these activities in the upper course of Pandeiros River, where the tablelands, due to their extensive planation surfaces and lower topographic constraints, have become preferred areas for the conversion of native vegetation into productive land uses (Silva, 2022; Couto; Fonseca, 2019).

Operational procedures

The adopted methodology was structured in two main stages. The first consisted of preparing the geomorphological map of Rio Pandeiros Environmental Protection Area. The second involved developing land use and land cover classifications, comprising: (I) data acquisition and download; (II) RGB composition; (III) vectorization of geomorphological units; (IV) organization of a database with auxiliary covariates; (V) model training and supervised classification; (VI) statistical validation of the land use and land cover map; and (VII) field validation of the generated products (Fig. 2).

Figure 2 - Methodological flowchart



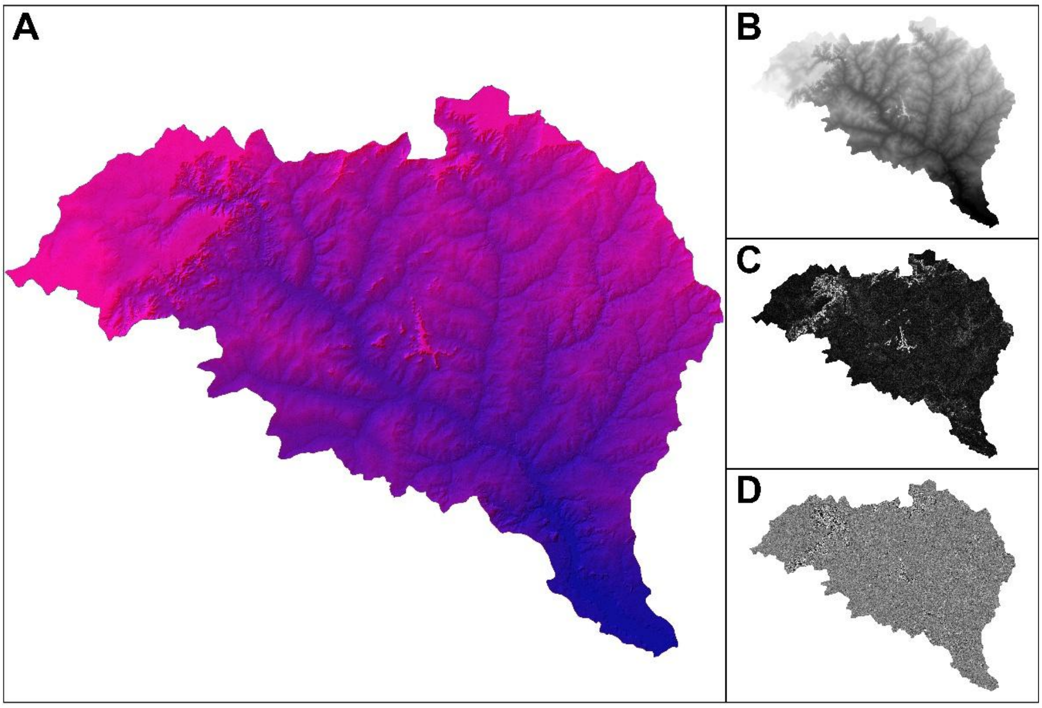
Source: The authors, 2025.

Geomorphological mapping

Initially, the procedures related to the mapping of geomorphological units in the study area were carried out, based on the methodological framework proposed by Ross (1992), Souza-Sena *et al*. (2013), and Souza-Sena *et al*. (2022). For this purpose, the SRTM Digital Elevation Model (DEM) with a spatial resolution of 30 meters, as well as slope and curvature variables, were downloaded via Google Earth Engine (GEE), both derived from the mask layer corresponding to the basin perimeter.

Using these derived variables, the raster datasets were normalized to 8-bit format (0–255), ensuring identical spatial extent and spectral resolution among them. Subsequently, the topographic data were combined into an RGB color composite, in which DEM was assigned to the red band (R), slope to the green band (G), and curvature to the blue band (B) (Fig. 3). The composite was generated using the "Composite Bands" tool within a GIS environment, allowing improved interpretation of the image information through enhanced visualization of relief features (Souza-Sena *et al*., 2013).

Figure 3 - Pandeiros River Basin: Generated RGB and morphometric parameters. (A) RGB composite; (B) DEM (Digital Elevation Model); (C) Slope; (D) Curvature.



Source: The authors, 2025.

The mapping of the units was carried out based on the RGB composition supported by hillshade visualization and geological and geomorphological data from CPRM (2010). The classification was performed via on-screen vectorization, based on the interpretation of relief features identified from distinct color and texture patterns. The interpretation key proposed by Sena-Souza *et al.* (2013) contributed significantly to the understanding and delimitation of landforms within the study area.

Land use and land cover mapping

Land use and land cover mapping was conducted using orbital remote sensing data and machine learning algorithms for the PRB. To compose the historical series, imagery from Landsat 5 (Thematic Mapper – TM) was used for the years 1985, 2000, and 2010, while Landsat 9 (Operational Land Imager 2 – OLI-2) imagery was used for the year 2024. These time points were selected to represent key moments in the study area, with 1985 corresponding to a period prior to the creation of the Pandeiros Environmental Protection Area, 2000 representing the period following its establishment, 2010 an intermediate stage, and 2024 the current scenario.

Based on these images, sample points were collected through photointerpretation, seeking to maintain a similar number of samples across the analyzed periods. Approximately 5,000 samples were compiled for each year, spatially distributed and representing spectral responses characteristic of each land-use class. Training samples were collected independently for each analyzed year through photointerpretation, however, as they are derived from the same study area, some degree of spatial and temporal dependence cannot be entirely ruled out. The selected classes and the number of base samples were: Savanna Formation (1.000), Pasture (900), Forest Formation (750), Agriculture (600), Wetland (500), Urban Area (350), Bare Soil (300), Forest Plantation (250), Water (200), and Rocky Outcrop (150). This distribution was defined based on the need for stratified sampling proportional to class area and spectral complexity, ensuring dataset balance and supporting the performance of the Random Forest algorithm (Melichar *et al.*, 2023).

Supervised classification using machine learning enables the incorporation of spectral and topographic covariates, allowing a given class to be discriminated based on reflectance attributes and landscape relationships (Table 1) (Bolfe *et al*., 2023; Martins Ruas *et al*., 2025b). Accordingly, for Landsat 5, bands covering the visible spectrum (Bands 1 to 3), the near-infrared (Band 4), and the shortwave infrared (Bands 5 and 7) were used. For Landsat 9, Bands 2 to 7 were employed, corresponding to the blue, green, red, near-infrared, and the two shortwave infrared ranges, respectively.

Table 1 - Covariates used in the classification

Data type	Variable / Index	Description
Landsat 5 bands	B1–B3 (visible), B4 (NIR), B5 & B7 (SWIR)	Visible, near-infrared, and shortwave infrared bands
Landsat 9 bands	B2–B4 (visible), B5 (NIR), B6–B7 (SWIR)	Blue, green, red, NIR, and SWIR bands
Spectral indices	NDVI, SAVI, EVI (vegetation); NDWI, MNDWI (moisture/water); NDBI (built-up areas); MDMI, SWIR (soil/organic matter)	Derived from spectral bands for environmental characterization
Topographic covariates	Elevation, slope, curvature, flow direction, flow accumulation, valley depth, aspect, TWI	Derived from DEM (30 m resolution)

Source: The authors, 2025.

From these spectral bands, the following spectral indices were derived: the Normalized Difference Vegetation Index (NDVI), the Normalized Difference Water Index (NDWI), and the Normalized Difference Built-up Index (NDBI), in addition to the use of the Shortwave Infrared (SWIR) band. Additionally, the Modified Normalized Difference Water Index (MNDWI), the Soil-Adjusted Vegetation Index (SAVI), the Enhanced Vegetation Index (EVI), and the Normalized Difference Moisture Index (MDMI) were also calculated. Furthermore, topographic covariates were obtained from the Digital Elevation Model (DEM), namely: elevation, slope, curvature, flow direction, flow width, valley depth, aspect, and the Topographic Wetness Index (TWI).

To reduce temporal noise and generate representative annual composites, the median of the image collection was calculated, resulting in synthetic scenes expressing the average spectral conditions from January to December for each analyzed year (Gorelick *et al*., 2017). Furthermore, an image filtering criterion was applied to select scenes with cloud cover lower than 10%, minimizing atmospheric interference and cloud-related artifacts (Zhu, 2017). All satellite data were acquired through GEE, with spatial resolution of 30 meters.

Prior to the classification procedures, the Caret package (Kuhn, 2023) was employed, applying the findCorrelation function based on the Pearson correlation coefficient (r), using a threshold of 0.90. Covariates exceeding this correlation level were removed to reduce multicollinearity effects and improve model stability. Subsequently, a feature matrix associating LULC classes and predictor variables was constructed. This dataset was partitioned into training and validation subsets using the createDataPartition function, allocating 60% of the samples for training and 40% for statistical validation.

Supervised classifications were then performed using the Random Forest (RF) algorithm within the RStudio environment. The RF algorithm consists of an ensemble of decision trees generated from multiple bootstrap samples and random subsets of predictor variables (Breiman, 2001). Each tree is independently built, and at each node split, only a random subset of variables is evaluated, reducing overfitting and increasing generalization capacity (Bolfe *et al*., 2023). The final classification is determined by majority voting across all trees, conferring robustness and predictive stability to the model (Maxwell; Warner; Fang, 2018). This algorithm has been widely applied in LULC studies and demonstrates high classification performance (Rodriguez-Galiano *et al*., 2012). The classification workflow followed the procedures described by Zeferino *et al*. (2020).

Given the spectral heterogeneity observed within the same land-use classes in the study area, a hierarchical classification strategy was adopted (Shimabukuro *et al*., 2023). At Level 1, an initial separation into three major classes was conducted: natural, anthropic, and water. Successive refinements were then applied up to Level 5, allowing greater thematic detail and class discrimination. During model training, the most influential variables were identified using the varImp function. Model performance was assessed using the validation subset (40% of samples), employing the Kappa Coefficient and Overall Accuracy, metrics commonly used in recent LULC studies (e.g., Babu; Chattoraji, 2025; Bethuel *et al*., 2025; Pandya; Gontia, 2025).

$$\text{Overall Accuracy} = \frac{TP+TN}{TP+TN+FP+FN} \tag{1}$$

where: TP (True Positives) denotes the number of samples correctly classified as positive; TN (True Negatives) represents the number of samples correctly classified as negative; FP (False Positives) represents the number of samples incorrectly classified as positive; and FN (False Negatives) represents the number of samples incorrectly classified as negative.

$$\text{Kappa Coefficient} = \frac{Po-Pe}{1-Pe} \tag{2}$$

where: Po represents the observed agreement, corresponding to the proportion of instances in which the model predictions and the reference (ground truth) classifications coincide; and Pe represents the expected agreement, corresponding to the proportion of agreement that would be expected by chance.

Omission and commission errors were also evaluated. Omission errors correspond to reference samples that were not classified into their respective classes, whereas commission errors correspond to samples incorrectly assigned to a given class, belonging in fact to other classes. To support the analysis of land use and land cover transitions, a Sankey diagram was generated using RStudio software, through the ggalluvial package, based on the intersection of maps from different years. Transition flows were obtained through the cross-tabulation of class changes over time, considering their distribution within the geomorphological units.

Field campaign

Finally, a field verification stage was conducted to validate both land use and land cover classifications and geomorphological units. This campaign was carried out on October 24 and 25, 2025. During this stage, strategic locations previously identified from satellite imagery were visited, totaling approximately 100 validation points corresponding to the nine land use classes. Representative points were selected across different relief sectors, with priority given to transition zones between distinct anthropogenic activities. In addition, areas that generated uncertainties during the mapping procedures were examined to support potential future corrections.

RESULTS

Performance of LULC classification

The land use and land cover classification in Rio Pandeiros Environmental Protection Area was performed using the Random Forest algorithm, incorporating spectral and topographic covariates. Model performance was consistently high across all years and classification levels. The hierarchical approach improved the separation of spectrally similar classes by structuring the classification process into progressive levels, reducing ambiguities and increasing the consistency of the final results.

Throughout the process, overall accuracy ranged from 99.05% to 100%, and the Kappa coefficient from 0.9712 to 1 (Table 2), demonstrating the high reliability of the model in distinguishing LULC classes over the analyzed years. Although minor variations in omission and commission errors occurred across classes and periods, the values remained low, indicating minimal confusion between classes.

Table 2 - Classification accuracy performance

Year	**Level 1 (A/K)**	**Level 2 (A/K)**	**Level 3 (A/K)**	**Level 4 (A/K)**	**Level 5 (A/K)**	**Overall Accuracy (%)**	**Kappa Coefficient**
1985	100 / 1	99.17 / 0.9837	100 / 1	99.67 / 0.9944	–	99.71	0.9945
2000	100 / 1	99.06 / 0.9861	100 / 1	100 / 1	–	99.76	0.9965
2010	99.52 / 0.9900	99.24 / 0.9886	100 / 1	98.75 / 0.9794	–	99.37	0.9895
2024	100 / 1	100 / 1	99.39 / 0.9775	98.95 / 0.9742	98.88 / 0.9814	99.44	0.9866

Source: The authors, 2025. Note: A = Overall Accuracy (%); K = Kappa Coefficient.

According to the confusion matrix, Kappa values equal to 1 occurred mainly at level 1, in the separation of water, anthropogenic activities, and natural areas (Table 3), where target discrimination was facilitated, particularly by the spectral covariates, whose structure reflects the hierarchical unfolding of classes across the classification levels. At more detailed levels, the high index values may reflect both the good spectral and topographic separability of some classes and the possibility of overfitting. Extremely high values of overall accuracy and Kappa coefficient, such as those observed at levels 3 and 4 of the classification, may indicate an excessive fit of the model to the training data, particularly in contexts where spectral responses exhibit high degree of spatial organization, and should therefore be interpreted with caution.

Figure 4 represents the mean values of the most important covariates across the processing stages. The Random Forest Mean Decrease Gini metric indicates which variables most contributed to the discrimination of land use and land cover classes. Within the analyzed set, spectral variables such as SWIR bands, spectral bands, NDVI, MNDWI, and NDWI stand out, highlighting their relevance for distinguishing vegetation, wetlands, and anthropogenic areas. Topographic variables, particularly flow width, also exerted influence, indicating that terrain characteristics affect the spatial distribution of the classes. The performance and importance of these indices have been examined in recent studies, such as Torres and Oliveira (2025) and Girma *et al*. (2025).

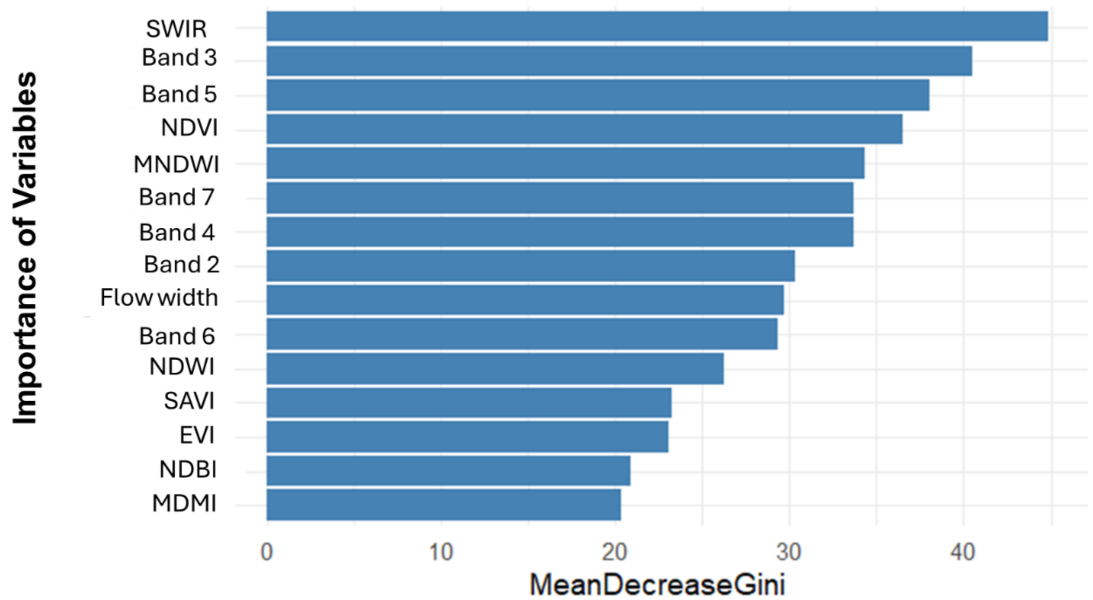
Table 3 - Confusion matrices for land use/land cover classification by level and year

Level		***1985***			***2000***				***2010***				***2024***		
	Ref	**1**	**2**	**3**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**
1	**1**	200	0	0	80	0	0	–	80	0	0	–	80	0	0
1	**2**	0	620	0	0	860	0	–	0	955	5	–	0	960	0
1	**3**	0	0	960	0	0	960	–	0	5	955	–	0	0	960
2	**1**	300	0	0	58	0	2	0	198	0	0	2	60	0	0
2	**2**	0	60	0	0	300	0	0	0	400	0	0	0	300	0
2	**3**	4	4	592	0	0	198	2	0	0	60	0	0	0	600
2	**4**	–	–	–	0	2	3	395	0	0	5	295	–	–	–
3	**1**	400	0	–	140	0	–	–	140	0	0	–	197	3	–
3	**2**	0	200	–	0	720	–	–	0	100	0	–	3	397	–

3	**3**	–	–	–	–	–	–	–	0	0	720	–	–	–	–
4	**1**	120	0	0	360	0	0	–	360	0	0	–	714	5	0
4	**2**	0	140	0	0	240	0	–	0	240	0	–	1	140	0
4	**3**	0	0	360	0	0	120	–	0	0	120	–	4	0	96
5	**1**	–	–	–	–	–	–	–	–	–	–	–	356	4	0
5	**2**	–	–	–	–	–	–	–	–	–	–	–	0	238	2
5	**3**	–	–	–	–	–	–	–	–	–	–		0	2	118

Source: The authors, 2025. Note: “Ref” indicates the reference classes, corresponding at level 1 to: 1 = water, 2 = anthropogenic use, and 3 = natural area. At subsequent levels, the values represent the subdivision of these classes into subclasses according to their occurrence in each year. The columns correspond to the map classifications for each level and year, and the values represent the confusion matrices derived from the land use and land cover classifications. Dashes (–) indicate classes not applicable for a given level/year combination

Figure 4 - Mean importance of variables in classifications, calculated from all Random Forest (RF) model runs.

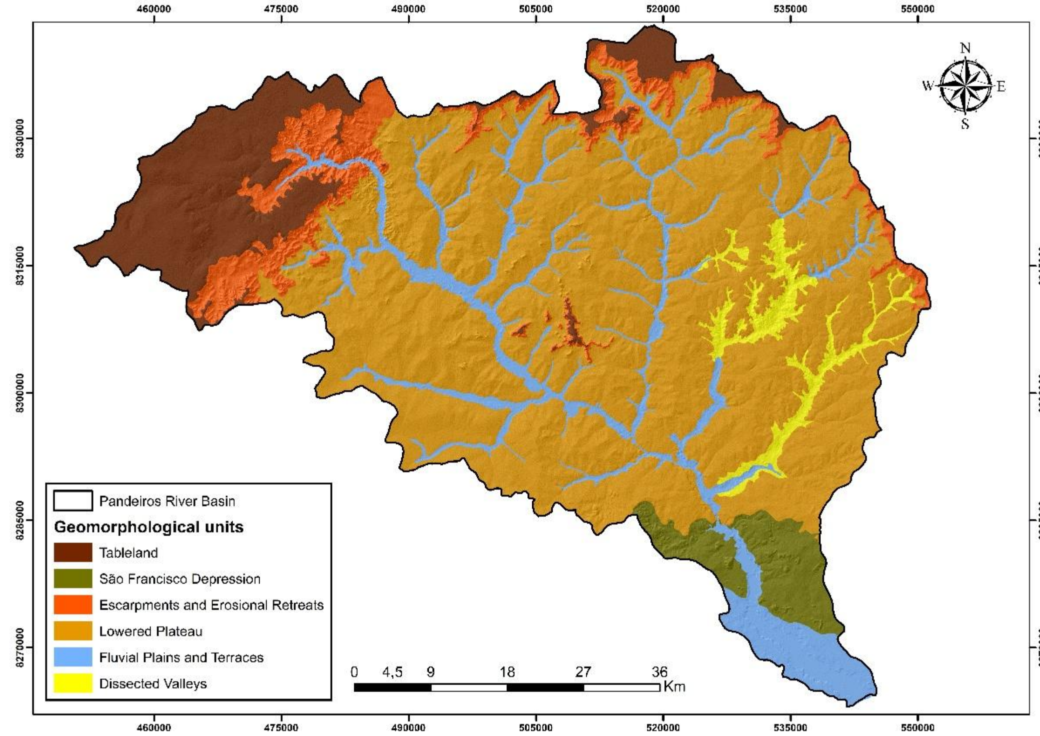


Source: The authors, 2025.

Mapping of geomorphological units and land-use classes

Based on the proposed methodology, six geomorphological units were identified: Tableland, São Francisco Depression, Escarpments and Erosional Retreats, Lowered Plateau, Fluvial Plains and Terraces, and Dissected Valleys (Fig. 5). The nomenclature was defined through an adaptation of the CPRM (2010) geomorphological framework. The classification criteria also considered the relief classification approach proposed by Ross (1992), which employs concepts such as morphostructure and morphosculpture, as well as the influence of climatic processes on the shaping of landforms.

Figure 5 - Pandeiros River Basin: Geomorphological units map



Source: The authors, 2025.

Regarding land use and land cover classes, Savanna Formation was the predominant class in all periods, reaching its greatest extent in 2000, when it occupied 69.9% (2742.66 km²) of the total area. Pasture areas showed a reduction during the first time period, with the smallest area recorded in 2000 (803.57 km²). However, this class gradually expanded again, reaching its maximum extent in 2024, when it covered 996.23 km².

Agricultural areas exhibited continuous growth, representing the largest proportional increase among the classes, expanding from absence in 1985 to 40.32 km² in 2024. The Urban Area followed similar trend, with gradual growth from 0.201 km² in 1985 to 3.05 km² in 2024 (Table 4).

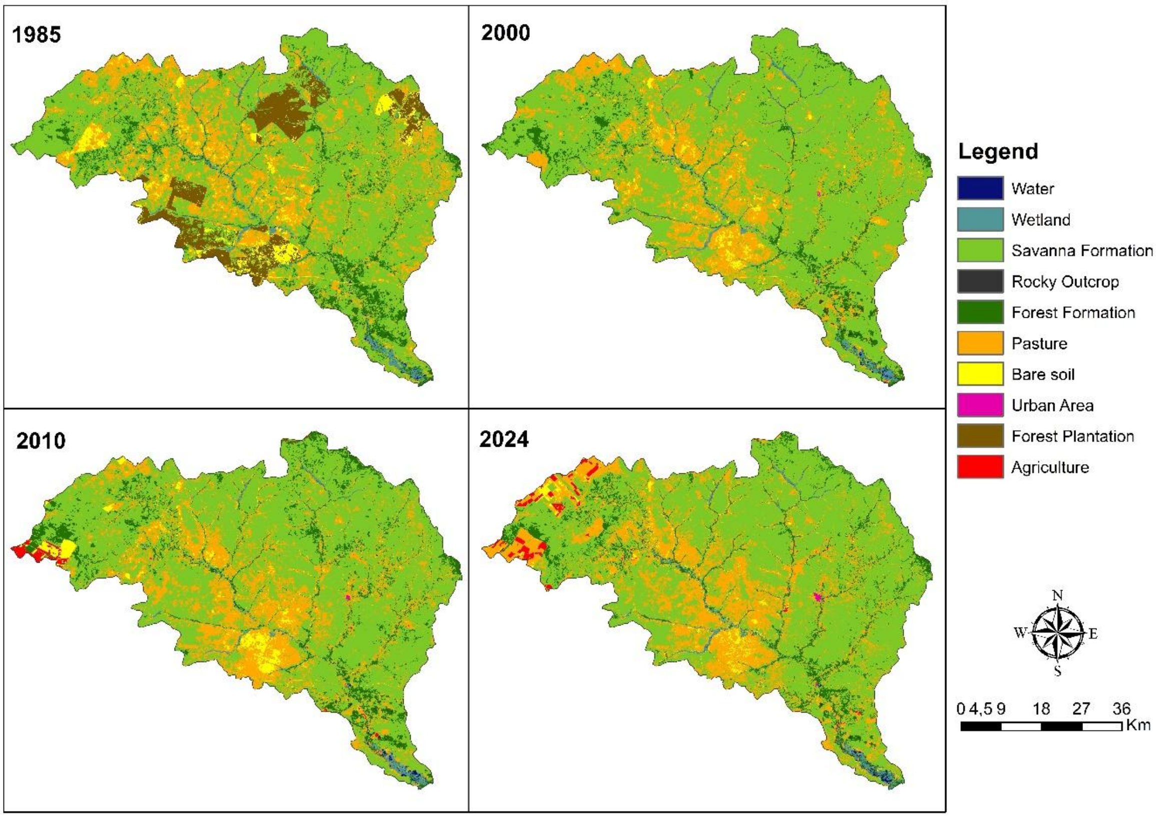
Table 4 - Pandeiros River Basin: Land use and land cover distribution

Class	**1985 (km²)**	**1985 (%)**	**2000 (km²)**	**2000 (%)**	**2010 (km²)**	**2010 (%)**	**2024 (km²)**	**2024 (%)**
Water	4.97	0.12	5.56	0.14	7.34	0.18	6.28	0.16
Wetland	92.19	2.35	68.11	1.73	50.08	1.27	77.21	1.97
Savanna Formation	2172.30	55.43	2742.66	69.96	2560.26	65.31	2453.09	62.57
Rocky Outcrop	1.86	0.04	3.054	0.07	2.42	0.06	1.82	0.04
Forest Formation	289.48	7.38	234.41	5.98	311.13	7.94	277.31	7.08
Pasture	886.55	22.61	803.57	20.50	862.31	21.99	996.23	25.42
Bare Soil	154.40	3.93	61.19	1.56	99.43	2.54	64.43	1.64
Urban Area	0.20	0.005	0.87	0.02	1.25	0.03	3.05	0.07
Forest Plantation	318.18	8.11	-	-	2.55	0.06	0.51	0.013
Agriculture	-	-	0.70	0.01	23.49	0.6	40.32	1.03

Source: The authors, 2025.

Forest plantations showed strong decline over the analyzed period, decreasing from 318 km² in 1985 to only 0.5 km² in 2024. Bare soil areas fluctuated across the periods, with no clearly defined trend; however, the considerable extent observed in 1985 (154.50 km²) may be associated with eucalyptus areas and more intensive land-use practices (Fig. 6). The remaining classes exhibited less pronounced and less consistent variations. Wetlands, for instance, after successive reductions, increased from 2010 to 2024, reaching 77.21 km². Despite oscillations in the Forest Formation class, its relative contribution remained stable throughout the time series, varying from 234.41 km² to 311.13 km² within the study area.

Figure 6 - Pandeiros River Basin: Land use and land cover mapping

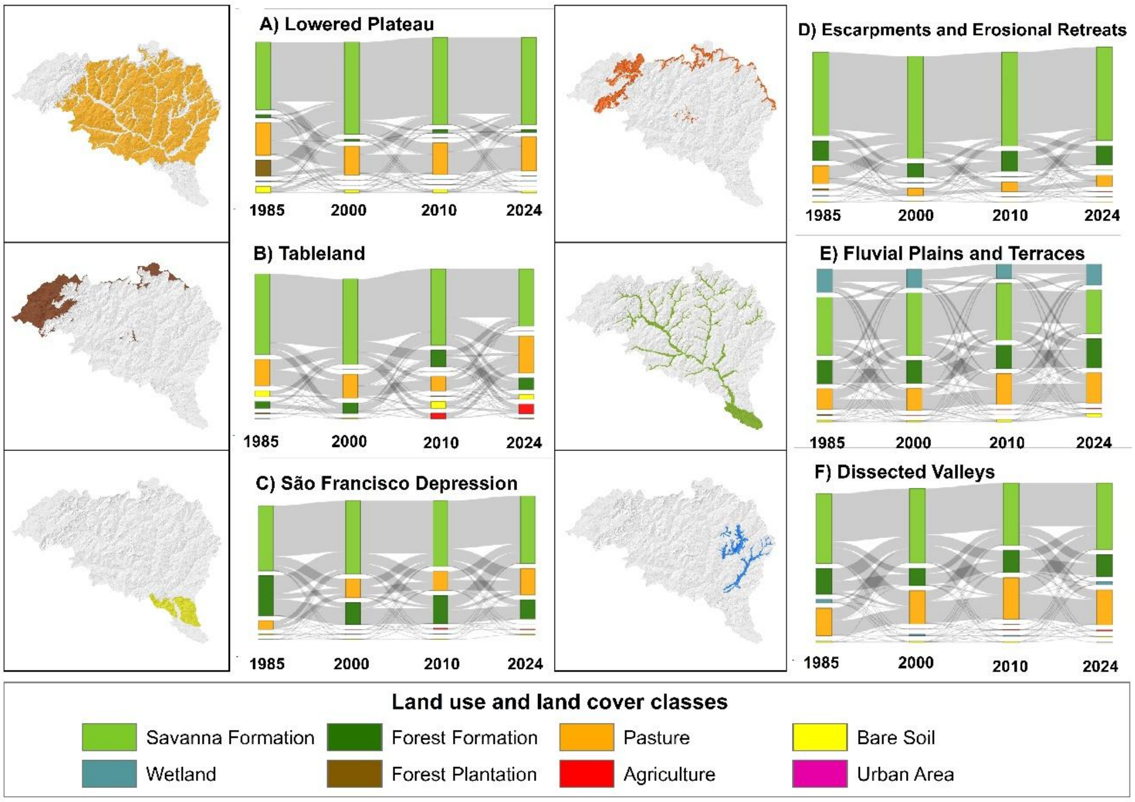


Source: The authors, 2025.

Dynamics between land use and geomorphology

The largest geomorphological unit corresponds to the Lowered Plateau, which occupies 62.87% of the study area, equivalent to approximately 2,465 km², with relief associated to sediments of São Francisco river basin. Within the Lowered Plateau unit, approximately 13% of the area was covered by Forest Formation in 1985; however, by 2000 this class had completely disappeared (Fig. 7). Although the eucalyptus cycle left large areas of exposed soil, savanna vegetation expanded, increasing from 53.62% to 73.09% from 1985 to 2000. In the following periods, this vegetation showed a slight regression, decreasing from 69.44% in 2010 to 69.35% in 2024, while pasture areas regained some extent.

Figure 7 - Pandeiros River Basin: Land use and land cover dynamics from 1985 to 2024 according to geomorphological units, based on the Sankey diagram



Source: The authors, 2025.

Tablelands occupy a considerable area, approximately 11.69% (458.2 km²), and are mainly characterized by the occurrence of detrital–lateritic covers over Serra das Araras Formation. Pasture is the main anthropogenic class within this unit, reaching its maximum extent in 2024, when it occupied 30.77% of the area. Despite the predominance of pasture, agriculture expanded considerably between 2000, 2010, and 2024, occupying 0%, 4.34%, and 7.79% of the unit, respectively.

Escarpments and Erosional Retreats account for 7.83% (307.07 km²) of the territory and are characterized by high slope gradients, the highest within the basin. Currently, this geomorphological unit exhibits the highest conservation rate. In 2024, Savanna Formation occupied 75.84% of the area, followed by Forest Formation, with 15.19%. These values are similar to those recorded in 1985, namely 67.36% and 15.68%, respectively.

Aggradational landforms, represented by the Fluvial Plains and Terraces unit, correspond to 10.35% (405.5 km²) of the total area and encompass alluvial and undifferentiated detrital sediments. Pasture is also the main anthropogenic class in this unit, showing an expansion from 15.83% in 1985 to 23.29% in 2024. Agriculture exhibited small and gradual increase in this unit, although it still did not reach 1% of the area in 2024. Wetlands, characterized as extremely sensitive ecosystems, showed slight variation, occupying 18.97% of the area in 1985 and 16.72% in 2024.

The São Francisco Depression and the Dissected Valleys correspond, respectively, to 4.17% (163.4 km²) and 3.09% (121.06 km²) of the total basin area. In the São Francisco Depression, the greatest intensity of variation along the historical series is observed: in 1985, Forest Formation accounted for 35.09% of the unit, but after moderate oscillations in 2000 and 2010, it reached its lowest value in 2024, only 17.19%. In contrast, pasture areas increased from 7.58% in 1985 to 22.80% in 2024. The Dissected Valleys exhibit similar pattern, with reduction in Forest Formation (from 19.75% to 16.92%

from 1985 to 2024) and expansion of pasture (from 21.77% to 27.45%). A slight increase in agricultural areas is also observed in both units; however, these remain spatially limited and below 1% of the total area.

DISCUSSION

The analysis of the high accuracy values raises the possibility of overfitting influence at some classification levels. However, in the present study, this potential limitation is minimized by different factors. First, the high separability among classes, supported by the integration of explanatory covariates and combined with the hierarchical approach, contributes to more consistent discrimination. In addition, field validation provided independent evidence regarding the coherence of the mapped features. Furthermore, recent studies involving land use mapping have reported similarly high levels of performance in terms of overall accuracy and Kappa coefficient (Aziz *et al*., 2023; Kasahun; Legesse, 2024), particularly when multispectral data and auxiliary variables are integrated.

Thus, although the possibility of overfitting cannot be ruled out, the convergence between metrics, spatial coherence, and empirical validation indicates that the results are robust. Nevertheless, it is important to emphasize the need to adopt additional strategies, such as spatially independent validation, in order to more rigorously reduce any potential bias associated with the model in future studies.

The results indicate that land-use changes occurred predominantly in flat to gently undulating relief areas, in the upper course of the basin, and in the vicinity of watercourses. This pattern is primarily explained by the presence of soil classes with good physical and chemical properties (Tenenwurcel *et al*., 2020), as well as other favorable conditions for agricultural and livestock management in the PRB. The main dynamics involved changes in agricultural and livestock activities as well as vegetation types, whereas classes such as Urban Area, Rocky Outcrop, and Water showed little change in the overall context of the study area.

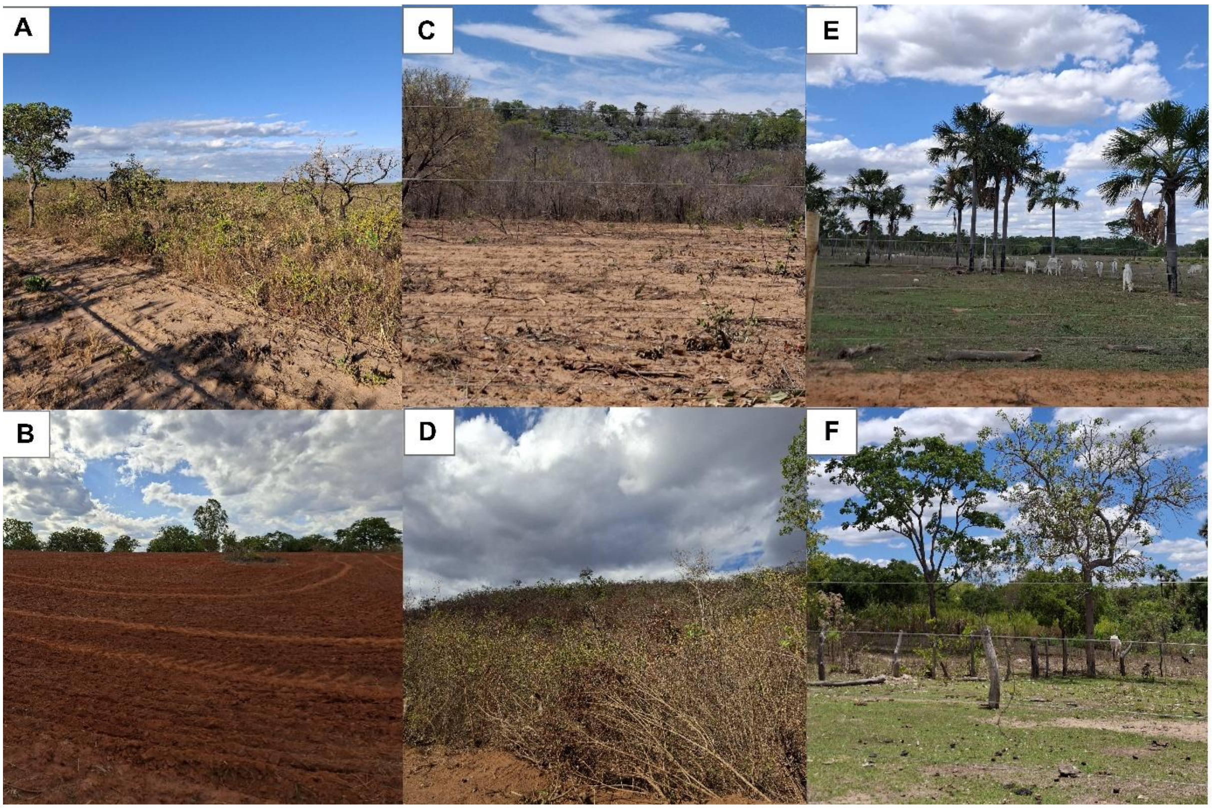
In the Lowered Plateau unit, the altimetric difference between São Francisco and Pandeiros rivers triggered a process of headward erosion in the latter, with headward retreat of drainage heads. As a result, hydrogeomorphological processes removed a large part of the rocks of Serra das Araras Formation, preserving only residual hills (inselbergs) and exposing the fine sandstones of Posse Formation (Augustin *et al*., 2022). In this context, the Lowered Plateau is situated at intermediate elevations between the Tablelands and the São Francisco Depression, the latter subjected to even more intense erosional processes.

Eucalyptus cultivation in regions such as this occurred due to the presence of flattened areas with deep and well-drained soils, as well as their low land value (Martins Ruas *et al*., 2025b). Furthermore, tax incentives provided by the Superintendence for the Development of the Northeast (SUDENE) intensified the expansion of eucalyptus plantations in the region, primarily due to the availability of cheap and undervalued lands, often located farther from river channels. However, even before the creation of the EPA, eucalyptus plantations had already been suppressed (Leite; Almeida; Silva, 2012), primarily due to the lack of state investment in the sector. In subsequent years, part of the abandoned areas was converted into Savanna Formation, confirming the remarkable regenerative capacity of Cerrado (Dias; Moschini; Trevisan, 2017). In other nuclei, successive deforestation cycles occurred, leading to the predominance of pasture.

In the Tablelands, a crucial factor to be considered is the climatic condition, as the local semi-arid context contributed to the action of planation processes (Costa *et al*., 2024). The widespread occurrence of lateritic crusts supporting the Tablelands in elevated areas and on fluvial terraces reflects the complexity of Cenozoic paleoclimatic dynamics, marked by alternation between dry and humid periods (Penteado; Ranzani, 1973; Silva, 2016). During humid phases, reducing conditions favor the mobilization and removal of iron from the soil profile, whereas during dry phases oxidation and precipitation of Fe^{3+} predominate, promoting the hardening and stabilization of lateritic crusts (Gidigasu, 2012; Sprafke e*t al*., 2024).

This unit was the most anthropogenically transformed over the analyzed period, exhibiting intense loss of native vegetation. Between 1985 and 2024, natural vegetation decreased by 69.64 km², resulting in an average annual loss rate of approximately 1.79 $km^2\ year^{-1}$. In this region, irrigated livestock production is organized within a complex paddock system, indicating high level of technological input and management intensity. Consistent with patterns observed in other Cerrado regions, agricultural and livestock activities expanded rapidly, influenced by the municipality of Chapada Gaúcha, a regional reference in meat and grain production (da Silva Brandão; Sobrinho, 2025). Moreover, pedogenesis is favored in these environments, promoting the formation of deep and well-drained soils such as Latosols (Assis *et al.*, 2016). Thus, in addition to institutional and economic drivers, soil quality and topographic conditions enable the development of mechanized and continuously expanding agricultural systems (Fig. 8).

Figure 8 - Interaction between geomorphological units and land use in the study area: (A) Pasture in a former eucalyptus area within the Lowered Plateau unit. (B) Area prepared for Agriculture on the Tablelands. (C) Deforested Forest Formation area in the São Francisco Depression, with a residual massif in the background. (D) Transition between Savanna Formation and Forest Formation on escarpments. (E) Pasture in the Fluvial Plains unit. (F) Anthropogenic activities carried out in the Dissected Valleys unit



Source: The authors, 2025.

Escarpments and Erosional Retreats occur mainly along a relief break that may exceed 80 m in height difference, between Posse Formation and the overlying Serra das Araras Formation, both belonging to the Urucuia Group. The dynamics of escarpment retreat are still active, intensified by the action of drainage lines showing evidence of gully erosion, associated with the loss of natural vegetation cover. The low presence of anthropogenic activities and the small temporal variation observed are related to the limitations imposed by relief on human occupation. Historically, flatter areas became priority zones for settlement, whereas regions with steeper slopes maintained higher rates of natural vegetation cover (How Jin Aik *et al.*, 2021).

Near the river channels occur Fluvial Plains, flat surfaces located adjacent to the riverbed and still subject to its current dynamics, and Fluvial Terraces, inactive surfaces positioned at higher elevations relative to the alluvial plain. In the middle and upper basin, these terrains are associated with the dynamics of Pandeiros River and its tributaries, whereas in the downstream sector, near the outlet and in the so-called "Pandeiros Wetland", they are directly influenced by São Francisco River (de Oliveira *et al*., 2022). The proximity and abundance of watercourses favor not only agriculture, but also other socioeconomic activities (Chen *et al*., 2024). Although this growth has not been as pronounced as in other areas, the anthropization of these environments raises serious concerns, particularly regarding wetland conservation. Despite showing limited variation, this remains a fragile ecosystem, threatened by human pressure and climatic variability (Durigan *et al*., 2022).

The weathering of carbonate rocks of Sete Lagoas Formation strongly characterizes the relief features of São Francisco Depression. In this context, landform development is associated with dissolution processes of both covered and exposed karst of the Bambuí Group, with the presence of limestone cliffs, lapies, dolines, and poljes. Thus, the main forest remnants within this unit are concentrated near small residual hills, which tend to prevent or hinder deforestation. The Dissected Valleys result from the uncommon outcropping of the basement in the region, exposing granitoids and gneisses of the Januária Complex. In this case, dissection is controlled by rock fracturing associated with low permeability, which favors surface runoff and the consequent shallow incision of the drainage network.

Owing to the lithological characteristics of both units, these regions exhibit relevant fragments of Forest Formation, possibly related to the presence of deeper soils and humid microenvironments within fractures and outcrops (Fagundes *et al*., 2020). Nevertheless, these remnants have been gradually suppressed over recent decades. During the analyzed period, both the Dissected Valleys and the São Francisco Depression presented similar transition patterns, marked by the advance of anthropogenic classes. Pasture expansion was more pronounced, whereas agriculture expanded in a more localized manner, mainly in areas with eutrophic soils derived from limestone (Zhang; Zhang, 2023).

It is important to highlight the occurrence of pastures under different contexts, ranging from rudimentary systems to irrigated and large-scale systems, as well as degraded pastures. Previous studies, such as those by Magalhães Filho (2020) and Couto and Fonseca (2019), classified the sparser vegetation formations within the basin as grassland vegetation or sparse vegetation. However, the analysis of historical image time series and field observations allowed the identification of these areas to be more closely related to degraded pastures. This degradation is largely associated with deforestation cycles following the eucalyptus cultivation period in the region, as well as with the recurrence of annual fires, as corroborated by Silva (2022).

The analysis of the dynamics revealed a recurrent pattern in most geomorphological units: natural vegetation initially reduced in 1985 showed a marked increase in 2000, and subsequently declined in 2010 and 2024. This pattern was also observed in other studies, such as Magalhães Filho (2020), who discusses the complexity of maintaining conservation in the PRB EPA, especially due to the presence of villages, communities, and a town within its boundaries. The vegetation peak observed in 2000 may be associated with the creation of the EPA in 1995, which initially restrained the intense anthropogenic pressure previously affecting the area. Considering the exceptional regenerative capacity of Cerrado, the gain in Savanna Formation cover is entirely plausible. However, the complexity of managing and enforcing protection in conservation areas with human occupation helps to explain the subsequent decline in vegetation in later periods.

CONCLUSIONS

The study revealed that relief plays a fundamental role in land use and land cover transformations within Rio Pandeiros Environmental Protection Area. The identified geomorphological units strongly determined land occupation patterns, especially in flatter areas. The Lowered Plateaus and Tablelands remained preferential regions for the expansion of agro-pastoral activities, with gentle topography and low slope values acting as facilitating factors for occupation. Particularly in Tablelands, pasture and mechanized agriculture grew exponentially from 2010 to 2024, resulting in reduction of savanna and forest formations. In contrast, more dissected areas with higher slopes acted as refuges for native vegetation, with Escarpments and Erosional Retreats presenting the lowest rates of conversion to anthropogenic activities.

The other geomorphological units, such as Fluvial Plains and Terraces, Dissected Valleys, and São Francisco Depression, showed greater resistance to conversion; nevertheless, the increase in anthropogenic areas from 1985 to 2024 raises concerns about the effectiveness of the territory as an Environmental Protection Area. The increase in native vegetation from 1985 to 2000 directly coincides with the creation of the APA in 1995; however, the subsequent expansion of anthropogenic activities may be related to a relaxation of monitoring and enforcement.

The results reinforce the importance of considering geomorphology as a central variable in studies involving territorial planning in protected areas. By identifying where anthropogenic pressures are concentrated, the study provides support for improving management and enforcement strategies in Rio Pandeiros Environmental Protection Area. Thus, understanding geomorphological controls becomes fundamental to ensure a sustainable relationship between human activities and conservation, aiming at the maintenance of this important hydrographic basin. In addition, it is worth highlighting the importance of validating the obtained results, which was done through the application of the overall accuracy and Kappa Coefficient, considering that future studies may apply other validation indices for thematic maps. Finally, although the results are robust, the influence of overfitting at some classification levels cannot be entirely ruled out. Therefore, it is recommended that future studies adopt additional strategies, such as spatially independent validation, to reduce potential biases associated with the model.

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