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Landscape dynamics analysis in Northern Minas Gerais from an environmental systems perspective

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LANDSCAPE DYNAMICS ANALYSIS IN NORTHERN MINAS GERAIS FROM AN ENVIRONMENTAL SYSTEMS PERSPECTIVE

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Abstract

Understanding the dynamics of landscapes in transition areas is currently a central challenge for environmental management. In this context, this research proposes the spatial delimitation and characterization of the environmental systems in the Northern Mesoregion of Minas Gerais. The methodology integrates multiple geobiophysical variables through advanced geoprocessing techniques, allowing the spatialization of landscape units. The analysis highlights the region's significant physiographic diversity and its systemic interactions. The unprecedented mapping generated consolidates itself not only as an instrument for reading local geophysical evolution but, above all, as strategic support for conservation policies, vulnerability mitigation, and territorial planning in northern Minas Gerais.

Keywords: Integrated Analysis, Mapping, Geoenvironmental Compartmentalization.

Resumo / Resumen

ANÁLISE DA DINÂMICA DA PAISAGEM NO NORTE DE MINAS GERAIS NA PERSPECTIVA DOS SISTEMAS AMBIENTAIS

Compreender a dinâmica das paisagens em áreas de transição é um desafio central para a gestão ambiental atualmente. Neste contexto, esta pesquisa propõe a delimitação espacial e a caracterização dos sistemas ambientais da Mesorregião Norte de Minas Gerais. A metodologia integra múltiplas variáveis geobiofísicas por meio de técnicas de geoprocessamento, permitindo a espacialização das unidades de paisagem. A análise evidencia a expressiva diversidade fisiográfica da região e suas interações sistêmicas. O mapeamento inédito gerado consolida-se não apenas como um instrumento para a leitura da evolução geofísica local, mas, sobretudo, como um suporte estratégico para políticas de conservação, mitigação de vulnerabilidades e ordenamento territorial no norte do estado.

Palavras-chave: : Análise integrada, Mapeamento, Compartimentação geoambiental.

ANÁLISIS DE LA DINÁMICA DEL PAISAJE EN EL NORTE DE MINAS GERAIS DESDE LA PERSPECTIVA DE LOS SISTEMAS AMBIENTALES

Comprender la dinámica del paisaje en zonas de transición constituye un desafío clave para la gestión ambiental contemporánea. En este contexto, la presente investigación propone la delimitación espacial y la caracterización de los sistemas ambientales en la mesorregión norte de Minas Gerais. La metodología integra múltiples variables geobiofísicas mediante técnicas de geoprocementamiento, lo que permite la cartografía espacial de las unidades del paisaje. El análisis pone de relieve la notable diversidad fisiográfica de la región y sus interacciones sistémicas. El mapa resultante, de carácter original, sirve no solo como herramienta para interpretar la evolución geofísica local, sino, ante todo, como apoyo estratégico para las políticas de conservación, la mitigación de la vulnerabilidad y la ordenación del territorio en la región norte del estado.

Palabras-clave: Análisis Integrado, Cartografía, Compartimentación Geoambiental.

INTRODUCTION

Environmental assessment has become established as an essential methodological foundation for understanding the processes that affect the natural environment, whether in areas of scarce human occupation or in densely populated ones. Within Physical Geography, these applications have emerged as a pathway toward establishing a systemic and holistic methodological approach (VICENTE and PEREZ FILHO, 2003; SOUZA and OLIVEIRA, 2011; FERNANDES et al., 2013).

The broadening of thematic strands within Geography, which has been decisive for the discipline's scientific advancement, does not pose an obstacle to conducting horizontal, integrated analyses. On the contrary, this expansion reinforces the foundations needed to grasp the interrelations among the many branches of physical geography (SOUZA, 2015).

From this perspective, the present study examines the geoenvironmental dynamics of the North of Minas Gerais Mesoregion, placing particular emphasis on the study of its environmental systems.

Northern Minas Gerais stands out above all for its singular geographic position, situated within transitional zones. The region mediates between humid Brazil and the semiarid Northeast; between forested domains and areas of open vegetation (encompassing cerrado, campo cerrado, caatinga, dry forests and high-altitude grasslands); and between mountainous relief and planed-surface landscapes (CARNEIRO, 2003; RODRIGUES et al., 2023; COSTA et al., 2024).

The methodology adopted seeks to decipher the interdependence of biophysical variables in order to outline the mosaic of environmental systems in the area, prioritizing an understanding of the integrated whole over a fragmented observation of its components (COSTA et al., 2016). The central aim of this article is therefore to present a proposed mapping of the environmental systems of this mesoregion, while simultaneously discussing the essential attributes that define them.

MATERIALS AND METHODS

STUDY AREA

The study area (Figure 1) comprises the northern portion of Minas Gerais, more specifically the mesoregion of the same name. It covers an area of approximately 128,389 km² across 89 municipalities, located between the parallels 14°13'00" S and 18°00'09" S and the meridians 41°20'19" W and 46°00'16" W (BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS – IBGE, 2022).

Environmentally oriented studies with an integrative approach have played an important role in understanding the flows of matter and energy within ecosystems and geosystems alike (FIGUEIRÓ, 2015; NEVES, 2014). Against this backdrop, the present study endeavors to present northern Minas Gerais from this perspective.

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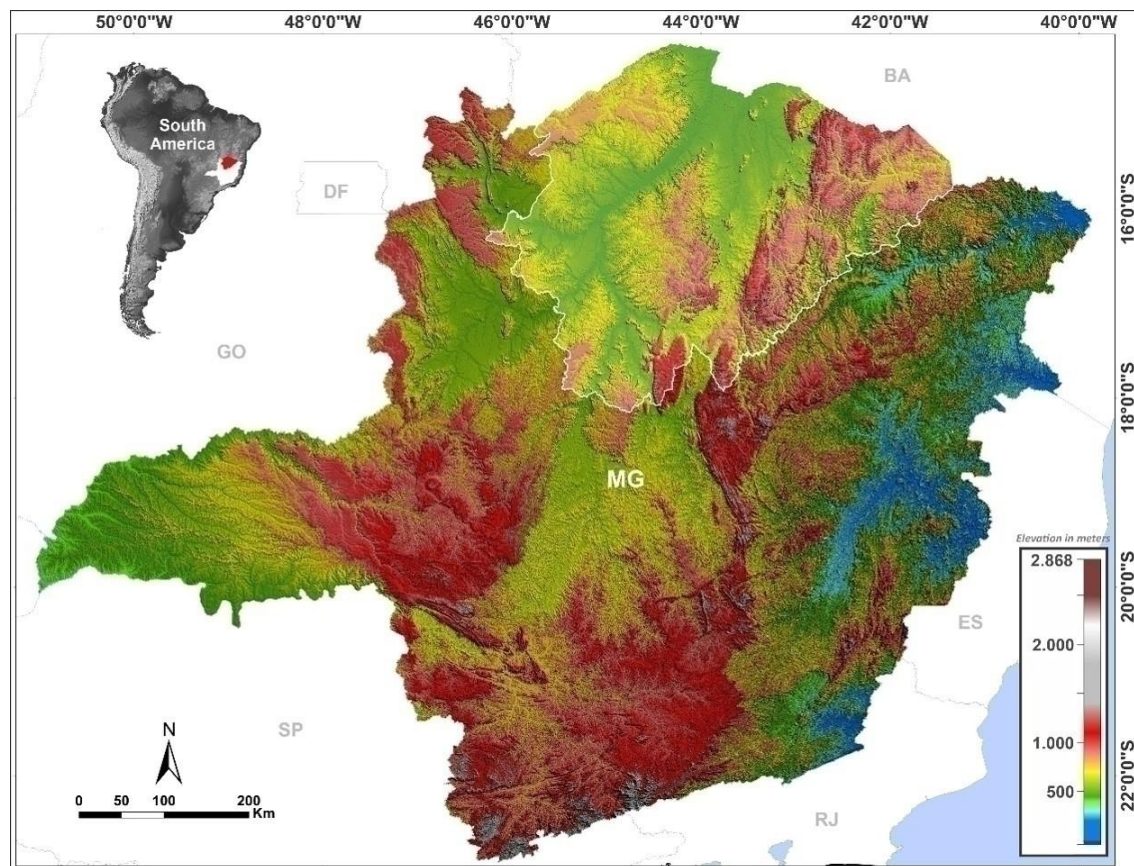


Figure 1 - Location of the study area. Source: Prepared by the authors based on SRTM imagery.

THEORETICAL FRAMEWORK

Studies involving environmental systems have played an important role within the natural sciences, and Geography, in this respect, occupies a singular and unifying position in this process. Authors such as Bertrand (1971), Tricart (1977, 1981), Ross (1994), Christofolletti (1999), Souza (2000), Souza and Oliveira (2011), Santos and Ross (2012), Souza et al. (2012), and Santos and Souza (2014) are examples of studies on this theme, with a focus on integrated analysis for applied physical geography studies.

These analyses are based on the premise that natural components possess a functionality that is intrinsic to each natural environmental system and/or one modified by anthropogenic activities. This is not intended, however, to deny the importance of sectoral studies; on the contrary, it is through them that an understanding of the whole can be reached (SOUZA, 2000; ROSS, 2006; SOUZA and OLIVEIRA, 2011; SANTOS and SOUZA, 2014; COSTA et al., 2016). A systemic approach is necessary to understand how physical environmental entities are structured and function as distinct complex units in themselves (CHRISTOFOLETTI, 1999), conferring on each environmental system its own organization with inherent characteristics.

In this regard, Souza and Oliveira (2011) discuss the importance of interdisciplinarity in environmental studies. To this end, the authors emphasize the need for a perception of the whole as a fundamental requirement of interdisciplinarity, which calls for consideration of the mechanisms that integrate the environment, taking into account its complexity and heterogeneity.

Within this context, geoenvironmental analysis seeks to establish itself as a tool for systemic analysis, since the latter aims to identify and rank environmental systems in order to define the carrying capacity of these various forms of use and occupation.

Santos and Souza (2014) emphasize that environmental systems are identified and ranked according to the interrelationship of their geoenvironmental components, their dimensions, and their characteristics of origin and evolution. In this respect, the concept of landscape takes on significance for the delimitation of these units, owing to the display of uniform, or relatively homogeneous, physiognomic patterns (SANTOS and SOUZA, 2014; COSTA et al., 2016).

Accordingly, the study of environmental systems can be applied to a variety of planning units, whether river basins or administrative units of varying sizes and scales of analysis (Figure 2). What matters most in the analysis is seeking to satisfy the criteria for integration among geobiophysical elements in accordance with the unit of analysis, scale, and territorial dimension involved.

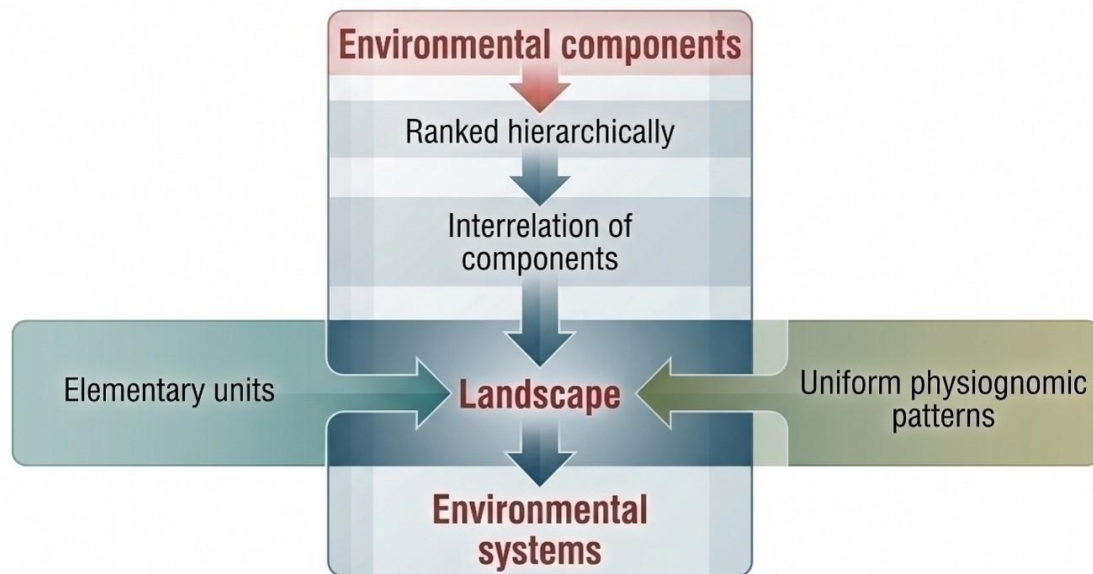


Figure 2 - Methodological synthesis for understanding environmental systems. Source: Adapted from Costa, 2017.

TECHNICAL PROCEDURES

Three stages were carried out to produce this article. In the first stage, an analysis was made of works addressing the region's sectoral components, such as geology, geomorphology, climate, water resources, soils, and vegetation. This stage was based on building the GIS, field verification work, and preliminary basic mapping.

The second stage consisted of cartographic production for the analysis of regional geology and geomorphological compartmentalization, using vector and raster data on geological and topographic aspects. To produce the geological map and identify the morphostructural units, the 2014 geological base map of the State of Minas Gerais was used, at a scale of 1:1,000,000. Topographic elements were analyzed with the aid of raster data from the Shuttle Radar Topography Mission (SRTM), with 30 m spatial resolution. All data were analyzed in a GIS environment, which made it possible to correlate the information using ArcGIS 10.5 software, in addition to CorelDRAW software for producing the block diagram representing the regional geology, as well as fieldwork to carry out photographic recording and to check the maps for cartographic validation. Field activities were carried out between 2019 and 2026, with excursions across all of the environmental systems identified.

Next, the Geomorphological Units were mapped and identified through the analysis of geological and vector data, with contour lines (100 m equidistance) extracted from the radar imagery. The polygons

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were adjusted through manual vectorization and visual interpretation of a color composite formed by raster layers of morphometric parameters. For image interpretation, the scale was set at 1:250,000.

The climate, hydrography, soils, and vegetation maps were prepared in a GIS environment, using the boundary of the North of Minas Gerais Mesoregion as the reference for clipping the base layers. Climate characterization used zoning based on the Thornthwaite moisture index, made available by the Spatial Data Infrastructure of the State System for the Environment and Water Resources (IDE-Sisema) (CARVALHO et al., 2008), together with the maps of annual accumulated precipitation and compensated annual average temperature from the 1991–2020 Brazilian Climatological Normals (INMET, 2022). The two datasets were used in a complementary way: the first to delimit moisture classes, and the second to characterize regional precipitation and temperature patterns. Hydrography was represented based on the main hydrographic stretches of Minas Gerais (IGAM, 2022), and the soil map was prepared from the Soil Map of the State of Minas Gerais (UFV et al., 2010), both available on IDE-Sisema. For vegetation, vector data from the IBGE Natural Resources Mapping, 2026 version, at a scale of 1:250,000, classified by the `legenda_2` field, were used (IBGE, 2026). The vector bases were harmonized to the SIRGAS 2000 reference system, clipped using the Clip tool, and cartographically organized in ArcGIS 10.5.

In the third stage, geological, geomorphological, climatic, hydrographic, pedological, and vegetational information was integrated. It should be noted that geomorphology served as the basis for producing the environmental systems map, given the greater applicability of topography in integrating geoenvironmental variables. Finally, using the full dataset available, the Environmental Systems were identified and mapped.

RESULTS AND DISCUSSION

ENVIRONMENTAL COMPONENTS

Several tectono-stratigraphic domains occur in the North of Minas Gerais region, conditioning the regional geomorphological framework. The two main domains at the regional level are the São Francisco and Mantiqueira structural provinces (ALMEIDA et al., 1981). Part of the São Francisco province is covered by Phanerozoic rocks and sediments belonging to the Sanfranciscana Basin.

In the portion where rocks of the São Francisco Province predominate, the rocks that mainly crop out are those of the Bambuí Basin (Bambuí Group), of Ediacaran–Cambrian age, and of the Sanfranciscana Basin (Areado and Urucuia groups), of Cretaceous age. Within the Mantiqueira province domain, rocks correlated with the Araçuaí Orogen occur, which in turn can be subdivided into the Porteirinha, Salinas-Macaúbas, Rio Doce Magmatic Arc, and Southern Espinhaço tectono-stratigraphic domains (the latter represented by part of the Serra do Cabral and Serra da Água Fria) (Figure 3).

Rocks ranging in age from the Paleoproterozoic, Neoproterozoic, and Mesozoic to the Cenozoic crop out in the study area, reflecting a broad spectrum of lithologies and tectono-stratigraphic domains (MARTÍNEZ, 2007). The following geological (or lithostratigraphic) units crop out: the Northern Espinhaço Basin, the Bambuí Basin, the Macaúbas Basin, the Sanfranciscana Basin, and Cenozoic detrital-lateritic, colluvial-eluvial, and alluvial deposits (CHAVES et al., 2011).

In geotectonic terms, three major compartments occur in the North of Minas Gerais mesoregion: the São Francisco Craton and its Proterozoic covers, the Araçuaí Orogen, and the Phanerozoic covers (Figure 3) (ALMEIDA, 1977; ALKMIN et al., 1993).

The São Francisco Craton is the fundamental entity for understanding most of the geological events that occurred in the region. Cratons correspond to the oldest portions of the continents, more than 1 billion years old, consolidated in pre-Brasiliano times (ALMEIDA, 1977; ALKMIN et al., 1993).

The eastern sector of the research area encompasses the Araçuaí Orogen, a large mountain system that was deformed during the Brasiliano orogeny, around 580 Ma (ALKMIN et al., 1993), where lithologies of the Espinhaço Supergroup and the Macaúbas Group occur, the latter composed of metamorphic rocks generated mainly through glacial action.

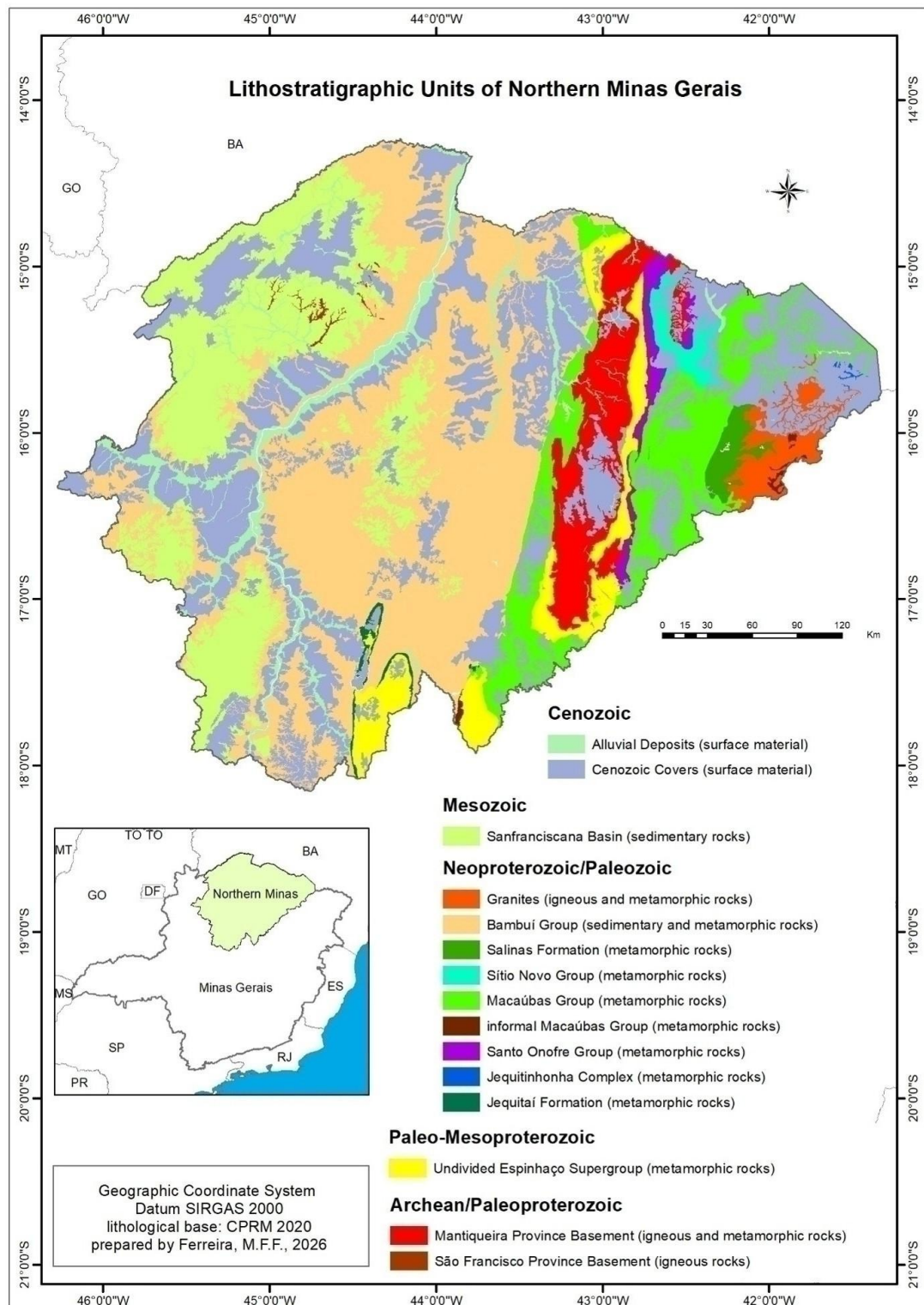


Figure 3 - Lithostratigraphic Units of Northern Minas Gerais. Source: Data compiled from CPRM and organized by the authors.

The Espinhaço Supergroup consists essentially of the Diamantina and Conselheiro Mata Groups, resulting from Mesoproterozoic sedimentation and the subsequent deformation of the layers, with west-directed transport during the Brasiliano Cycle at the end of the Proterozoic (UHLEIN et al., 1986; DOSSIN et al., 1990; CHAVES et al., 2011; CPRM, 2014).

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The São Francisco Supergroup is composed of the Macaúbas and Bambuí groups. The Macaúbas Group is formed by quartzites, phyllites, schists, and conglomerates linked to formation in a cratonic and glacio-marine environment (BRANDT, 1980; CHAVES et al., 2011).

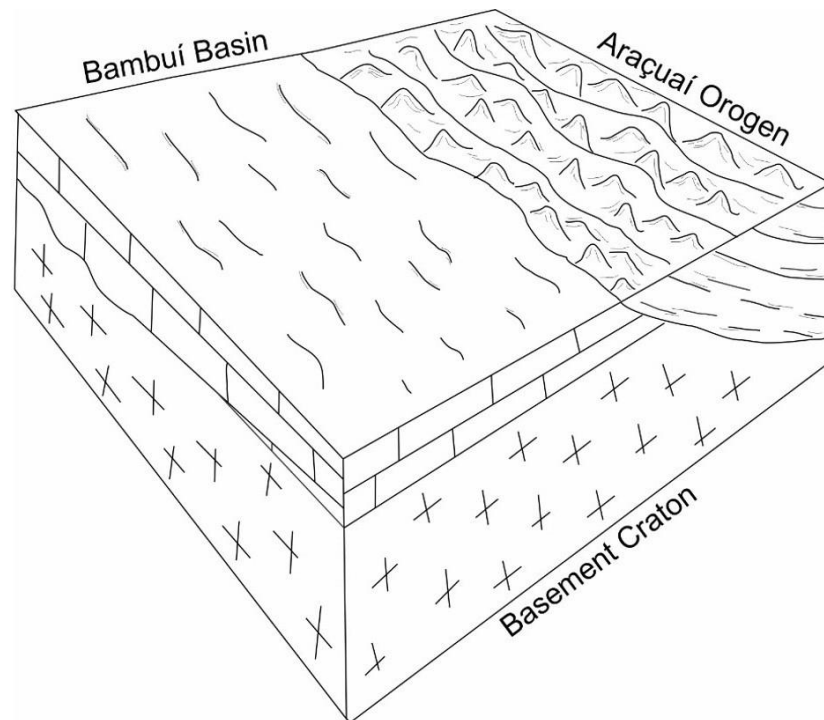


Figure 4 - Block diagram showing the boundary between the São Francisco Craton and the Araçuaí Orogen. Source: Organized by the authors based on Cavalcanti, 2022.

The Bambuí Group is composed, from base to top, of the Sete Lagoas, Serra de Santa Helena, Lagoa do Jacaré, Serra da Saudade, and Três Marias formations (IGLESIAS and UHLEIN, 2009; CPRM, 2014). The rocks of the Bambuí Basin are of great importance for their metallogenic (Pb-Zn-Ag, F), hydrogeological, speleological, and archaeological potential (BRANDT, 1980).

The Sanfranciscana Basin constitutes the Phanerozoic cover of the Bambuí Basin and is subdivided into the Santa Fé, Areado, Urucuia, and Mata da Corda groups; it is partially covered by detrital-lateritic covers and by Cenozoic alluvial and fluvial sediments (CAMPOS and DARDENNE, 1997; CPRM, 2014).

The Cenozoic covers are characterized mainly by the occurrence of detrital-lateritic deposits, colluvial-eluvial covers, and alluvial and fluvial deposits, identified at various points across the research area (CPRM, 2014).

The hypsometry is diverse, with elevations ranging from around 320 m to 1,800 m, which allows for the analysis of landforms at a regional scale. The geomorphological units (Figure 5) are organized into two major groupings: the set of landforms (denudational, circumdenudational, and aggradational) and the morphostructural units, which help clarify the relationship between the geomorphological units and the geological domains present in the mesoregion (COSTA et al., 2024).

Noteworthy is the extensive occurrence of natural cavities (karst), which highlights the importance of carbonate lithologies and their influence on the region's endokarst. Areas of great significance recording these features can be observed in the Peruaçu Caves National Park and the Lapa Grande State Park.

Taken together, these major features in the North of Minas Gerais Mesoregion reveal the dynamics of the regional relief, contributing to the spatial characterization of the landforms that make up the local geomorphological framework.

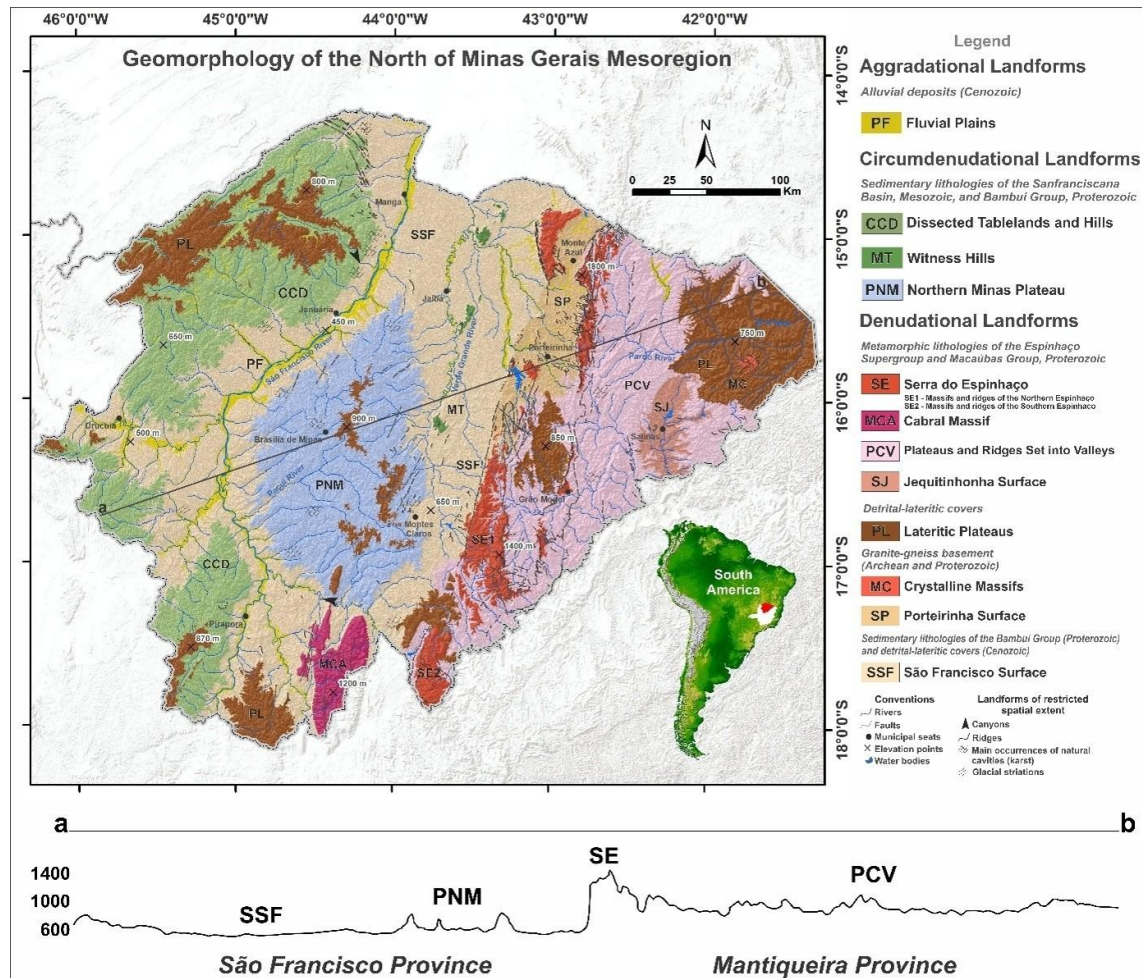


Figure 5 - Geomorphology of the North of Minas Gerais mesoregion. Source: Costa et al., 2024.

The climate characterization of northern Minas Gerais, based on the Thornthwaite moisture index, shows a predominance of conditions with lower water availability. This index is derived from the relationship among the annual values of potential evapotranspiration, water deficit, and water surplus, allowing for the delimitation of climatically homogeneous areas. The zoning was prepared based on the 1961–1990 Climatological Normals, using data from 39 stations of the National Institute of Meteorology (INMET), whose results were spatialized using the cokriging technique (CARVALHO et al., 2008).

In the North of Minas Gerais Mesoregion, the moist subhumid, dry subhumid, and semiarid climate classes are identified (Figure 6). The dry subhumid climate, corresponding to moisture index values between -33.3 and 0, has the widest spatial coverage, extending across much of the central, eastern, and western portions of the study area. The semiarid climate, characterized by indices between -66.7 and -33.3, is concentrated mainly in the northern portion, along the boundary with the state of Bahia. The moist subhumid climate, with a moisture index between 0 and 20, in turn occurs mainly in the southern and southwestern sectors of the mesoregion. This distribution reflects a regional climatic differentiation marked by decreasing moisture conditions toward the north and relatively wetter conditions in the southern portion (CARVALHO et al., 2008).

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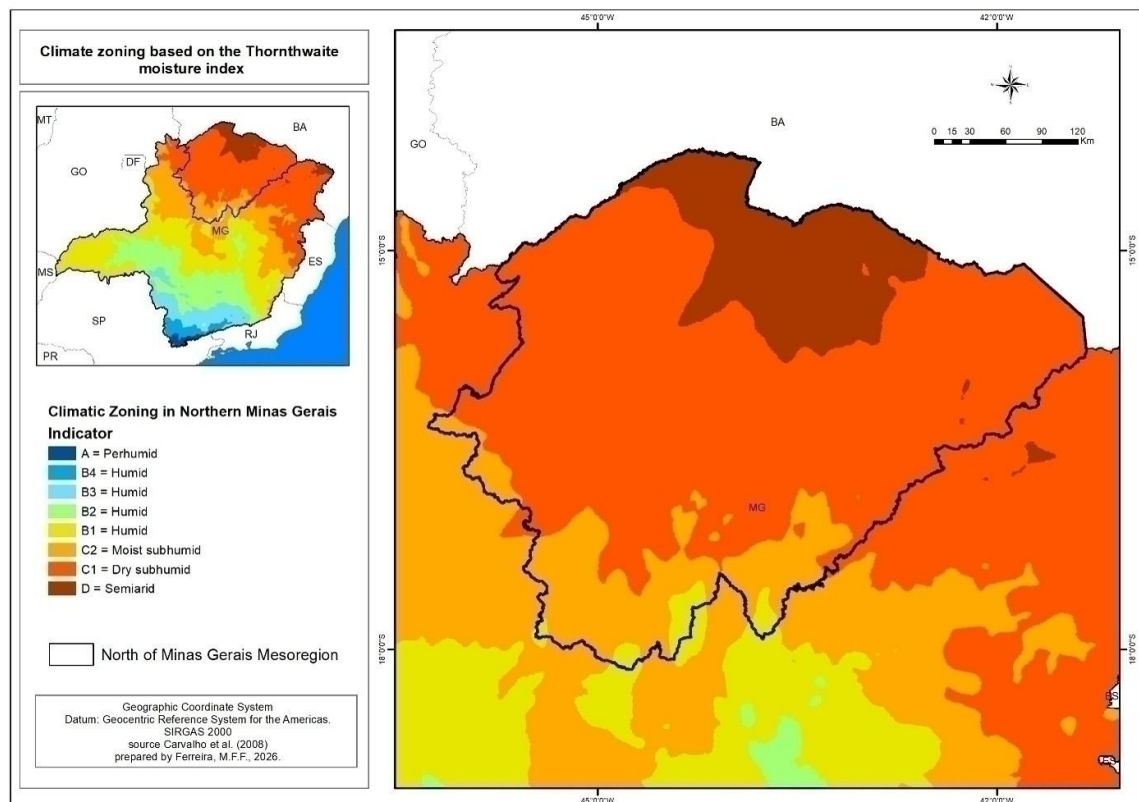


Figure 6 - Climate zoning of the North of Minas Gerais Mesoregion according to the Thornthwaite moisture index. Source: prepared by the authors based on Carvalho et al. (2008), with data made available by IDE-Sisema.

According to the 1991–2020 Brazilian Climatological Normals, annual accumulated precipitation in northern Minas Gerais predominantly ranges between 800 and 1,400 mm. The lowest rainfall totals are observed mainly in the northern portion, while values increase toward the southern and western sectors of the mesoregion (Figure 7, map A) (INMET, 2022).

With respect to compensated annual average temperature, values predominantly range between 22 and 26 °C. The highest average temperatures, mainly between 24 and 26 °C, are observed in the northern portion, while values between 22 and 24 °C occur in the more southerly sectors. A joint analysis of these parameters shows that areas with lower annual precipitation totals, located mainly in the north, also display higher average temperatures, highlighting the climatic differentiation that exists within the mesoregion (Figure 7, map B) (INMET, 2022).

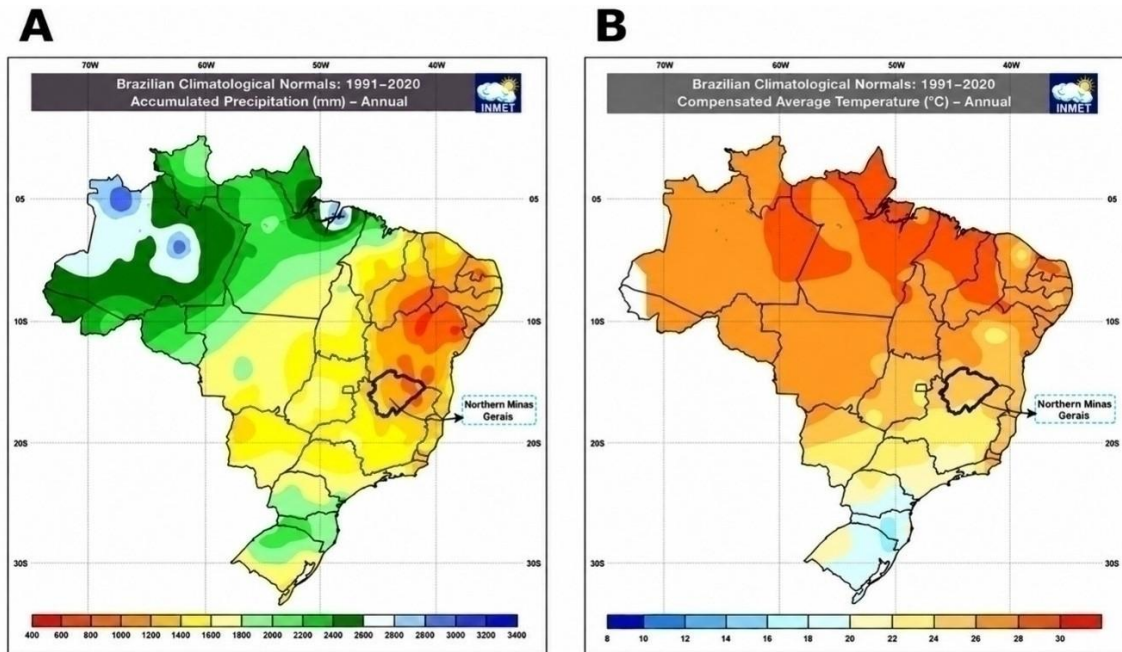


Figure 7 - Distribution of annual accumulated precipitation (A) and compensated annual average temperature (B), highlighting the North of Minas Gerais Mesoregion. Source: adapted from the 1991–2020 Brazilian Climatological Normals (INMET, 2022).

The hydrographic network of the North of Minas Gerais Mesoregion is widely distributed spatially, organized mainly around the São Francisco, Verde Grande, and Pardo rivers, which constitute the main regional drainage axes (Figure 8). The São Francisco River runs through the western sector of the mesoregion and receives numerous tributaries distributed across the central and western portions. Among these tributaries, the Verde Grande River stands out, its course extending through the central part of the region and establishing an important hydrographic connection with the São Francisco basin. In the northeastern portion, the Pardo River stands out, draining part of the municipalities located near the boundary with the state of Bahia (MINAS GERAIS WATER MANAGEMENT INSTITUTE – IGAM, 2022).

The spatial configuration of the drainage shows that the territory of northern Minas Gerais does not display a homogeneous hydrographic organization, being situated across different basins and catchment areas. The network of secondary channels converges toward the main watercourses, forming a drainage system that follows the spatial variations of the relief and crosses different environmental systems.

The soil cover of northern Minas Gerais shows high diversity, related to the differentiation of geological substrates, landforms, and drainage conditions found in the region (FERNANDES et al., 2026) (Figure 9). Despite this diversity, Latosols predominate, occupying approximately 48.8% of the mapped area. Within this group, dystrophic Red-Yellow Latosols stand out, corresponding to around 34.7% of the area and widely distributed across the northern, northwestern, and eastern portions of the mesoregion. Cambisols represent approximately 18.1%, while Neosols cover around 21.6%. Together, these three orders correspond to approximately 88.5% of the region's soil cover. The remaining 11.5% comprises Argisols, Gleysols, Nitosols, Planosols, rock outcrops, water bodies, and other classes of smaller spatial extent. The percentages were calculated by the authors based on data from the Soil Map of the State of Minas Gerais (FEDERAL UNIVERSITY OF VIÇOSA – UFV et al., 2010).

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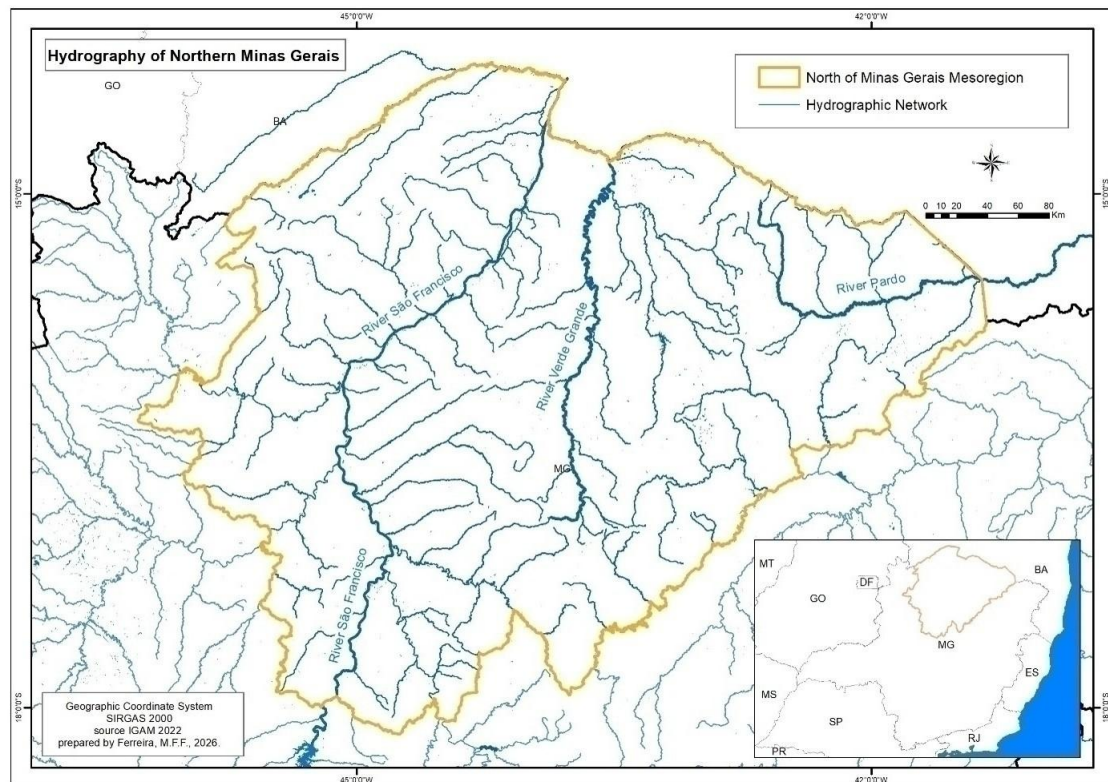


Figure 8 - Hydrographic network of the North of Minas Gerais Mesoregion. Source: prepared by the authors based on IGAM data made available by IDE-Sisema.

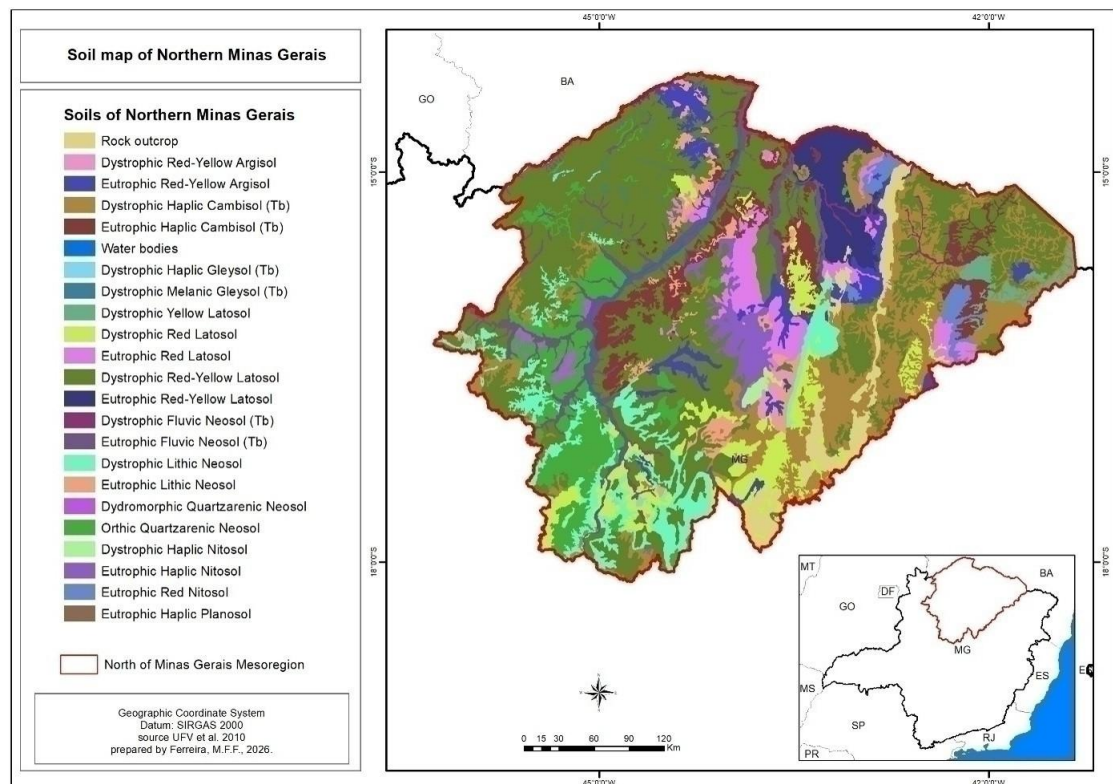


Figure 9 - Spatial distribution of soils in the North of Minas Gerais Mesoregion Source: prepared by the authors based on UFV et al. (2010).

The predominance of dystrophic classes points to the widespread occurrence of soils with low base saturation and natural fertility limitations, an aspect relevant to understanding land use and occupation patterns. Latosols, characterized by a high degree of weathering and generally deep profiles, are generally associated with the more developed and relatively stable geomorphological surfaces. Cambisols and Lithic Neosols, in turn, show less pedogenetic development and are frequently shallower, conditions that can increase susceptibility to erosion processes when these soils are subjected to vegetation removal or inadequate management. Quartzarenic Neosols display a predominantly sandy texture, high permeability, and low water- and nutrient-retention capacity, while Fluvic Neosols and Gleysols occur mainly in valley bottoms and in environments influenced by fluvial dynamics and drainage conditions. Although less widespread, Argisols, Nitosols, Planosols, and rock outcrops are also recorded, reinforcing the pedological heterogeneity of the regional landscape (UFV et al., 2010).

The vegetation cover of northern Minas Gerais displays significant diversity, characterized by the distribution of different savanna and forest formations, as well as contact areas between distinct vegetational sets. According to the IBGE Natural Resources Mapping (2026), savanna formations are widely distributed across the region, with Wooded Savanna standing out as predominant over extensive areas of the northern, western, and eastern portions of the mesoregion (Figure 10). Areas of Grass-Shrub Savanna, Park Savanna, and Forested Savanna are also identified.

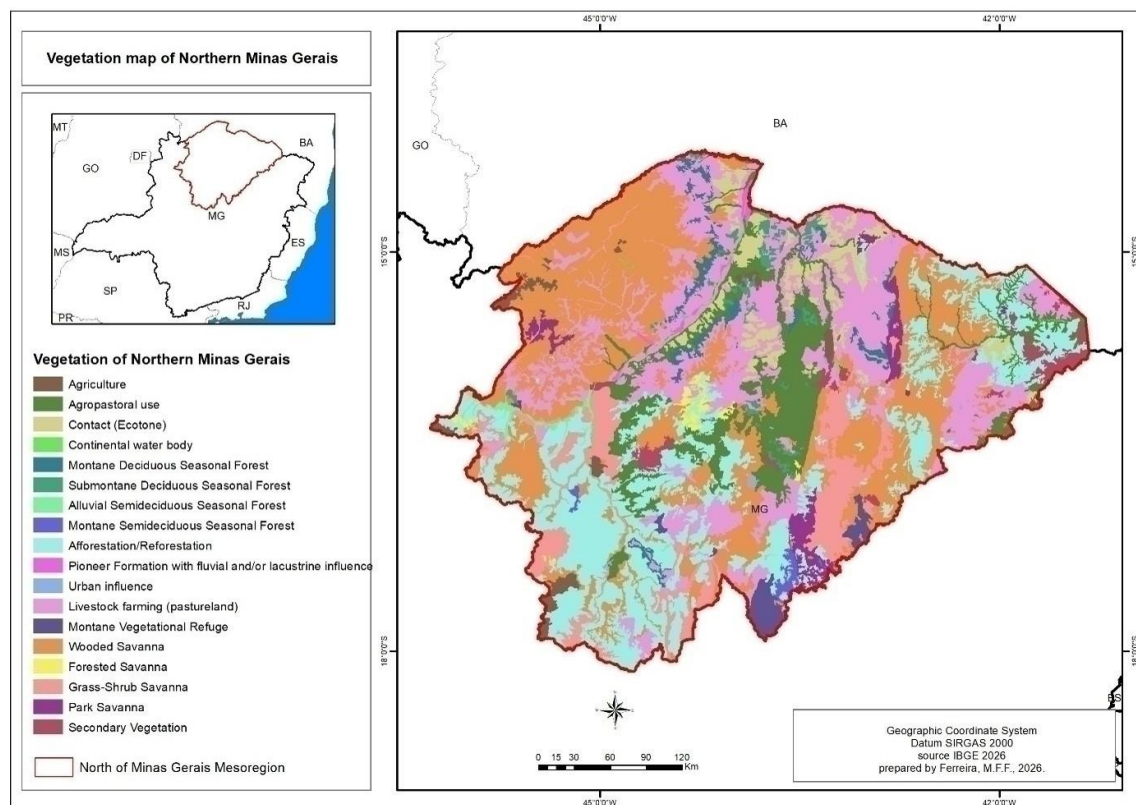


Figure 10 - Spatial distribution of vegetation and areas of anthropic use in the North of Minas Gerais Mesoregion. Source: prepared by the authors based on the IBGE Natural Resources Mapping (2026).

Forest formations are represented mainly by Montane and Submontane Deciduous Seasonal Forests and, to a lesser extent, by Montane and Alluvial Semideciduous Seasonal Forests. Also notable are the ecological contact areas, where different vegetational formations associate with one another, reinforcing the transitional character of the northern Minas Gerais landscape. Pioneer formations with fluvial and/or lacustrine influence have a more restricted distribution and are related to environments subject to surface-water dynamics, while montane vegetational refuges occur in a localized manner. The regional cover also includes extensive areas occupied by pastureland, farming activities, agriculture, and

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afforestation or reforestation, as well as patches of secondary vegetation and areas subject to urban influence (BRAZILIAN INSTITUTE OF GEOGRAPHY AND STATISTICS – IBGE, 2026).

ENVIRONMENTAL SYSTEMS

The integration of landscape components made it possible to delimit ten environmental systems in northern Minas Gerais (Figure 11). Geomorphology was the main criterion guiding this compartmentalization, complemented by an analysis of the relationships among geology, climate, hydrography, soils, and vegetation cover. This approach made it possible to identify individual units with distinct organizational characteristics, summarized in Table 1.

The distribution of these units reveals a differentiation among the western, central, and eastern portions of the mesoregion. In the western sector, the Dissected Tablelands and Hills and the São Francisco Sertões stand out, characterized by broader surfaces, a predominance of Latosols, and a significant presence of savanna formations and areas of agropastoral use. In the central portion, the Planalto Norte-mineiro (Northern Minas Plateau) stands out, associated mainly with carbonate rocks of the Bambuí Group, karst relief, and the occurrence of Latosols, Lithic Neosols, rock outcrops, Deciduous Seasonal Forest, and savanna formations.

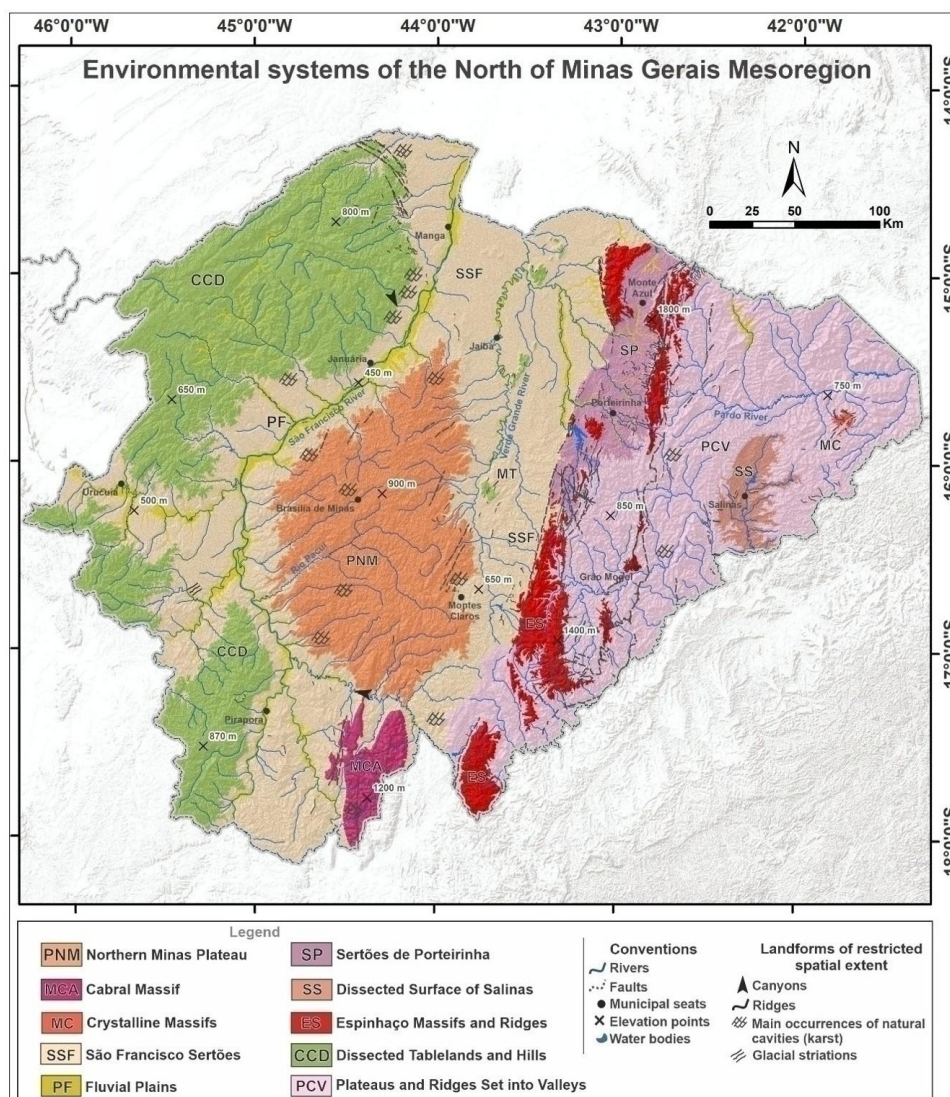


Figure 11 - Environmental systems of the North of Minas Gerais mesoregion. Source: prepared by the authors.

In the eastern portion, systems with more dissected and rugged relief predominate, represented by the Sertões de Porteirinha, the Dissected Surface of Salinas, the Plateaus and Ridges Set into Valleys, and the Crystalline Massifs. In these units, the greater compartmentalization of the relief is associated with the occurrence of Cambisols, Lithic Neosols, and Argisols, as well as savanna and forest formations and areas of secondary vegetation. The Espinhaço Massifs and Ridges and the Cabral Massif stand out for their higher elevations, quartzitic substrates, the presence of poorly developed soils and rock outcrops, and the occurrence of montane vegetational refuges.

The Fluvial Plains have a linear configuration and mainly follow the São Francisco River and its tributaries. Formed by Cenozoic alluvial deposits, these units are associated with Fluvic Neosols, Gleysols, and pioneer formations with fluvial or lacustrine influence. Their dynamics are directly related to variations in watercourses, drainage conditions, and flooding processes, as observed in the São Francisco River floodplain in the municipality of Pirapora (Figure 12E).

The São Francisco Sertões, the Planalto Norte-mineiro, and the Dissected Tablelands and Hills have great regional expression and are marked, to a greater or lesser degree, by the occurrence of karst features. The dissolution of the carbonate rocks of the Bambuí Group favors the formation of caves, dolines, natural arches, and other surface and subterranean features. The diversity of these landscapes can be observed in the dissection features of the Planalto Norte-mineiro, at the Ponte de Pedra (Stone Bridge), in the Lapa Grande State Park, in the cavities of the Jequitaiá region, and at the Janelão, located in the Peruaçu Caves National Park (Figure 12A–D).

Karst environments play an important role in the storage and circulation of groundwater and hold significant ecological, cultural, archaeological, and scenic relevance. Weathering of the carbonate rocks can also contribute to calcium availability and to differentiation in soil chemical properties, influencing vegetation patterns and agricultural use conditions. These characteristics, together with the presence of caves, cliffs, natural arches, and other landforms, give these environments potential for the development of geotourism and activities aimed at conserving the natural heritage (COSTA et al., 2023; MORO et al., 2024).

The integrated analysis shows that environmental potentials and limitations are not homogeneously distributed across northern Minas Gerais. The flatter surfaces with deep soils present more favorable conditions for certain agropastoral uses, while the dissected reliefs, karst environments, mountainous massifs, and fluvial plains require greater attention owing to their susceptibility to erosion processes, their importance for water recharge, the singularity of their vegetation cover, or the influence of flooding.

In this context, Conservation Units (UCs) play a fundamental role in maintaining regional ecosystem services. The effectiveness of protected areas as a conservation strategy can vary according to their location and the pressures present in the surrounding area. Regions that are difficult to access or have low agricultural suitability may have lower market value and remain subject to less intense anthropogenic pressures.

Although they hold high value for biodiversity conservation, the creation and management of Conservation Units should take into account the systems of greatest ecological relevance and those subject to higher risks of external interference. In this context, the possible effects of climate change on water availability, vegetation cover, and the functioning of the identified environmental systems should also be considered (CLEMENTE et al., 2020; SILVA et al., 2024).

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Environmental System	Geology and geomorphology	Predominant soils	Predominant vegetation cover
Fluvial Plains (PF)	Cenozoic alluvial deposits; aggradational valley-bottom landforms.	Fluvic Neosols and Gleysols (associated with flooding dynamics and hydromorphism).	Pioneer formations with fluvial/lacustrine influence (riparian and gallery forests) and Alluvial Seasonal Forest.
Dissected Tablelands and Hills (CCD)	Rocks of the Sanfranciscana Basin and the Bambuí Group; circumdenudational landforms characterized by tabular relief and dissected slopes.	Latosols (on flat tops) and Haplic Cambisols (on dissected slopes).	Wooded Savanna, Forested Savanna, and ecotonal contacts (areas with a strong presence of pastureland).
Planalto Norte-mineiro (PNM)	Carbonate rocks of the Bambuí Group; surfaces with strong structural control and karst relief (caves and dolines).	Latosols and Lithic Neosols associated with carbonate rock outcrops.	Deciduous Seasonal Forest (Dry Forests) and Savanna.
São Francisco Sertões (SSF)	Cenozoic detrital-lateritic covers; planation surfaces comprising broad denudational landforms.	Dystrophic Red-Yellow Latosols and Cambisols.	Wooded Savanna (Cerrado–Caatinga transition) and extensive areas of agropastoral use.
Sertões de Porteirinha (SP)	Sedimentary lithologies of the Bambuí Group and detrital-lateritic covers; dissected surfaces at the margins of higher relief and ridges.	Haplic Cambisols and Neosols.	Savanna and patches of Seasonal Forest, with a high degree of anthropization.
Dissected Surface of Salinas (SS)	Lithologies of the Macaúbas Group (Araçuaí Orogen); strongly dissected denudational landforms.	Cambisols and Argisols (environments with higher erosion susceptibility).	Wooded Savanna and ecotonal contacts.
Plateaus and Ridges Set into Valleys (PCV)	Metamorphic lithologies of the Espinhaço Supergroup and Macaúbas Group; denudational landforms with rugged relief and valleys deeply incised by the drainage network.	Dystrophic Lithic Neosols and Cambisols.	Wooded Savanna and secondary vegetation at various stages of regeneration.
Espinhaço Massifs and Ridges (ES)	Quartzitic ridges of the Espinhaço Supergroup; high-elevation denudational relief (up to 1,800 m).	Lithic Neosols, Quartzarenic Neosols, and prominent rock outcrops.	Montane Vegetational Refuges (high-altitude Rupestrian Grasslands) and Savanna.
Cabral Massif (MCA)	Metamorphic lithologies associated with the Espinhaço Supergroup; mountainous relief and massifs with elevations above 1,200 m.	Lithic Neosols and rock outcrops.	Montane Vegetational Refuges and strips of Seasonal Forest.
Crystalline Massifs (MC)	Granite-gneiss basement (Archean and Proterozoic) of the Mantiqueira Province; denudational landforms supporting massif relief.	Cambisols and Lithic Neosols.	Wooded Savanna and Montane Semideciduous Seasonal Forest.

Table 1 - Summary of the components of the environmental systems of northern Minas Gerais. Source: prepared by the authors



Figure 12 - A: Dissection features in the foreground, with karst massifs in the background, on the Planalto Norte-mineiro; B: Karst represented by the Ponte de Pedra (Stone Bridge), in the Lapa Grande State Park; C – cavities in the Jequitai region, at Curral de Pedras; D – view of the Janelão, in the Peruaçu Caves National Park; E – fluvial plain of the São Francisco River, in the municipality of Pirapora. Source: organized by the authors.

CONCLUSION

In light of the results obtained, it is important to highlight the contribution of geoenvironmental studies to landscape analysis, with emphasis on how natural components such as relief, hydroclimatology, soils, and vegetation can produce differentiated responses, culminating in the classification and ranking of environmental systems.

Understanding this dynamic is essential for supporting integrated environmental analyses, so that the outcome is not merely diagnostic but so that the data analysis can generate information important for territorial planning in protected areas, mitigating possible environmental impacts in their surroundings.

It is worth highlighting the need for further studies to identify the subsystems of the area, so that applications can be directed with a focus on the potentialities and limitations of each unit, whether for maintaining ecosystem services, planning urban expansion areas, or assessing the potential for agricultural activities.

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DATA AVAILABILITY

Not applicable.

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Costa, L.R.F. - The author contributed to the design, methodological conception, mapping, and writing
Ferreira, M.F.F. - The author contributed to the design, mapping, and writing
Freitas, L.D.A.S. - The author contributed to the design, mapping, and writing

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The authors declare that there is no conflict of interest.

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Use of AI

No Artificial Intelligence tools were used.

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