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Papers

Mapping and Analysis of the Landscape Units in the Brazilian Humid Tropics: An Integrated Study in the Municipality of Rio Claro (Rio de Janeiro, Brazil)

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Abstract

The Serra do Mar mountain system, which is a fundamental region for Atlantic Forest, has high environmental and geomorphological relevance for the southeast of Brazil. It is a territory that is characterized by an intense morphoclimatic dynamic, topographic contrasts, and recurrent hydrogeomorphological events. Despite these particularities, there is a lack of detailed studies and systemic cartographic production aimed at fully understanding its landscapes and its dynamic. The present study aims to carry out mapping and cartographic analysis of the landscape units in the municipality of Rio Claro, located in the state of Rio de Janeiro, in the Fluminense area of the Serra do Mar. The adopted methodology was based on the integration of physical-geographic and socioenvironmental variables – precipitation, mean annual temperatures, lithology, altitude, slope, relief forms, land use and coverage, and soil types – through geoprocessing and spatial analysis techniques. This approach enabled the mapping of the landscape units on three hierarchical levels, enabling understanding of their structure, dynamic, and inter-relations. The resulting cartographic synthesis constitutes a detailed representation of the landscape and offers a consistent basis for future studies aimed at hydrogeomorphological risk analysis, environmental planning, and territorial planning. Furthermore, by enabling the transition of more generic data to a level of detail compatible with the municipal scale, the employed methodology demonstrates high potential for replicability in other areas of the Serra do Mar and in regions with similar climatic and morphostructural conditions.

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INTRODUCTION

In recent years, landscape cartography studies have consolidated essential methodological approaches for the identification and definition of landscape units. By articulating multiple methods, techniques, and analytical procedures they provide qualified support to territorial and environmental management (Medeiros *et al.*, 2022; Rosa; Ferreira, 2022; Schiattarella *et al.*, 2024; Brito *et al.*, 2023; Medeiros *et al.*, 2023; Salinas; Medeiros, 2024; *Menjibar-Romero et al.*, 2024; Cribari *et al.*, 2025). These studies have become especially relevant with the intensification of anthropogenic activities (Simensen *et al.*, 2018; Albuquerque *et al.*, 2023) and the socioenvironmental impacts of climate change (Salinas *et al.*, 2019; IPCC, 2023), especially in areas of elevated geomorphological complexity, reinforcing the central role of territorial and environmental planning.

As a theoretical-methodological basis, Landscape Geoecology interprets the landscape as a geosystem based on a holistic, inter- and transdisciplinary approach, which integrates physical-geographic and socioeconomic aspects. In this conception, the landscape is understood as a complex, open spatial-temporal system, resulting from the interaction between society and the planet's natural physical processes, endowed with its own structure, operation, dynamic, and evolution, the limits and hierarchies of which are subject to classification and analysis (Salinas *et al.*, 2019).

Within this perspective, various methodological proposals for the classification of landscape units have been developed, varying according to research aims and territorial particularities (Giné *et al.*, 2019). However, many procedures have the potential for broad application (Alcántara-Manzanares; Muñoz-Álvarez, 2015), especially with the advances in Geographic Information Systems and geospatial technology (Qin *et al.*, 2024), making methodological adaptation to specific contexts fundamental to ensuring coherence between the results and the analyzed landscape (Mücher *et al.*, 2010; Herr *et al.*, 2024). In this process, the vision of the researcher takes on a central role, both in the methodological adaptation and the interpretation of the results.

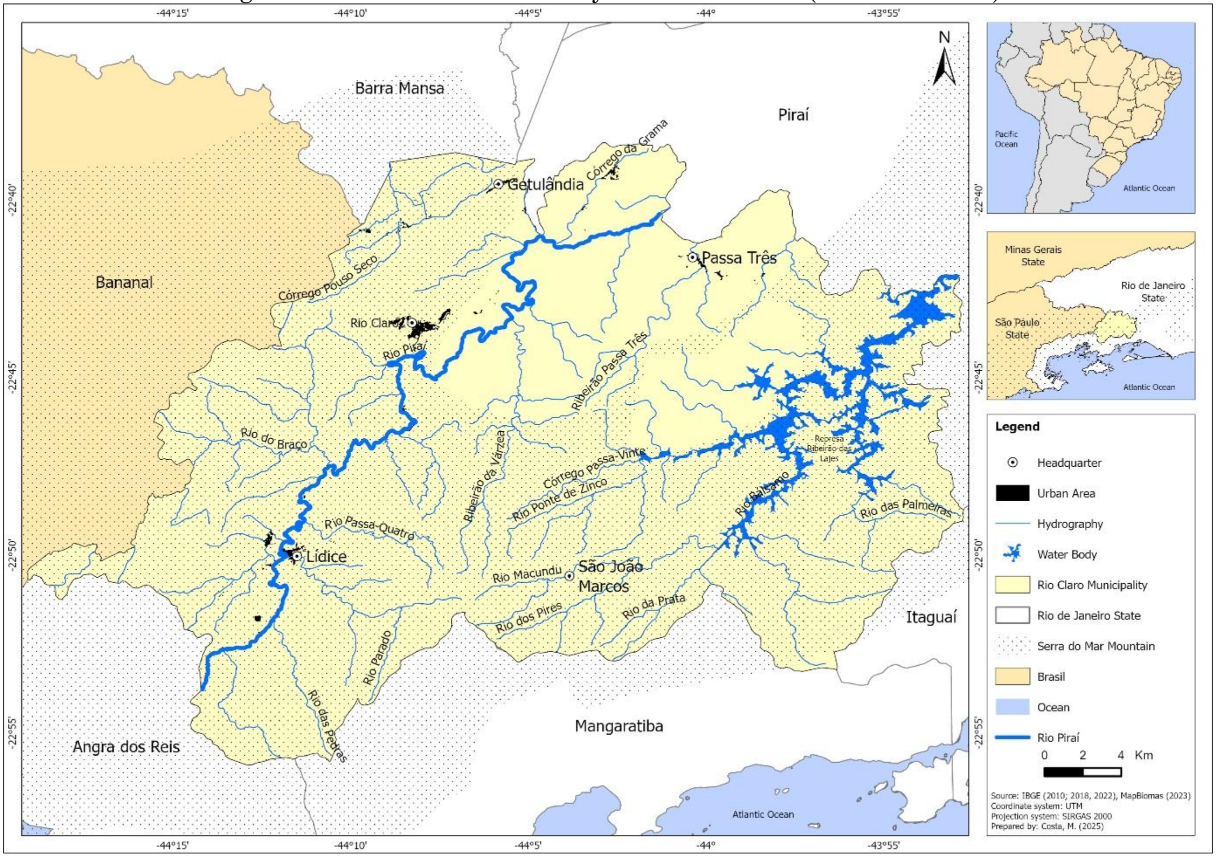
In the context of the study area, the municipality of Rio Claro (Rio de Janeiro, Brazil), it can be observed that there is a lack of maps on a detailed scale that enable an integrated analysis of the landscape. Inserted among the scarps of the Serra do Mar, the region has a complex set of geological faults and geomorphological features, with strongly dissected relief and accentuated slopes (Veloso *et al.*, 2025). In the humid tropics, high levels of rainfall are a structuring factor on the landscape, influencing relief modeling, vegetation distribution, soil development, and the recurrence of extreme hydrogeomorphological events.

In light of the above, the present study aims to develop a detailed map of the landscape units of the municipality of Rio Claro through the integration of physical-geographic and socioenvironmental data, with the aim of adaptation and operationalization of methodologies for mountain and hill contexts in the humid tropics of southeast Brazil. It is thus intended to provide methodological, cartographic, and analytical support that contributes to the understanding, planning, and management of the landscape, considering its natural complexity and the transformations resulting from anthropic action.

MATERIALS AND METHODS

Study area

Figure 1 – Location of the study area: Rio Claro (Rio de Janeiro)



Source: The authors (2026).

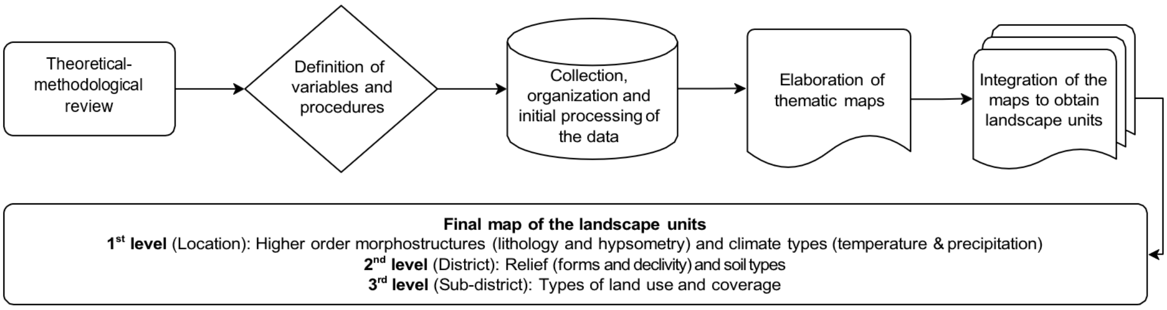
The municipality of Rio Claro (Figure 1), located in the south of the state of Rio de Janeiro, between latitudes 22º38'26" S and 22º55'54" S and longitudes 44º19'05" W and 43º52'52" W, is part of the geomorphological domain of the Serra do Mar mountain system. The municipal territory is like a transition zone between the mountainous landforms of the Serra do Mar, which are predominant in the south and southeast areas, where altitudes exceed 1,600 m, and the depressions of the middle Vale do Paraíba do Sul (Paraíba do Sul Valley), towards the north, where a minimum altitude of approximately 362 m has been recorded. This geographic position gives the municipality a highly heterogenous landscape resulting from the articulation between mountain areas, dissected hills, and fluvial plains.

The municipal territory has an area of approximately 837 km² and an estimated population of 17.9 thousand inhabitants (IBGE, 2025), which results in a very low demographic density and a predominance of natural environments. The municipality is inserted in a morphoclimatic domain of "mares de morros", or "seas of hills" (Ab'Sáber, 2003), which is characteristic of the humid tropics of the Brazilian Southeast, and has high levels of annual rainfall, with values exceeding 1,800 mm (Costa *et al.*, 2024). The elevated level of rainfall is associated, to a great extent, with the strong orographic influence exerted by the slopes of the Serra do Mar (Mendes *et al.*, 2015), conditioning the structure, dynamic, and evolution of the landscape.

Study Design

The methodological construction of this study was based on a theoretical-conceptual review of landscape cartography and its forms of data integration, enabling the analysis of consolidated methodological references and recent contributions (Ramón; Salinas, 2012; Salinas; Ramón, 2013; Gómez-Zotano *et al.*, 2018; Frolova, 2019; Giné *et al.*, 2019; Prodanova, 2021; Mateo *et al.*, 2022; Medeiros *et al.*, 2022; Brito *et al.*, 2023; Medeiros; Santos, 2024). This stage guided the definition of the analyzed variables and the methodological procedures adopted in the study (Figure 2).

Figure 2 – Flow diagram of the general study design



Source: The authors (2026).

Based on this review, the organization and analysis of the study area databases were carried out, defining the variables to be mapped. Thematic maps of the main physical-geographic and socioenvironmental components were elaborated – climate, lithology, altitude, slope, relief forms, land use and coverage, and soils. The integration of these variables provided a basis for elaboration of the landscape cartography, the results of which are discussed and presented throughout this work.

Elaboration of the Thematic Maps

Thematic maps were elaborated based on open-access, secondary data from national and international institutions (Table 1). The spatial information was organized and integrated in a GIS environment, using R (R Core Team, 2024, version 4.4.0) to process climatic data and ArcGIS Pro (ESRI, 2023, version 3.2.0) for the elaboration of the thematic maps.

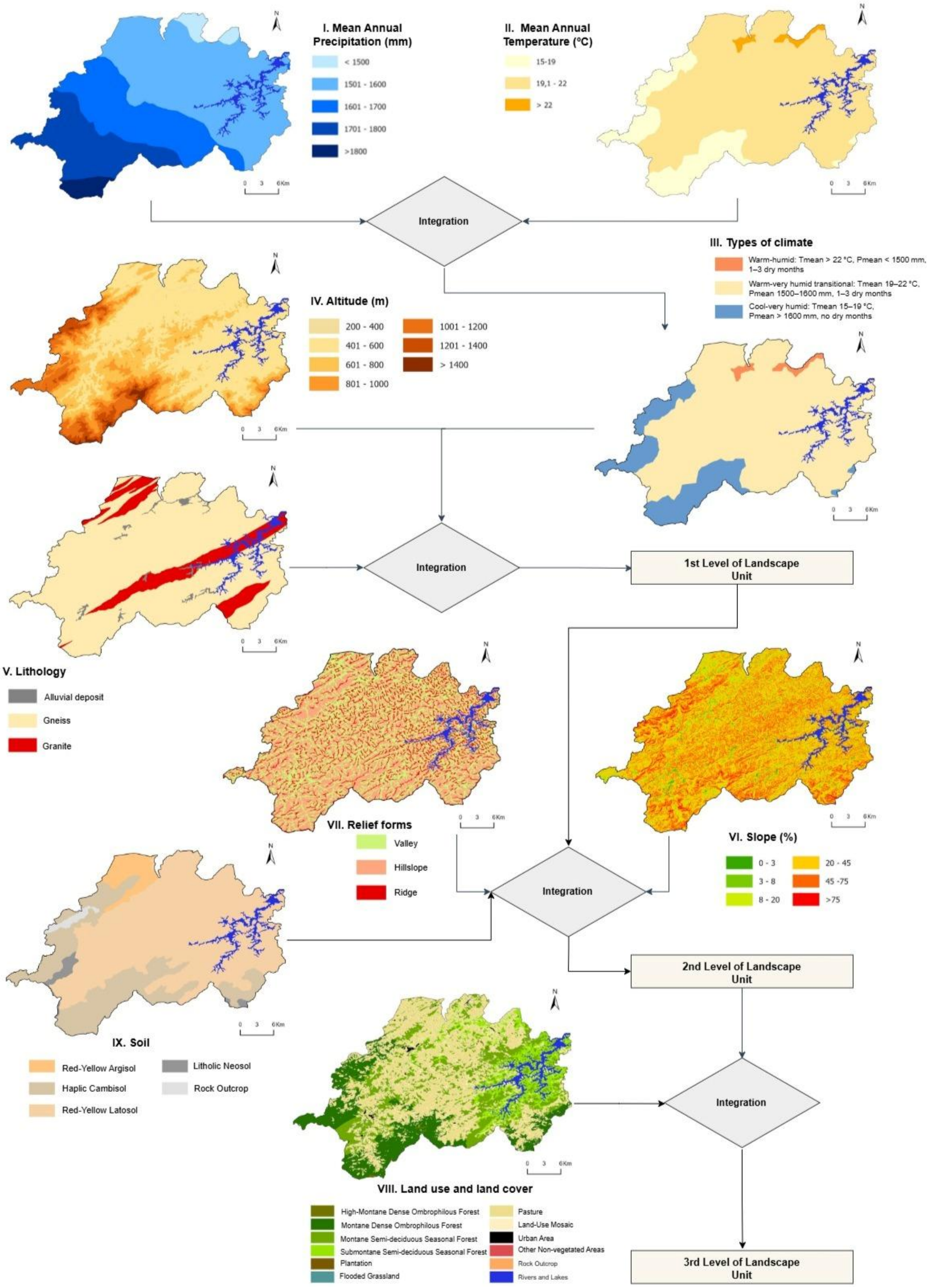
Table 1 – Description of the procedures adopted to elaborate the thematic maps

Information	Source	Scale/ Resolution	Data treatment	Final classes
Mean Annual Precipitation (1990-2022)	CHIRPS 2.0 (Funk *et al.*, 2015)	5 km	Calculation of the mean of the annual totals in the R environment, with value extraction by pixel. Spatialization carried out through IDW interpolation on ArcGIS Pro. Note: The period was selected as it had previously undergone accuracy assessment by the authors.	<1,500 mm 1,501-1,600 mm 1,601-1,700 mm 1,701-1,800 mm >1,800 mm
Mean Annual Temperature (1979-2013)	CHELSA (Karger *et al.*, 2017)	1 km	Extraction of the value of each pixel in R and spatialization through IDW interpolation on ArcGIS Pro. Note: This dataset has the highest spatial resolution available and was corrected by the authors based on independent stations, considering the effects of orographic wind.	15-19 ºC 19.1-22 ºC >22 ºC
Lithology	CPRM (2016)	1:400,000	Identification of the dominant lithology based on the description of the technical note associated with the "Geological Unit". Simplified final map elaborated on ArcGIS Pro.	Gneiss Granite Alluvial deposit
Altitude	MDE Copérnicus (ESA, 2023)	30 m	Reclassification of the digital elevation model and elaboration of the final map on ArcGIS Pro.	200-400 m 401-600 m 601-800 m 801-1,000 m 1,001-1,200 m 1,201-1,400 m >1,400 m
Slope	MDE Copérnicus (ESA, 2023)	30 m	Calculation of slope inclination and elaboration of the final map on ArcGIS Pro.	0-3 % 3-8 % 8-20 % 20-45 % >45 %
Relief forms	MDE Copérnicus (ESA, 2023)	30 m	Automatic extraction of the relief forms on ArcGIS Pro. The following classes were initially generated, subsequently reclassified: Valleys (flat, hollow, footslope, valley, and pit). Slopes (spur, slope) and Peaks (peak, ridge, shoulder). Manual adjustments were made based on the researchers' experience and expertise.	Valleys Slopes Peaks
Land use and coverage	Map Biomas (2023) and INEA (2022)	10 m	Integral use of the data from Map Biomas, with the exception of the forest vegetation class, reclassified based on the potential vegetation of INEA. Processing and final map carried out on ArcGIS Pro.	Dense High-Montane and Montane Ombrophilous Forest, Semi-deciduous Seasonal Montane and Sub-Montane Forest, Silviculture, Flooded field, Pasture, Mosaic of Uses, Urbanized area, Other non-vegetated areas, Rocky outcrops and Rivers and Lakes.
Soils	Embrapa (1999)	1:500,000	Integral use of the data made available by Embrapa. Final map elaborated on ArcGIS Pro.	Red-yellow Acrisol, Haplic Cambisol, Red-yellow Latosol, Litholic Neosol, and Rocky outcrops.

Source: The authors (2026).

Spatial Integration for the Elaboration of Landscape Cartography

Figure 3 – Flow diagram of the landscape cartography integration



Source: The authors (2026).

Data integration in a GIS environment can follow distinct methodological paths according to the nature of the information used (raster or vector), which conditions the adopted spatial analysis procedures (Chang, 2020). In this study, the integration was carried out through the crossover of vectorial layers (Figure 3), using the Union and Eliminate functions of ArcGIS Pro, as discussed by Trombeta (2019) and Brito (2023). The data originally in raster format were reclassified into the classes defined in Table 1 and subsequently converted to vector format using the Raster to Polygon function in ArcGIS Pro, under its default settings, with boundary line simplification and generation of multiple polygons, in order to enable subsequent integration among layers.

The Eliminate function was applied after each crossover with the aim of generalizing polygons with an area of less than 0.04 km², ensuring the Minimum Mapping Unit (MMU). This threshold was defined to ensure compatibility with the adopted work scale (1:50.000), thus allowing an appropriate level of detail to ensure legibility, based on Priego *et al.*, (2011) and on the researchers' empirical knowledge of the study area.

All data were georeferenced in the geographic coordinate system, in decimal degrees, using the SIRGAS 2000 datum, zone 23S.

The cartographic crossover sequence (Figure 3) followed a hierarchical-taxonomic logic of the landscape. The first level integrated elements of macrostructural control, such as climate, altitude and lithology, these being higher order determinants of the morphostructure in the context of the humid tropics. On the second level, the crossover of geomorphological variables (relief forms and slope), associated with the pedological characterization, enabled the discrimination of the second order units, linked to the morphology and dynamic of the geosystems. Finally, the integration of the land use and coverage layer enabled identification of the incidental anthropic attributes in each unit, demonstrating pressures, transformations, and states of conservation relevant to environmental planning and management.

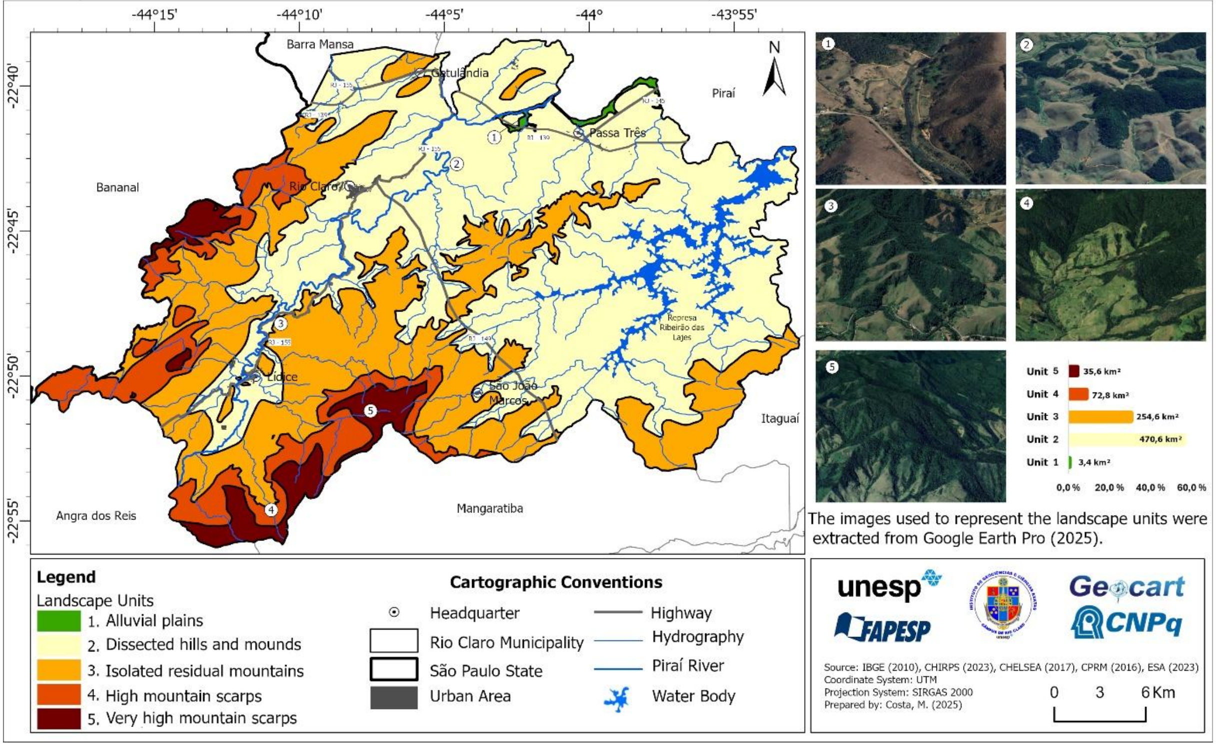
RESULTS AND DISCUSSION

The results obtained from the elaboration of landscape cartography enabled the delimitation and characterization of 5 first level landscape units (locations), 14 second level units (districts), and 31 third level units (sub-districts), demonstrating the environmental complexity and heterogeneity of the municipality of Rio Claro.

First level units

Compartmentation of the first-level landscape units in the municipality of Rio Claro (Figure 4) results from the integration of the elements of macrostructural control that organize the environmental operation of the territory. This integration enabled the identification of five units, the spatial distribution of which reflects the contrasts between climate types, altitude variations, and the dominant lithology. These units constitute the structural framework of the municipal landscape, serving as a basis for hierarchical differentiation and for understanding its dynamic and evolution.

Figure 4 – 1st level landscape units in the municipality of Rio Claro (Rio de Janeiro, Brazil)



Source: The authors (2026).

Unit 1, which corresponds to the alluvial plains (Figure 5), is the least representative in territorial extension, occupying around 3.4 km² (0.4%) of the municipality. It is located on the lowest sections of the relief, with altitudes below 400 m, especially to the north and northeast of Rio Claro, and is characterized by flat and gently undulating surfaces formed through the accumulation of fluvial sediments along the Piraí River and its tributaries. From the geological point of view, these areas lay on recent alluvial deposits that discontinuously cover the regional gneiss basement. The low energy of the relief, associated with tropical humid climate conditions, with high temperatures and a short dry period (1 to 3 months), favors recurrent flooding, which plays a central role in the sedimentary dynamic and the morphological configuration of these plains (Leopold *et al.*, 1964; Tucci, 2007). This elevated environmental dynamic makes the unit particularly sensitive to anthropic interventions and relevant to analyses on land use and hydrogeomorphological risk management.

Figure 5 – Iconographic records of the alluvial plains (Unit 1) of the municipality of Rio Claro (Rio de Janeiro, Brazil). a: Piraí River; b: Alluvial plain associated with an arm of the Piraí River, in transition to less flat areas of relief

Source: The authors (2026).

Unit 2, which has a greater territorial extension and corresponds to dissected hills and mounds (Figure 6), occupies approximately 470.6 km², the equivalent to 56.2% of the area of the municipality, making it the dominant compartment in the environmental arrangement of Rio Claro. Its configuration results from the combination between intermediate altitudes (401–600 m) and mild but very humid climate conditions, characterized by a short dry period, estimated at between one and three months. This set of factors establishes an environment with high potential energy and an intense hydric dynamic, representative of a large part of the so-called “Brasil Atlântico” (Atlantic Brazil), as discussed by Silva (2022).

From the geological point of view, the gneiss basement predominates, with occasional occurrences of granite outcrops. It is, therefore, the unit that sustains the predominant physical structure of the municipal territory and conditions a large part of the interactions between the natural environment and the use of the land.

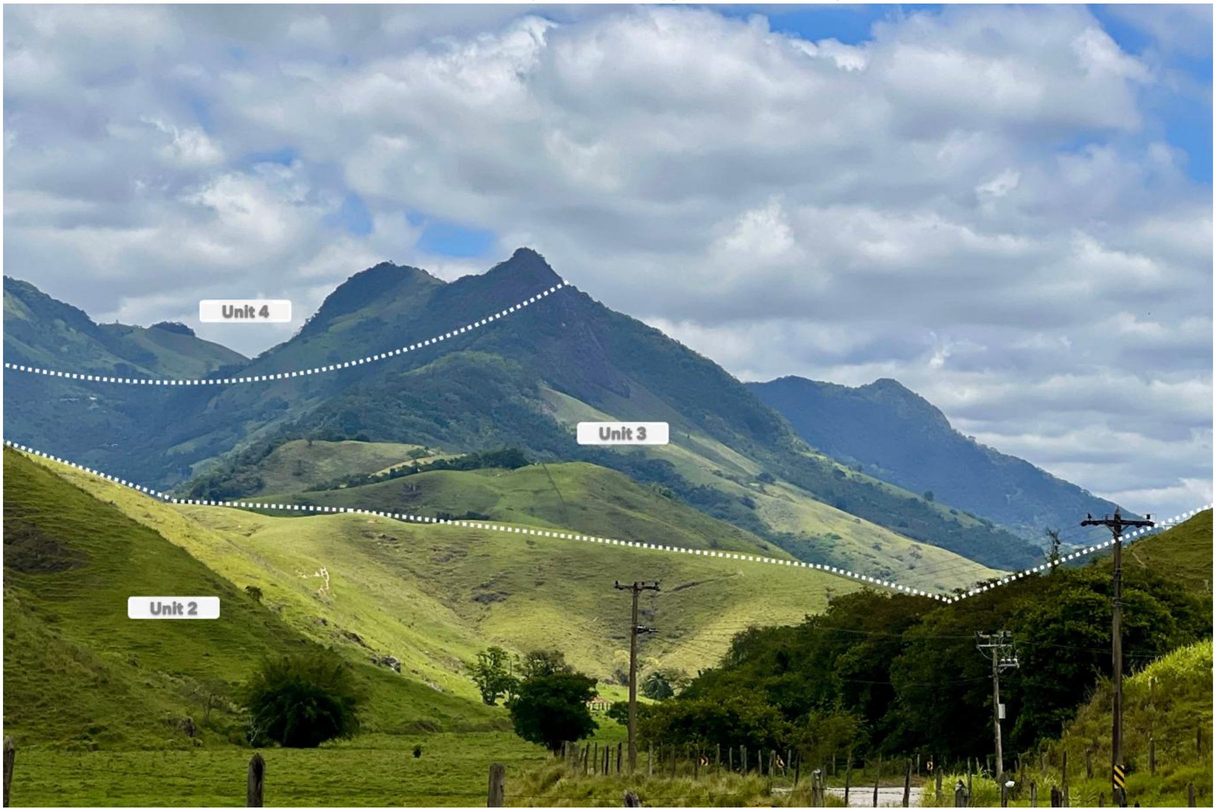
Historically, it was this combination between altitude and climate conditions that favored the development of coffee plantations in the South Fluminense region (Lamego, 1963), promoting intense transformations on the landscape over time, the reflexes of which are perceptible in the current configuration of land use and coverage.

Figure 6 – Iconographic records of the dissected hills and mounds (Unit 2) of the municipality of Rio Claro (Rio de Janeiro, Brazil). Note: a) area with a predominance of pasture; b) area with arboreal vegetation associated with pasture; and c) area with urban occupation

Source: The authors (2026).

Unit 3, corresponding to isolated residual mountains (Figure 7), constitutes the second largest landscape compartment of the municipality, occupying approximately 254.6 km², which is the equivalent to 30.4% of the total area. This unit covers high altitudes, predominantly between 601 and 1,000 m, and has a mostly mild and very humid climate, characterized by a short dry period, estimated at one to three months.

Figure 7 – Iconographic records of the isolated residual mountains (Unit 3) of the municipality of Rio Claro (Rio de Janeiro, Brazil). Note: Transition from the seas of hills to the isolated mountains to the northeast of the municipality, extending up to the high mountain scarps



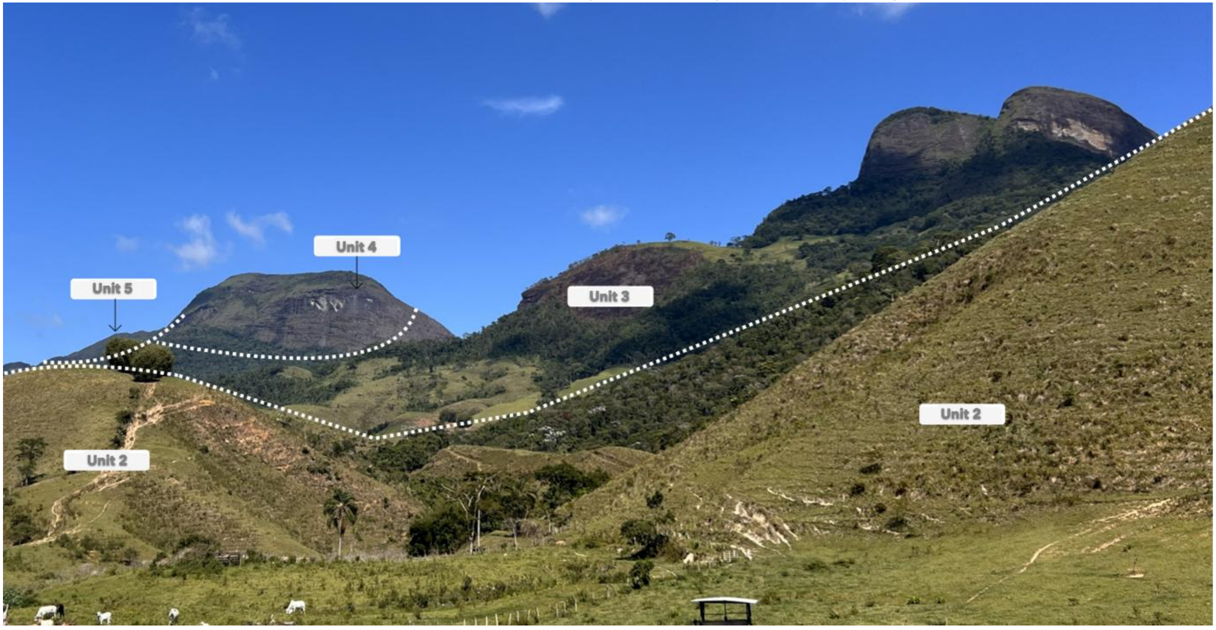
Source: The authors (2026).

Geomorphologically, the isolated residual mountains represent higher and more dissected relief forms, resulting from long-term differential denudation processes, standing out in relation to the adjacent compartments. These features mark the transition between the seas of hills and the higher mountain sectors, performing an essential role in topographic compartmentation and control of local morphodynamic processes.

These mountains correspond to residual elevations sculpted by erosive processes on the gneiss basement, occurring in isolation in relation to the Paraíba do Sul valley (Girão *et al.*, 2022), with occasional occurrences of granite outcrops. From the hydrological point of view, these relief forms perform the function of drainage dividers, since, in the northern sectors of isolated mountains, the water courses are mostly oriented towards the northeast, draining into the Paraíba do Sul River, while, in the eastern section of the territory, the rivers are directed towards the Ribeirão das Lajes Reservoir (Dutra, 2013). Furthermore, these mountains significantly influence the local atmospheric circulation, as observed in other sectors of the Serra do Mar (Pellegatti; Galvani, 2010; Sobral *et al.*, 2018), which performs a central role in the spatial organization of the landscape by conditioning the hydrogeomorphological dynamic and the microclimatic patterns of the territory.

Unit 4, corresponding to the high mountain scarps (Figure 8), occupies 72.8 km² (8.7%) of the municipal territory and covers the high altitudes (1,001–1,200 m), predominantly on gneiss lithologies with occasional granite outcrops. It is characterized by a cold, very humid climate, without a defined dry season. Being strongly conditioned by faults and structural alignments, the scarps have high natural susceptibility to erosive processes and gravitational movements, the intensity of which varies according to land use and coverage. In the areas where the vegetation remains dense and continuous, greater slope stability can be observed, with a significant reduction in the occurrence of geomorphological instabilities (Silva, 2022; Alcântara *et al.*, 2025).

Figure 8 – Iconographic record of the high (Unit 4) and very high (Unit 5) mountain scarps of the municipality of Rio Claro (Rio de Janeiro, Brazil). Note: The transition from the sea of hills to the isolated, residual mountains, culminating in the high and very high mountain scarps



Source: The authors (2026).

Finally, Unit 5, corresponding to very high mountain scarps (Figure 8), totals 35.6 km² (4.25%) and constitutes the highest compartment of the municipal landscape. It lies on gneisses and covers altitudes above 1,200 m, which can surpass 1,600 m on some of the highest peaks. In these areas, the climate is even colder and very humid, resulting from the intense orographic influence of the Serra do Mar. The abrupt slopes, narrow crests, and frequent outcrops demonstrate the combined action of extreme altitude and persistent rains, configuring an environment that is naturally more susceptible to erosive processes and mass movements. As observed in Unit 4, this susceptibility is significantly modulated by land use and coverage, since suppression of the vegetation tends to intensify slope instability (Sidle; Ochiai, 2006; Crozier, 2010; Lehmann; Von Ruette; Or, 2019).

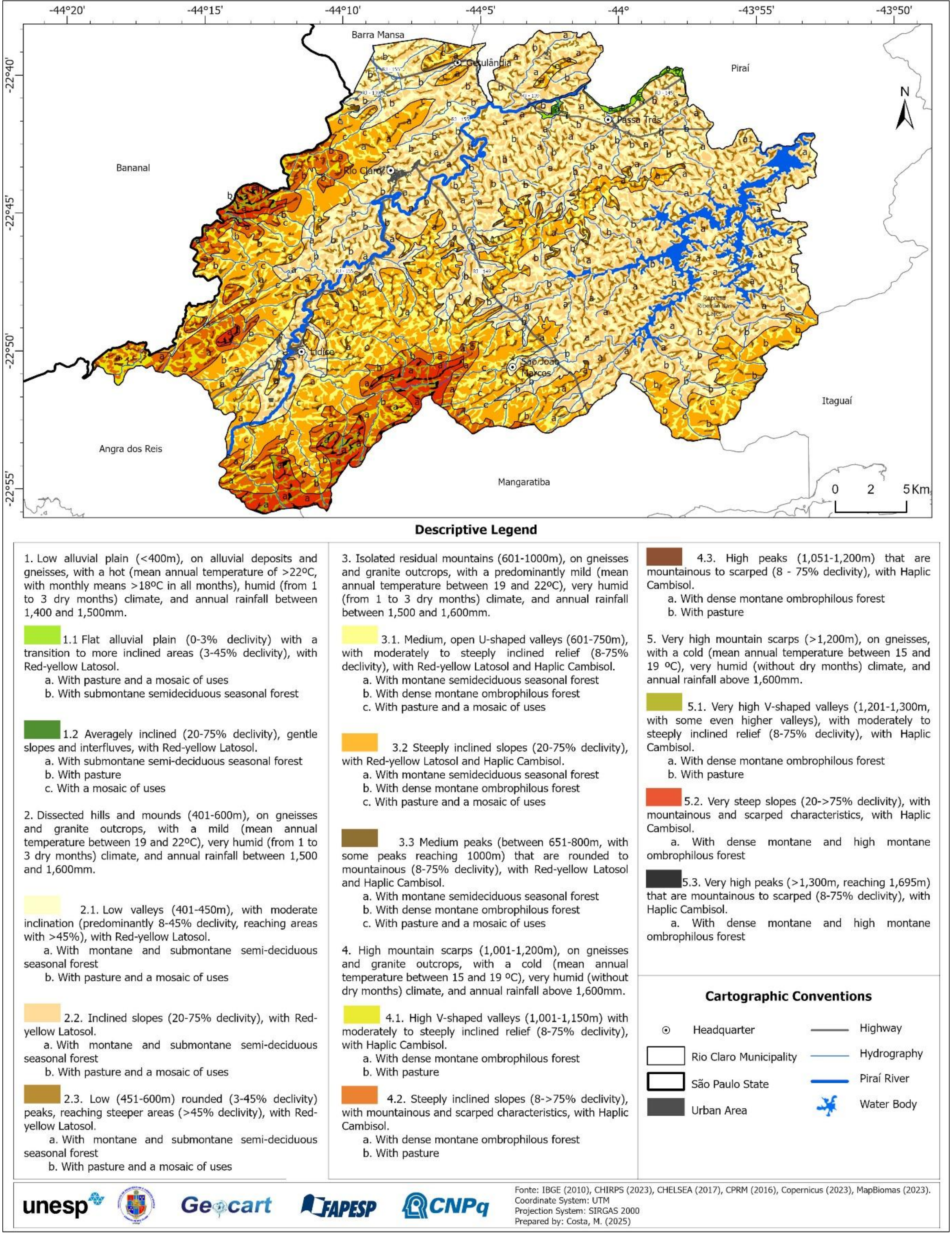
The compartmentation of the first-level landscape units in Rio Claro has a high level of agreement with the regional geomorphology described in the most recent mapping of the state of Rio de Janeiro (Girão *et al.*, 2022). Despite being elaborated with distinct purposes, the patterns recognized in the state product – such as the predominance of dissected hills and mounds, mountain scarps and residual mountains – corroborate the coherence of the mapping carried out here, reinforcing the influence of the lithology and the altitude associated with the Atlantic Orogenic Belt in the configuration of the regional relief (Heilbron *et al.*, 2016).

It should be emphasized, however, that the adopted methodology enabled greater detail, with the individualization of two mountain scarp units, better representation of the residual mountains, and identification of small-scale depositional features, such as the alluvial plains of the Piraí River, which are not discriminated on the map by Girão *et al.*, (2022) due to the scale. Thus, in addition to being coherent with the regional morphostructure of the Brazilian Southeast, the study shows morphostructural compartments and variations not captured by regional scale cartographic products.

Second and Third Level Units

This segment covers a more detailed scale, with the integrated presentation of the second and third level units of the landscape map (Figure 9). The analysis focuses on the general patterns of the 14 districts and 31 sub-districts, highlighting their main internal variations and spatial articulations. This approach of synthesis-description, based on iconographic records, enables understanding of how these compartments refine and structure the previously presented landscape.

Figure 9 – 2nd and 3rd level landscape units of the municipality of Rio Claro (Rio de Janeiro, Brazil)



Descriptive Legend

1. Low alluvial plain (<400m), on alluvial deposits and gneisses, with a hot (mean annual temperature of >22ºC, with monthly means >18ºC in all months), humid (from 1 to 3 dry months) climate, and annual rainfall between 1,400 and 1,500mm.

🟩 1.1 Flat alluvial plain (0-3% declivity) with a transition to more inclined areas (3-45% declivity), with Red-yellow Latosol.
a. With pasture and a mosaic of uses
b. With submontane semideciduous seasonal forest

🟩 1.2 Averagely inclined (20-75% declivity), gentle slopes and interfluves, with Red-yellow Latosol.
a. With submontane semi-deciduous seasonal forest
b. With pasture
c. With a mosaic of uses

2. Dissected hills and mounds (401-600m), on gneisses and granite outcrops, with a mild (mean annual temperature between 19 and 22ºC), very humid (from 1 to 3 dry months) climate, and annual rainfall between 1,500 and 1,600mm.

🟨 2.1. Low valleys (401-450m), with moderate inclination (predominantly 8-45% declivity, reaching areas with >45%), with Red-yellow Latosol.
a. With montane and submontane semi-deciduous seasonal forest
b. With pasture and a mosaic of uses

🟧 2.2. Inclined slopes (20-75% declivity), with Red-yellow Latosol.
a. With montane and submontane semi-deciduous seasonal forest
b. With pasture and a mosaic of uses

🟫 2.3. Low (451-600m) rounded (3-45% declivity) peaks, reaching steeper areas (>45% declivity), with Red-yellow Latosol.
a. With montane and submontane semi-deciduous seasonal forest
b. With pasture and a mosaic of uses

3. Isolated residual mountains (601-1000m), on gneisses and granite outcrops, with a predominantly mild (mean annual temperature between 19 and 22ºC), very humid (from 1 to 3 dry months) climate, and annual rainfall between 1,500 and 1,600mm.

🟨 3.1. Medium, open U-shaped valleys (601-750m), with moderately to steeply inclined relief (8-75% declivity), with Red-yellow Latosol and Haplic Cambisol.
a. With montane semideciduous seasonal forest
b. With dense montane ombrophilous forest
c. With pasture and a mosaic of uses

🟧 3.2 Steeply inclined slopes (20-75% declivity), with Red-yellow Latosol and Haplic Cambisol.
a. With montane semideciduous seasonal forest
b. With dense montane ombrophilous forest
c. With pasture and a mosaic of uses

🟫 3.3 Medium peaks (between 651-800m, with some peaks reaching 1000m) that are rounded to mountainous (8-75% declivity), with Red-yellow Latosol and Haplic Cambisol.
a. With montane semideciduous seasonal forest
b. With dense montane ombrophilous forest
c. With pasture and a mosaic of uses

4. High mountain scarps (1,001-1,200m), on gneisses and granite outcrops, with a cold (mean annual temperature between 15 and 19 ºC), very humid (without dry months) climate, and annual rainfall above 1,600mm.

🟨 4.1. High V-shaped valleys (1,001-1,150m) with moderately to steeply inclined relief (8-75% declivity), with Haplic Cambisol.
a. With dense montane ombrophilous forest
b. With pasture

🟧 4.2. Steeply inclined slopes (8->75% declivity), with mountainous and scarped characteristics, with Haplic Cambisol.
a. With dense montane ombrophilous forest
b. With pasture

🟫 4.3. High peaks (1,051-1,200m) that are mountainous to scarped (8 - 75% declivity), with Haplic Cambisol.
a. With dense montane ombrophilous forest
b. With pasture

5. Very high mountain scarps (>1,200m), on gneisses, with a cold (mean annual temperature between 15 and 19 ºC), very humid (without dry months) climate, and annual rainfall above 1,600mm.

🟩 5.1. Very high V-shaped valleys (1,201-1,300m, with some even higher valleys), with moderately to steeply inclined relief (8-75% declivity), with Haplic Cambisol.
a. With dense montane ombrophilous forest
b. With pasture

🟥 5.2. Very steep slopes (20->75% declivity), with mountainous and scarped characteristics, with Haplic Cambisol.
a. With dense montane and high montane ombrophilous forest

⬛ 5.3. Very high peaks (>1,300m, reaching 1,695m) that are mountainous to scarped (8-75% declivity), with Haplic Cambisol.
a. With dense montane and high montane ombrophilous forest

Cartographic Conventions

⊙ Headquarter
— Highway
☐ Rio Claro Municipality
— Hydrography
☐ São Paulo State
— Piraí River
⬛ Urban Area
Water Body

Fonte: IBGE (2010), CHIRPS (2023), CHELSEA (2017), CPRM (2016), Copernicus (2023), MapBiomas (2023).
Coordinate System: UTM
Projection System: SIRGAS 2000
Prepared by: Costa, M. (2025)

Source: The authors (2026).

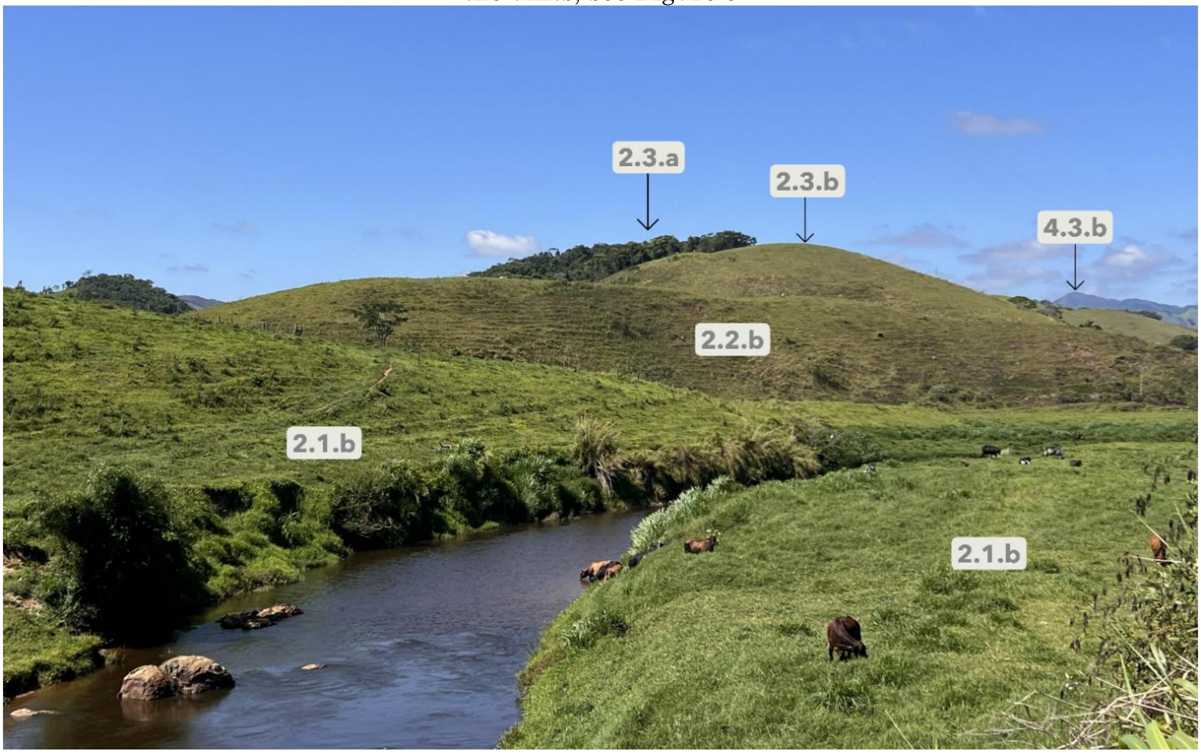
The second level units demonstrate the internal complexity of the large landscape compartments, by making explicit how the variations in slope, relief forms, and soil types organize the landscape. On the third level, this structure is deepened by the differentiation of land use and coverage, which functionally requalify the defined compartments. However, low functional diversity can be observed in this reclassification, since, despite the expressive structural heterogeneity of the landscape, the recurrent use of pasture predominates. This pattern indicates a process of functional simplification, in which a dominant anthropic activity is superimposed on the natural-physical diversity, making it necessary to pay specific analytical attention to the role of pasture in the organization, dynamic, and socioenvironmental impacts of these compartments.

On the alluvial plains (Unit 1), the districts and sub-districts are distributed between flat surfaces and areas of transition to more inclined sectors, where latosols support agriculture and livestock, forest fragments, and land use mosaics. It is a compartment with low levels of urban occupation, restricted to occasional buildings in the proximity of the Piraí River.

In the dissected hills and mounds (Unit 2) and isolated, residual mountains (Unit 3) (Figures 10 and 11) units, the reclassification at the second and third levels is particularly relevant given the high diversity of relief forms and slope classes. The differentiation of land use and occupation demonstrates a predominance of pasture, showing the contrast between the structural complexity of the physical environment and the functional simplification associated with anthropic use.

In these sectors, the combination of moderate and steeply inclined slopes, rounded to more rugged peaks, and predominantly U-shaped embedded valleys, gives rise to differentiated patterns of soil use, organized in mosaics that alternate pasture areas, seasonal forest remnants, and, in the higher units, stretches of dense ombrophilous forest.

Figure10 – Iconographic record of the dissected hills and mounds (Unit 2) and the high mountain scarps (Unit 4), highlighting the reclassification into second and third levels. For the description of the units, see Figure 9



Source: The authors (2026).

The latosols and cambisols present in these units influence both the types of land use and the susceptibility to erosive processes and severe hydrogeomorphological events, especially considering the history of intense anthropic transformations. These are marked by deforestation associated with the previous expansion of coffee growing and, subsequently, the consolidation of pasture areas (Costa *et al.*, 2024).

It is also worth highlighting the spatial distribution of the forest coverage, with dense ombrophilous forest predominating in the higher sections of the study area, especially to the east and the south of the municipal territory, while semi-deciduous seasonal forest occurs mostly in the units situated in the proximity of the Ribeirão das Lajes Reservoir.

Figure 11 – Iconographic record of the dissected hills and mounds (Unit 2), isolated residual mountains (Unit 3), and very high mountain scarps (Unit 5), highlighting the reclassification into second and third level units. For the description of the units, see Figure 9

Source: The authors (2026).

In the higher altitude units, corresponding to high (Unit 4) and very high (Unit 5) mountain scarps (Figures 10 and 11), the reclassification into second and third levels demonstrates environments dominated by extremely inclined slopes, with slopes that surpass 75%, narrow V-shaped valleys, and scarped peaks. The presence of shallow soils associated with high humidity imposes strong limitations on land use, favoring the maintenance of more continuous, less fragmented forest cover. This coverage plays a fundamental role in slope stability and the regulation of hydrogeomorphological processes. Therefore, while the intermediate units concentrate greater anthropic pressure and intensive pasture usage, the higher altitude compartments configure areas of high geomorphological complexity and ecological relevance, finalizing the structural and functional organization of the municipal landscape.

CONCLUSIONS

The mapping and analysis of the landscape units in the municipality of Rio Claro achieved the central research aim, which consisted of deepening the understanding of a territory marked by high morphostructural and climatic heterogeneity, characteristic of the Brazilian humid tropics. The integration of physical-geographic and socioenvironmental variables, through geoprocessing and spatial analysis procedures demonstrated as effective for revealing the structural and functional complexity of the landscape, from the low-altitude alluvial plains to the very high mountain scarps of the Serra do Mar.

In general, the organization of the landscape units has three hierarchical levels enabling identification of the large compartments, their internal subdivisions, and the patterns of land use and coverage, highlighting anthropic actions. This hierarchical structure contributed to an integrated interpretation of the territory on the municipal scale, enabling recognition of the relevant internal differences and their reflexes in the environmental dynamic.

The results show that the intermediate landscape units — dissected hills and mounds and isolated mountains — have accentuated slope, more susceptible soils, and predominant pasture usage, configuring areas with greater propensity to erosive processes and hydrogeomorphological events. In contrast, the higher altitude units, corresponding to high and very high mountain scarps, have a lower intensity of anthropic use and high continuity of forest cover. This continuity of the vegetation confers relevance to slope stability, the conservation of biodiversity, and environmental regulation, demonstrating the strategic role of these areas in the functionality of the municipal territory. These contrasts between the landscape compartments indicate significant differences in the structure, coverage, and environmental operation, suggesting that territorial planning and management should consider both the fragility of the intermediate units and the ecological importance of the higher areas.

As its main contribution, this study highlights the potential of the landscape cartography methodology to cover the gaps in the detailed mapping of mountainous and hilly areas of the humid tropics, which are frequently dealt with in a generalized manner in regional surveys. The integration of multiple data sources, scales of analysis, and hierarchical levels enabled consistent interpretation of the landscape, with high capacity for replicability in other sectors of the Serra do Mar and in regions with similar environmental conditions.

Among the limitations, the dependence on secondary databases, with varied time periods and spatial resolutions, stands out. Future studies could advance with more homogenous time-series and higher resolution data, especially regarding land use and coverage and soil use, detailing anthropic usage. Such improvements would contribute to refining the landscape cartography and strengthening its application in environmental planning and territorial management of humid tropical areas.

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AUTHORS CONTRIBUTION

Marcelo Costa: Conceptualization, Data curation, Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Eduardo Salinas Chávez: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing, Supervision. Rafael Martins Brito: Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing. Andréa Aparecida Zacharias: Conceptualization, Formal analysis, Visualization, Writing – review & editing, Supervision. Marcilene dos Santos: Formal analysis, Writing – review & editing, Supervision.

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DATA AVAILABILITY: The data that underpin the results of this study may be made available by the corresponding author, upon duly justified request. [Marcelo Costa].