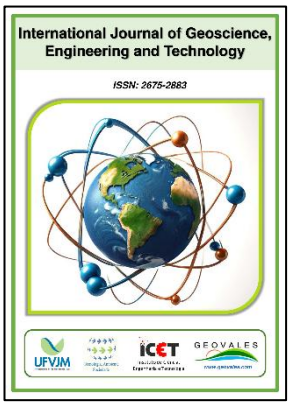
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Environmental Suitability and Conilon Coffee Productivity in Northwestern Minas Gerais, Brazil: Supporting the Productive Diversification of Family Farming

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Abstract

This study evaluated the environmental suitability and productivity of conilon coffee in northwestern Minas Gerais, Brazil, with the aim of supporting strategies for the sustainable expansion of the crop and the diversification of family farming. By integrating altitude, slope, temperature and precipitation data within a Geographic Information System (GIS) environment, areas potentially suitable for cultivation were identified, and the productivity of the municipalities participating in the CAPUL Conilon Coffee Project was assessed. The results showed that only 22.46% of the study area presented suitable environmental conditions for cultivation, with precipitation identified as the main limiting factor. The municipalities of Arinos, Buritis and Riachinho exhibited the greatest potential for crop establishment, while Buritis achieved yields of up to 55 bags ha^{-1}, comparable to those reported for the leading conilon coffee-producing regions in Brazil, such as Espírito Santo, and even higher than in other regions such as Vales do Jequitinhonha e Mucuri and Norte de Minas Gerais. The findings confirm the effectiveness of multicriteria analysis as a tool for territorial planning and indicate that conilon coffee represents a viable alternative for enhancing the economic resilience and sustainability of regional family farming.

Keywords: *Coffea canephora*, Environmental suitability, Geoprocessing, Multicriteria analysis.

1. Introduction

Coffee cultivation is recognised worldwide as one of the most economically significant agricultural activities, as it provides the raw material for the production of one of the most widely consumed beverages globally (Ferreira et al., 2024; Castro-Díaz et al., 2025; Lwiza and Barkley, 2025). It is estimated that approximately 400 billion cups of coffee are consumed annually (International Coffee Organization – ICO, 2025). In 2023, global coffee production generated an estimated revenue of US$23 billion, while the entire coffee value chain accounted for more than US$200 billion during the same period (Food and Agriculture Organization of the United Nations – FAO, 2025). In this context, global production of conilon coffee (*Coffea canephora* var. *conilon*) has come to represent approximately 40% of total world coffee production, reflecting an increase in productivity of around 15% since the beginning of the crop's commercial expansion in the 1990s (Kawuki et al., 2025). In this global context, Brazil

stands out not only as the largest producer of arabica coffee but also as a growing player in the conilon coffee sector.

For more than 150 years, Brazil has maintained its position as the world's largest coffee producer and has also established itself as a leading producer of speciality coffees (De Moraes-Neto et al., 2024). Regarding total coffee production (arabica and conilon together), the 2025 coffee harvest, characterised by the negative phase of the biennial production cycle, reached 56.5 million bags of processed coffee, representing an increase of 4.3% compared with the 2024 harvest, despite being adversely affected by climatic conditions, including prolonged drought periods and high temperatures (Companhia Nacional de Abastecimento – CONAB, 2025).

According to CONAB, in 2025 the total area allocated to conilon coffee cultivation in Brazil amounted to 415.2 thousand hectares, of which 371.9 thousand hectares were under production and 43.2 thousand hectares were in the establishment phase. The state of Espírito Santo has the largest cultivated area in the country and, in 2021, accounted for approximately 69% of the national *Coffea canephora* production, reaching 673.2 thousand tonnes (Zaidan et al., 2023).

Although Minas Gerais is recognised as Brazil's leading producer of arabica coffee, the state also possesses favourable edaphoclimatic conditions for conilon coffee cultivation. According to a 2020 study conducted by the Technical Assistance and Rural Extension Company of the State of Minas Gerais (Emater-MG), 291 municipalities present significant potential for conilon coffee cultivation, of which 107 are recommended exclusively for irrigated cultivation and 185 are suitable for both irrigated and rainfed production systems (Pereira et al., 2020; De Melo Moura et al., 2022). In this context, the north-western region of Minas Gerais stands out as a promising area for the expansion of conilon coffee cultivation owing to its favourable edaphoclimatic and topographical conditions for crop development.

The suitability of this region for conilon coffee cultivation is directly associated with the thermal requirements of the species, as different coffee varieties exhibit distinct responses to climatic conditions. *Coffea arabica* is less tolerant of high temperatures and more sensitive to thermal variation, whereas conilon coffee demonstrates greater heat tolerance but is more susceptible to very low temperatures than arabica coffee (Bunn et al., 2015). In addition to thermal conditions, other environmental factors directly influence the vegetative and reproductive development of the crop, thereby affecting yield, bean quality, and the characteristics of the beverage produced.

Among the factors influencing crop performance are water availability, air temperature, solar radiation, precipitation, terrain slope, wind, relative humidity, and altitude (Santinato et al., 2016; Custodio et al., 2022; Lorençone et al., 2024; Jordaim et al., 2025). Consequently, studies aimed at identifying areas suitable for cultivation are essential to support agricultural planning and to reduce the risks associated with establishing the crop under unsuitable environmental conditions.

The geographic region classified as intermediate of Patos de Minas, located in Minas Gerais (Instituto Brasileiro de Geografia e Estatística – IBGE, 2017), has a vast territorial extension and high environmental diversity, and encompasses the Northwest of Minas, where agricultural and livestock activities show significant concentration, but with strong economic dependence on dairy farming (Silva et al., 2012; Dos Santos et al., 2024). Approximately 80% of the region's milk production originates from small-scale family farms, with around half of these households' gross income being derived from this activity (Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA, 2022). However, factors such as market fluctuations, high production costs, and prolonged periods of drought compromise the economic stability of these farming systems, reinforcing the need for productive diversification and the adoption of complementary income sources, such as conilon coffee cultivation.

In this context, multicriteria analyses have become relevant tools for identifying areas suitable for coffee cultivation. Studies on arabica coffee have assessed characteristics associated with the ideal production habitat, such as altitude, slope, land use and land cover, and temperature, aiming to improve territorial technological suitability (Nzeyimana et al., 2014; Liu et al., 2025). Other studies have assessed agricultural suitability by considering climatic, edaphic, physiographic, and socioeconomic characteristics, as well as environmental constraints (Salas López et al., 2020; Nigussie et al., 2024). For conilon coffee, in turn, studies conducted in the state of Espírito Santo have addressed the risks and agroclimatic zoning of these

areas (Pezzopane et al., 2010; Taques and Dadalto, 2019). Despite the existing agricultural potential, studies assessing the climatic and topographic suitability of north-western Minas Gerais for the cultivation of this crop remain limited, particularly in properties supported by rural extension and technical assistance programmes, such as the Conilon Coffee Project of the Cooperativa Agropecuária de Unaí (CAPUL). The lack of integrated assessments limits the identification of the most suitable areas for the expansion of conilon coffee, hindering technical planning aimed at family farming, production diversification, sustainability, and the strengthening of regional income.

In view of this scenario, the present study aimed to analyse the climatic and topographical parameters associated with the suitability of conilon coffee cultivation in north-western Minas Gerais, in accordance with the guidelines established by the CAPUL Conilon Coffee Project, with the objective of supporting agricultural planning and the sustainable expansion of the crop in the region. In addition, the study sought to identify the municipalities with the greatest potential for crop establishment based on altitude, slope, temperature, and precipitation criteria, and to evaluate the spatial distribution of the productivity achieved by producers participating in the project.

1.1. Conilon Coffee Project

The project was initiated in 2019 with the aim of introducing conilon coffee cultivation in north-western Minas Gerais. To develop an agronomic understanding of the crop, initial cultivation was established at a farm owned by CAPUL, located in Unaí, Minas Gerais, Brazil, covering an area of 0.8 hectares (ha) equipped with micro-sprinkler irrigation systems. Fourteen genotypes were introduced in this experimental area, totalling approximately 3.600 seedlings. The cooperative's technical team was responsible for monitoring potential resistance to biotic stresses (pests and diseases) and abiotic stresses (adverse climatic effects) among the evaluated conilon coffee varieties, aiming to support future local expansion of the crop (CAPUL, 2019).

In 2020, the project underwent a commercial expansion through the implementation of conilon coffee cultivation on six CAPUL cooperative members' farms, covering a total cultivated area of 12 ha. These cultivation areas are located in north-western Minas Gerais, mainly in the municipalities of Uruana de Minas, Buritis, and Unaí. The project promoted by CAPUL aims to establish conilon coffee cultivation as a means of contributing to income diversification among associated family farmers, who also engage in other agricultural activities, such as passion fruit production, free-range broiler chicken farming, and dairy cattle production (CAPUL, 2021).

Furthermore, to ensure the proper management of conilon coffee cultivation, cooperative members receive full technical support through the Rural Technical Assistance and Extension Project (ATER), from crop establishment to commercialisation (CAPUL, 2021). In 2021, the Conilon Coffee Project reached a planted area of approximately 44 ha involving 19 cooperative members (CAPUL, 2022). Currently, CAPUL, together with ATER, provides technical assistance to cooperative members and new participants engaged in conilon coffee cultivation, as well as other agricultural activities, including pasture management, beef and dairy cattle production, broiler and laying poultry production, and crops such as sugarcane, sorghum, maize, soybean, and passion fruit (CAPUL, 2023; 2024; 2025).

2. Materials and Methods

The methodological workflow adopted in this study is summarised in Figure (1). The procedure was organised into six sequential stages: (1) definition of the study area and acquisition of secondary data; (2) selection of the environmental variables, including altitude, slope, mean annual temperature, and mean annual precipitation; (3) processing and standardisation of the environmental variables through Geographic Information System (GIS) procedures, including classification and reclassification; (4) multicriteria analysis based on the simultaneous intersection of the thematic layers to delimit environmentally suitable areas and areas $\leq$ 3 ha; (5) spatial analysis of conilon coffee productivity using municipal productivity data and the Inverse Distance Weighting (IDW) interpolation method, followed by anomaly classification; and (6) generation of the final environmental, suitability, productivity, and anomaly maps. Each stage is described in detail in the following sections.

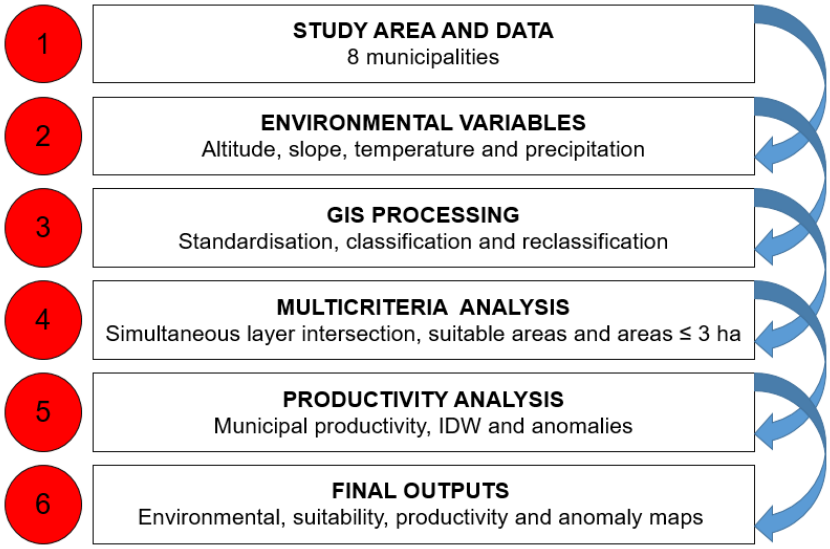


Figure 1 – Methodological workflow adopted for the environmental suitability and productivity analysis of conilon coffee in northwestern Minas Gerais, Brazil.

2.1. Study Area: Location and Climatic Characteristics

The study area comprised eight municipalities: Unaí, Cabeceira Grande, Buritis, Arinos, Bonfinópolis de Minas, Paracatu, Riachinho, and Natalândia, located in the north-western region of Minas Gerais, Brazil. Initially, the municipalities of interest were selected from the municipal boundary dataset provided by the IBGE (2025), exported, and subsequently merged into a single vector layer using the Merge Vector Layers tool in QGIS. This procedure generated the spatial boundary adopted for all subsequent analyses, as illustrated in Figure (2A–C).

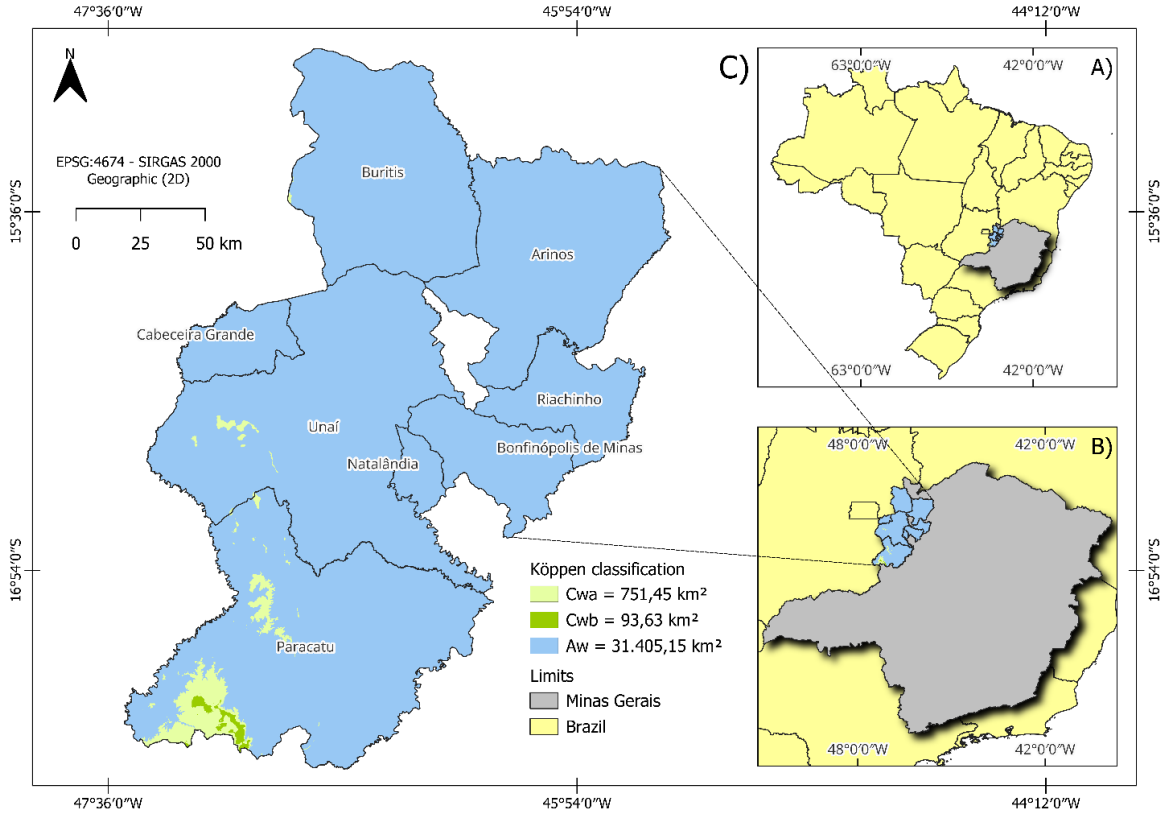


Figure 2 – Location of the study area and Köppen–Geiger climate classification. (A) Brazil; (B) Minas Gerais State; and (C) the eight municipalities in north-western Minas Gerais participating in the CAPUL Conilon Coffee Project: Unaí, Cabeceira Grande, Buritis, Arinos, Bonfinópolis de Minas, Paracatu, Riachinho, and Natalândia. The highlighted areas represent the municipalities included in the study, while the unhighlighted areas correspond to municipalities outside the study area.

The north-western region of Minas Gerais exhibits a set of climatic and geomorphological attributes that provide it with a distinct environmental identity within the state. According to the Köppen–Geiger classification (Peel et al., 2007), three climatic classes occur within the study area: Aw, Cwa, and Cwb (Figure 2C). From a climatic perspective, the region is predominantly characterised by a hot semi-humid tropical climate, with a well-defined dry season lasting four to five months, generally from June to September (Silva and Jardim, 2019). During this period, rainfall becomes scarce or virtually absent, resulting in prolonged drought conditions that pose challenges for agricultural planning and water resource management.

Annual precipitation in the region ranges from 800 to 1,500 mm, with a marked concentration during the six-month period between October and March, coinciding with the spring and summer seasons. This pattern is consistent with the historical rainfall series presented by Jardim and Silva (2017), in which the highest precipitation volumes occur between November and March, whereas the months of June, July, and August exhibit values close to zero.

This seasonal pattern reflects the South American monsoon regime, characterised by the alternation between wet and dry periods, influenced by atmospheric systems such as the South Atlantic Convergence Zone (SACZ) and by the influence of tropical and polar air masses. Interannual rainfall variability is high, as evidenced by the differences among the annual totals recorded at the analysed weather stations, with values ranging from approximately 631 mm to 1,765 mm in the evaluated historical series.

Topography plays a fundamental role in regulating local climatic conditions. The region exhibits a diverse relief, ranging from plains to elevated plateau areas, with emphasis on the presence of the Espinhaço Mountain Range and interfluves that separate important hydrographic basins, including the Paraná, Tocantins–Araguaia, and São Francisco basins (Silva and Jardim, 2019). Higher-altitude areas, with elevations above 1,000 m, tend to record milder temperatures and a higher frequency of rainfall, whereas depressions located below 400 m exhibit higher temperatures and lower relative air humidity.

According to Reboita et al. (2015), temperatures in north-western Minas Gerais range from 20°C to 31°C, varying according to altitude and geographic position. Higher-altitude areas record milder temperatures, whereas the depressions of the middle São Francisco region exhibit the highest thermal values. The vertical thermal gradient is estimated at approximately −0.65°C for every 100 m increase in elevation, demonstrating the direct influence of altitude on thermal conditions (Silva and Jardim, 2019).

These climatic and topographical characteristics provide north-western Minas Gerais with considerable potential for agribusiness, particularly for grain production. However, the pronounced seasonality of rainfall and the occurrence of dry spells during the rainy season require the adoption of appropriate management practices, such as the use of irrigation systems and the planning of agricultural calendars based on continuous meteorological monitoring. In this context, studies focused on the consistency assessment and estimation of rainfall data are essential to support regional agricultural and water resource planning, as highlighted by Jardim and Silva (2017) in their evaluation of different methods for filling gaps in historical precipitation series in north-western Minas Gerais.

2.2. Data Sources

The data used in this study were obtained from the Spatial Data Infrastructure of the State System of Environment and Water Resources of Minas Gerais (IDE-SISEMA, 2025), including vector layers of mean annual precipitation and mean annual temperature from the Ecological-Economic Zoning of Minas Gerais (ZEE-MG, 2008), climatic zoning based on the Köppen–Geiger classification (Peel et al., 2007), and raster layers of elevation and slope derived from the TOPODATA geomorphometric database of the National Institute for Space Research (INPE, 2008). Municipal and state boundaries were obtained from the IBGE (2025). Conilon coffee productivity data were provided by the technical department of CAPUL in CSV format, containing the average municipal yield expressed in bags per hectare for producers participating in the Conilon Coffee Project.

2.3. Study Variables

The analysed variables were subjected to a multicriteria analysis based on the integration of

data within a GIS, aiming to characterise the previously defined parameters. Subsequently, the variables were evaluated to improve the accuracy of the criteria definition. This procedure contributed to achieving the proposed objectives by enabling the selection and characterisation of the most relevant variables through different stages of spatial data processing, including standardisation, classification, reclassification, matrix transformation, definition of spatial weights, and generation of the final configurations. Additionally, calibration and validation procedures were performed for the models used in order to adequately integrate the studied variables into map algebra calculations, enabling the development of thematic maps of the study area (Oviedo-Pastrana et al., 2014). Table (1) presents the variables of interest and the procedures adopted for the implementation of the project in north-western Minas Gerais.

Table 1 – Variables used for the implementation of conilon coffee cultivation in the north-western region of Minas Gerais.

Variable	Description	Values and units	Literature
Altitude	Altitude plays an important role in coffee cultivation, directly influencing bean quality and the sensory characteristics of the beverage produced.	400–850 m	Barbosa et al. (2014); Martins et al. (2019); Braga et al. (2022); De Souza et al. (2022)
Slope	Terrain slope directly influences both coffee crop development and harvesting operations, potentially affecting crop productivity, crop management practices, and the mechanisation of agricultural activities.	Low (0–8%), moderate (8–20%), high (>20–30%)	Trabaquini et al. (2010); Höfig and Araujo-Júnior (2015); Hasni et al. (2024)
Rainfall	Rainfall plays a fundamental role in crop development and water availability.	Average annual (1,100–1,200 mm)	Colodetti et al. (2026)
Temperature	Temperature plays an essential role in coffee plant development and influences the suitability of climatic conditions for crop establishment.	Average annual (22–26°C)	Taques and Dadalto (2019); Colodetti et al. (2026)

The raster layers of elevation and slope were reclassified using a table-based approach to identify the ranges considered suitable for conilon coffee cultivation. For elevation, the range between 400 and 850 m above sea level was selected, whereas for slope, areas with inclinations between 0 and 20% were considered suitable. After reclassification, the resulting rasters were converted into vector format using the Polygonize tool, enabling their integration with the other vector datasets used in the study.

In the vector layers of mean annual temperature and mean annual precipitation, only the features compatible with the environmental conditions considered suitable for conilon coffee cultivation were selected. For mean annual temperature, the attribute table expression-based selection tool was used, adopting the expression described in Equation (1):

$$\text{"indicator"} \geq 22 \text{ AND "indicator"} \leq 26 \quad (1)$$

where indicator represents the attribute field of the mean annual temperature vector layer, expressed in degrees Celsius (°C), and the values 22 and 26 correspond, respectively, to the lower and upper thresholds of the suitable temperature range for conilon coffee cultivation.

For mean annual precipitation, the expression presented in Equation (2) was applied:

"indicator" ≥ 1100 AND "indicator" ≤ 1200 (2)

the term indicator refers to the attribute field within the mean annual precipitation vector layer, measured in millimetres (mm), while the values 1100 and 1200 denote, in turn, the lower and upper limits of the precipitation range suitable for conilon coffee cultivation.

After obtaining all vector layers of interest, the Vector General → Create Spatial Indexes tool was executed using batch processing to optimise subsequent spatial operations. Subsequently, all layers were processed using the Vector Geometry → Fix Geometries tool, adopting the "Structure" repair mode, also executed in batch processing, with the aim of eliminating topological inconsistencies that could compromise spatial overlay analyses.

The delimitation of potential areas for conilon coffee establishment was performed using the Multiple Intersection tool, simultaneously incorporating the four thematic vector layers considered determinants of crop suitability: elevation, slope, mean annual precipitation, and mean annual temperature. The intersection output enabled the identification of areas that simultaneously met all established environmental criteria. Subsequently, suitable areas were calculated for each municipality and expressed in square kilometres.

The vector layer resulting from the intersection was subsequently processed using the Multipart to Singleparts tool, allowing the individualisation of the generated polygons. Subsequently, the area of each polygon was calculated in hectares. Considering that the CAPUL Conilon Coffee Project provides funding for areas of up to 3 hectares, the attribute-based selection tool was applied to identify and quantify all polygons with an area equal to or smaller than this limit.

For the spatial analysis of productivity, the centroids of the eight studied municipalities were initially generated. The mean municipal productivity values, expressed in bags per hectare, were associated with their respective centroids and exported as a point vector layer in shapefile format. Based on these points, spatial interpolation was performed using the IDW method, adopting a power coefficient (P) of 2, an extent corresponding to the study area, and a pixel size of 0.0001 degrees for both the X and Y axes. This procedure resulted in a continuous surface of estimated productivity for the entire study region.

To evaluate the relative spatial distribution of productivity, a percentage deviation map in relation to the regional mean was generated using the QGIS Raster Calculator. The calculation was performed using the expression presented in Equation (3):

$$D = \frac{(P_{IDW} - 29.3)}{29.3} \times 100 \quad (3)$$

where D represents the percentage deviation from the mean regional productivity, P_{IDW} represents the productivity estimated by the IDW interpolation, and the mean regional productivity corresponds to the arithmetic mean of the municipal productivity values.

The percentage deviation represents the deviation of interpolated productivity in relation to the regional mean, with positive values indicating productivity above the mean and negative values representing productivity below the regional mean. For cartographic interpretation purposes, the resulting surface was classified into five thematic classes using discrete symbology and predefined intervals: Very Low (< −20%), Low (−20 to −10%), Near Average (−10 to +10%), High (+10 to +20%), and Very High (> +20%).

Although the interpolation was performed using only eight points represented by municipal centroids, rather than directly from the coordinates of the producing farms, this approach was applied as an exploratory methodology aimed at proposing a geospatial framework for regional assessment of the productivity of producers participating in the Conilon Coffee Project. This approach enabled the identification of spatial patterns and provided support for future analyses at more detailed spatial scales.

3. Results and Discussion

3.1. Individual Analysis of Environmental Variables

The total area covered by the eight studied municipalities was 32,252.55 km², distributed among Unaí (8,445.43 km²), Paracatu (8,231.03 km²), Arinos (5,279.42 km²), Buritis (5,225.19 km²), Bonfinópolis de Minas (1,850.49 km²), Riachinho (1,719.27 km²), Cabeceira Grande (1,033.06 km²), and Natalândia (468.66 km²). This extensive territorial area highlights the importance of spatial planning for identifying environments

suitable for the expansion of conilon coffee cultivation in north-western Minas Gerais.

The individual analysis of environmental factors demonstrated that slope was the variable with the greatest spatial coverage, with 28,954.81 km² classified within the 0–20% range, representing approximately 89.77% of the total studied area (Figure 3B). Subsequently, the elevation range between 400 and 850 m covered 22,304.70 km², corresponding to 69.16% of the regional area (Figure 3A).

Studies conducted in regions with similar characteristics to those presented in Figure (3A), such as the municipality of Morrinhos, in the state of Goiás, have shown that conilon coffee genotypes cultivated at an altitude of 850 m exhibited good adaptation to local conditions, as demonstrated by satisfactory plant growth and development. Throughout the cultivation cycle, high vegetative vigour and significant leaf production were observed. Additionally, cultivation at this altitudinal range did not demonstrate high susceptibility to pest and disease attacks, nor did it result in damage associated with flowering and pollination processes during the reproductive phase of the coffee plant (Partelli et al., 2019). These findings highlight that the selection of genotypes adapted to specific environmental conditions influences the success of coffee cultivation in these regions.

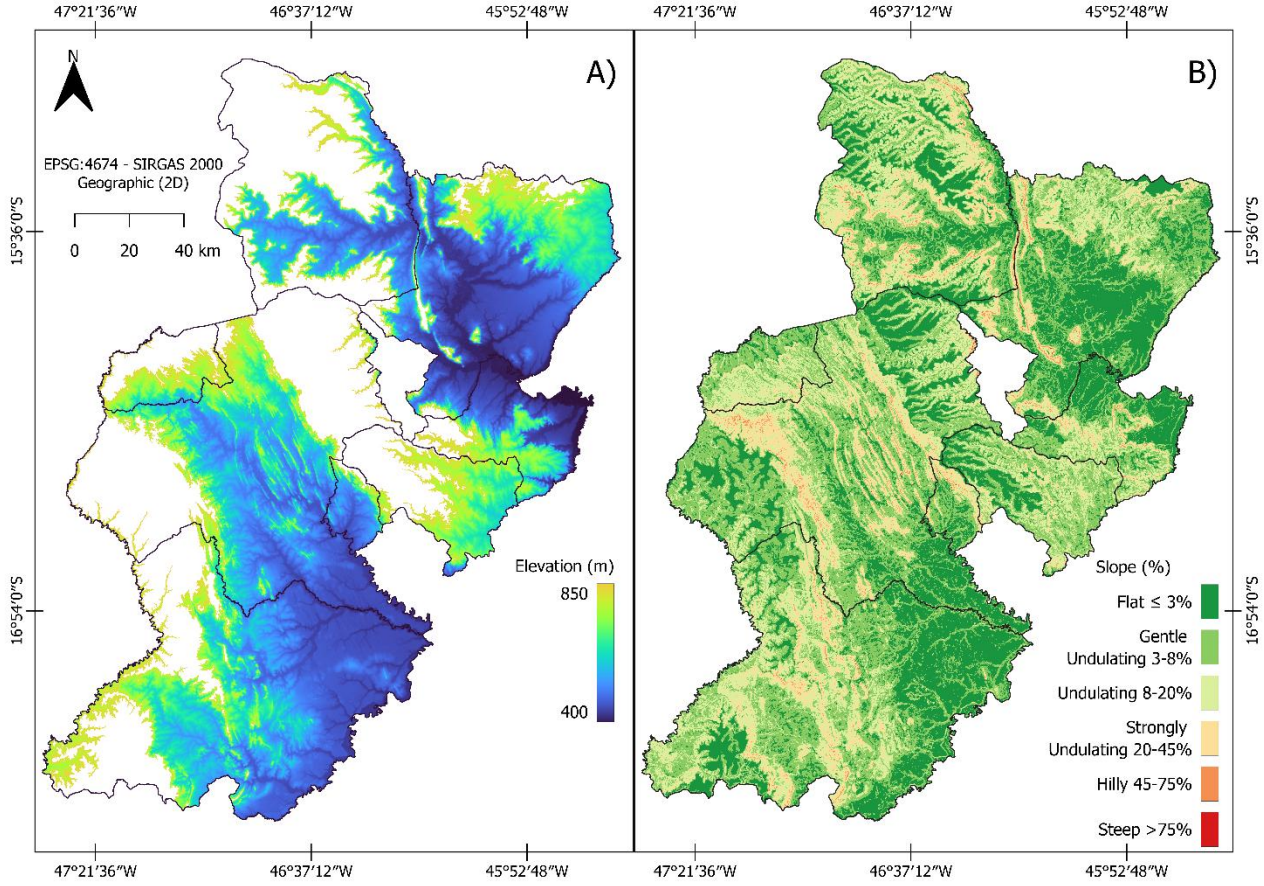


Figure 3 – Topographic characterisation of the experimental area: elevation (A) and slope (B).

The mean annual temperature range between 22 and 26°C was observed across 18,246.20 km² (56.57%) (Figure 4A), whereas the mean annual precipitation range between 1,100 and 1,200 mm showed the lowest spatial coverage, totalling 11,385.21 km², equivalent to 35.30% of the study area (Figure 4B). These results indicate that precipitation represented the most restrictive factor among the criteria considered, significantly reducing the availability of environmentally suitable areas for cultivation.

The results obtained in Figure (4A) corroborate the observations of Ferrão et al. (2024), who highlighted the high adaptability of robusta/conilon coffee to warm environments, with improved growth and greater yield potential in low-altitude regions under temperatures ranging from 17 to 33°C. In this context, the predominance of areas

with mean annual temperatures between 22 and 26°C in the study region demonstrates favourable thermal conditions for crop development. Furthermore, the authors reported that certain conilon coffee genotypes exhibit positive responses to increasing temperatures, resulting in higher productivity levels. Therefore, the results indicate that temperature does not represent a limiting factor for the environmental suitability of the crop in the evaluated area, whereas water availability, represented by precipitation, constitutes the main restrictive element for the expansion of suitable cultivation areas.

Research integrating climatic, environmental, and topographic factors indicates that these components exert a significant influence on precipitation regimes, affecting water availability and the retention of micro- and macronutrients essential for coffee plant development. Consequently, a heterogeneous spatial distribution of cultivation areas is observed, which may increase agroclimatic risks associated with the establishment and expansion of coffee cultivation (Pezzopane et al., 2010; Zhang et al., 2021; Cunha et al., 2023; Liu et al., 2025). Water availability represents one of the most relevant components for coffee crop establishment, as deviations from the precipitation range considered optimal may compromise crop development. Supporting this interpretation, studies conducted in the state of Bahia demonstrated that high water deficits, close to 1,000 mm, may render certain areas unsuitable for coffee cultivation (Lorençone et al., 2024). These studies contribute to the findings presented in Figure (4B).

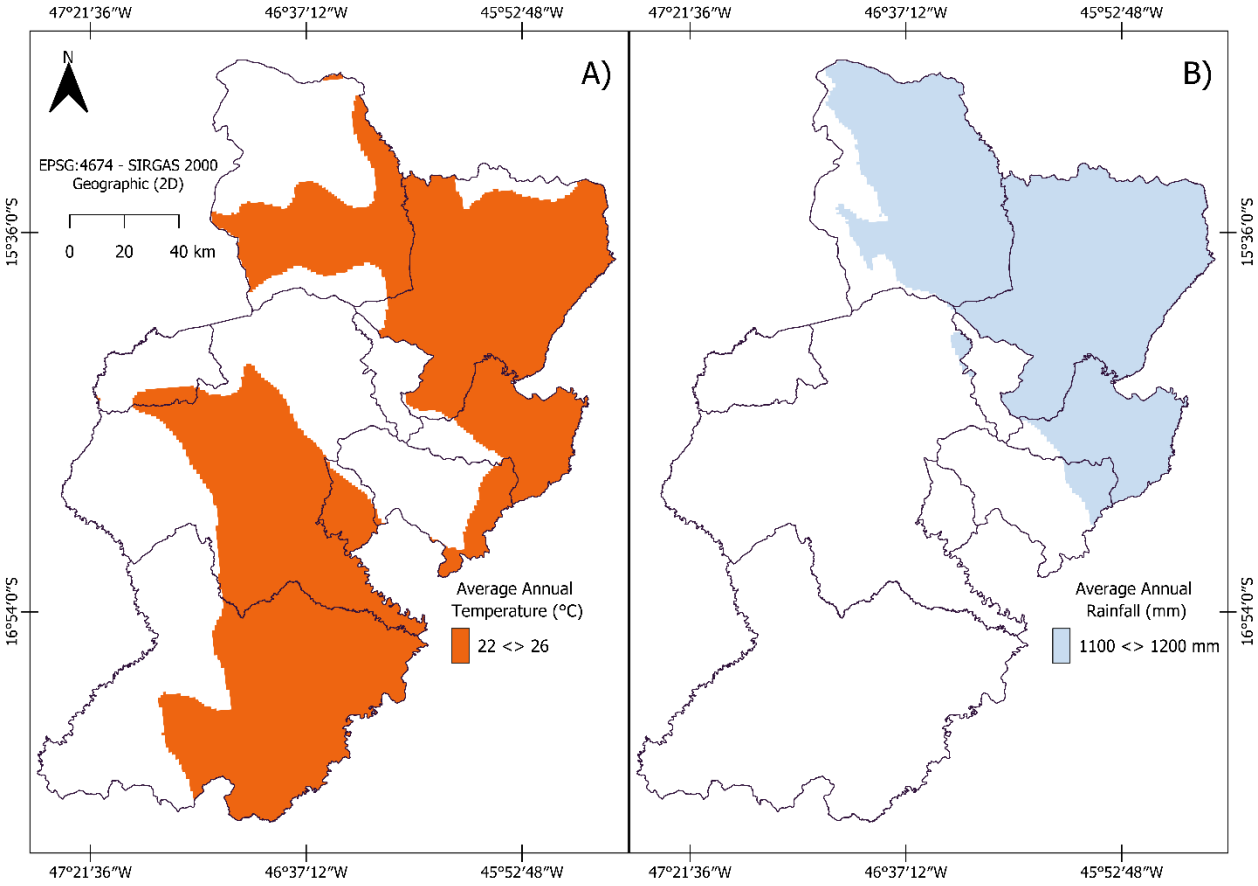


Figure 4 – Spatial distribution of mean annual temperature (A) and mean annual precipitation (B) in the study area.

3.2. Multicriteria Assessment of Environmental Variables

The simultaneous integration of the four variables through the Multiple Intersection tool enabled the identification of areas that concurrently met the criteria of elevation, slope, temperature, and precipitation considered suitable for conilon coffee cultivation. The resulting total area was 7,243.78 km², representing approximately 22.46% of the total area of the evaluated municipalities. However, the spatial distribution of these areas was highly heterogeneous among the municipalities (Figure 5A).

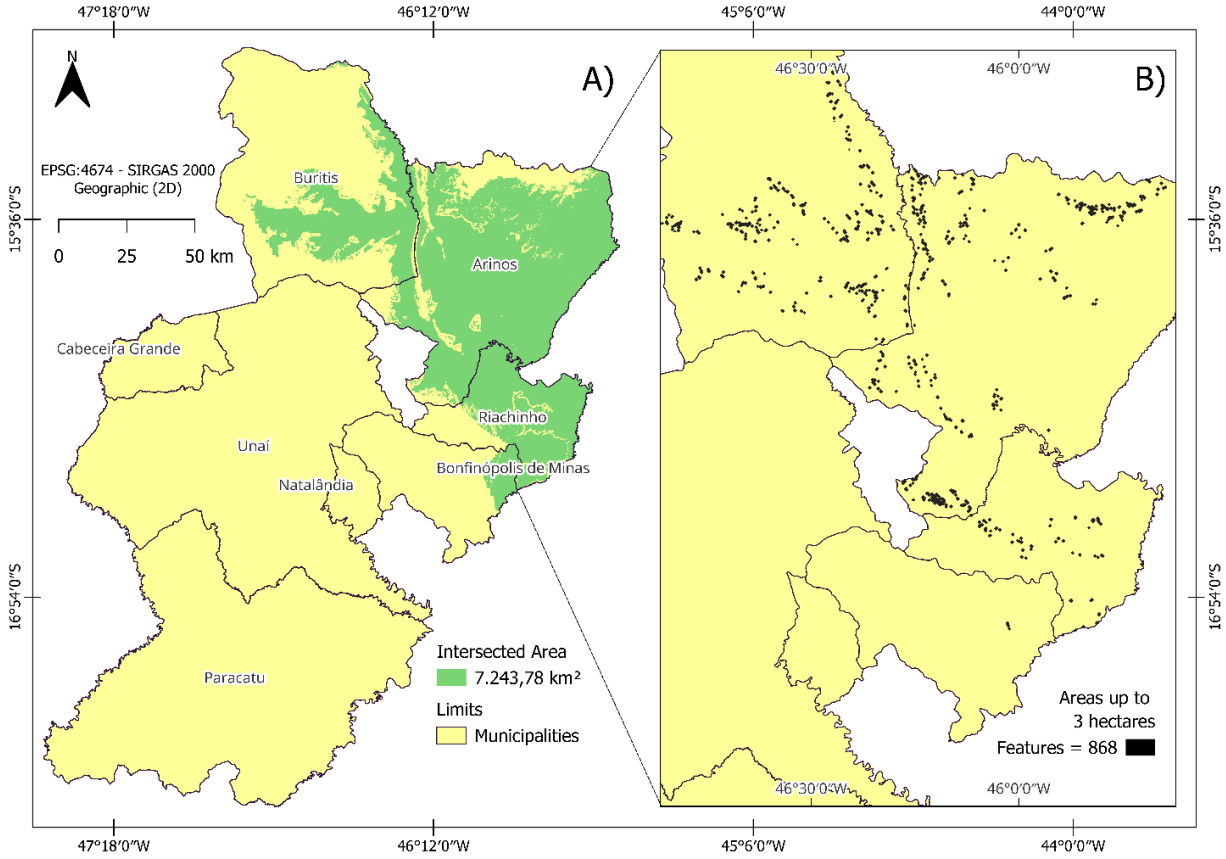


Figure 5 – Delimitation of the intersected area of interest (A) and areas up to three hectares (B) for the experimental study.

Arinos exhibited the largest extent of suitable areas, totalling 4,347.91 km², corresponding to 82.36% of its territorial area. Buritis ranked second, with 1,408.13 km² classified as suitable, equivalent to 26.95% of the municipality. Riachinho presented 1,279.99 km² of areas considered suitable, representing 74.45% of its territory. Bonfinópolis de Minas showed only 207.75 km² simultaneously meeting the established criteria, corresponding to 11.23% of its municipal area. No areas meeting all environmental criteria simultaneously were identified in the municipalities of Unaí, Cabeceira Grande, Paracatu, and Natalândia (Figure 5B).

Among the factors evaluated in the multicriteria analysis, Figure 5B demonstrates that the areas resulting from the intersection of the different criteria exhibited a heterogeneous spatial distribution, indicating that not all considered requirements were simultaneously fulfilled across all municipalities within the study area. This pattern suggests the existence of constraints imposed by the combination of climatic, environmental, and topographic factors, leading to a reduction in the areas potentially suitable for cultivation. According to Zignol et al. (2023), the interaction between atmospheric factors of a macroclimatic nature, such as solar radiation, temperature, and atmospheric evaporative demand, and local aspects, including topography, environment, and climate, promotes the formation of heterogeneous microclimatic conditions across space and time in coffee cultivation systems.

3.3. Interpolated Productivity and Percentage Deviation from the Mean

In addition to the quantification of suitable areas, the resulting intersection polygons were individualised to identify areas of up to 3 hectares, in accordance with the funding criteria established by the CAPUL Conilon Coffee Project. A total of 868 features were identified among the evaluated municipalities, covering 572.90 ha. Arinos presented the highest number of areas meeting this criterion, with 488 polygons and a cumulative area of 263.23 ha, followed by Buritis, with 320 polygons totalling 255.26 ha. Riachinho presented 55 polygons corresponding to 53.44 ha, whereas Bonfinópolis de Minas recorded only five areas, totalling 0.97 ha. These results demonstrate the existence of a significant number of small areas potentially suitable for crop establishment,

particularly in the municipalities of Arinos and Buritis, where greater territorial availability is associated with favourable environmental conditions.

The spatial analysis of mean municipal conilon coffee productivity revealed considerable variation among the municipalities participating in the CAPUL Conilon Coffee Project. Spatial interpolation using the IDW method, as described in the Materials and Methods (Section 2.3), enabled the visualisation of the regional productivity distribution (Figure 6A) and the identification of spatial gradients associated with the values observed in the municipalities. Based on the data provided by CAPUL, the mean regional productivity was 29.3 bags ha^{-1}, which was used as a reference for the development of the percentage deviation from the mean map (Figure 6B).

Compared with values reported for other coffee-producing regions, the results obtained in the present study demonstrate the productive potential of north-western Minas Gerais for conilon coffee cultivation. According to CONAB (2026), the Northern, Jequitinhonha, and Mucuri regions of Minas Gerais presented a mean productivity of 41.0 bags ha^{-1} in the 2025 harvest, with an estimated productivity of 39.7 bags ha^{-1} for the 2026 harvest. In the state of Espírito Santo, the main Brazilian producer of conilon coffee, mean productivity reached 54.8 bags ha^{-1} in the 2025 harvest, with an estimated 50.3 bags ha^{-1} for 2026. Although the mean regional productivity observed among the municipalities participating in the CAPUL Conilon Coffee Project was 29.3 bags ha^{-1}, municipalities such as Buritis presented mean productivity values of up to 55 bags ha^{-1}, similar to those recorded in Espírito Santo and higher than those observed in the Jequitinhonha and Mucuri Valleys and Northern Minas Gerais regions. These results demonstrate that north-western Minas Gerais contains areas with high suitability for conilon coffee cultivation, capable of achieving productivity levels comparable to those observed in Brazil's main production centre for this species, as demonstrated in Figure (6B) of the study.

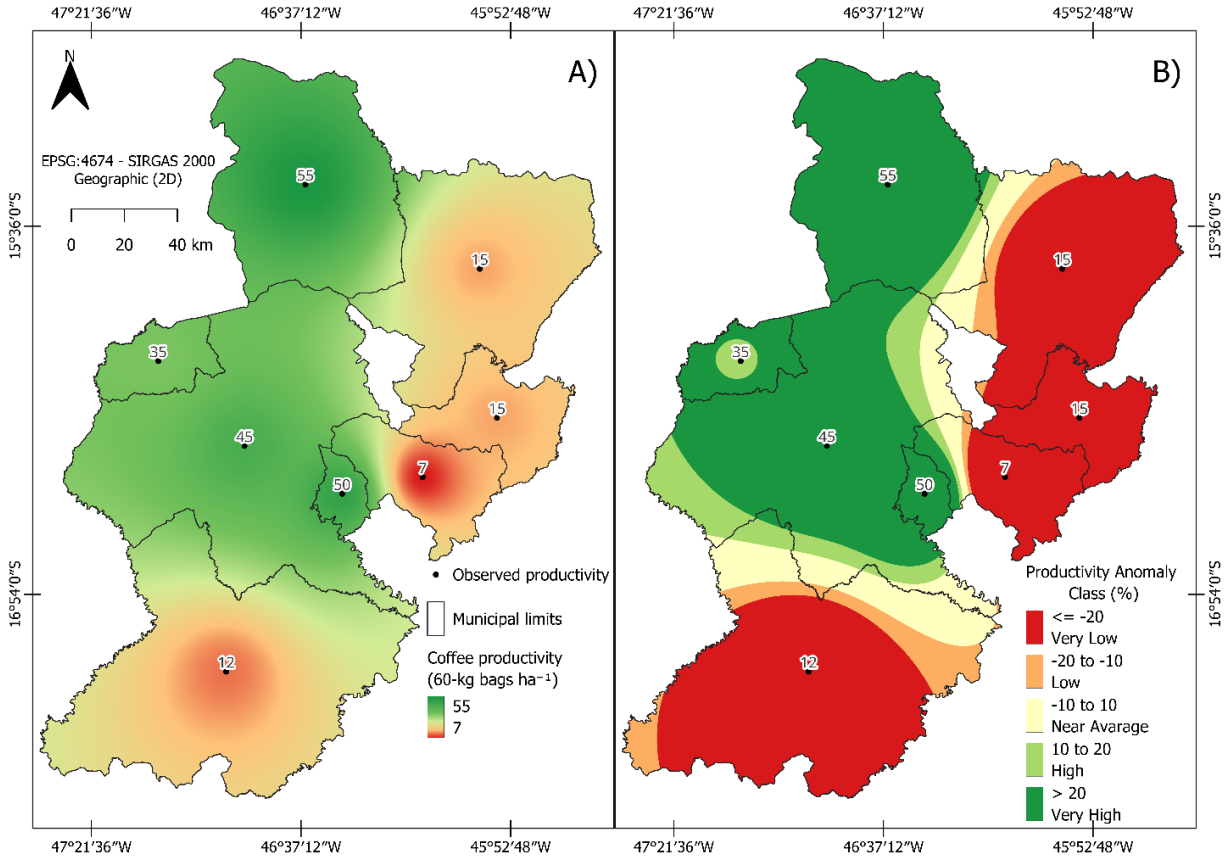


Figure 6 – Spatial distribution of mean coffee productivity in the study area. (A) Inverse Distance Weighting (IDW) interpolation of municipal coffee productivity (bags ha^{-1}), showing the productivity values observed at municipal centroids. (B) Productivity anomaly (%) in relation to the regional mean productivity (29.3 bags ha^{-1}). Municipal boundaries are shown for reference.

The classification of the interpolated surface into five anomaly classes indicated a predominance of areas close to the regional mean. The "Near Average" class (−10 to +10%) covered 34,986.85 km², representing 54.24% of the total analysed area. Areas classified as "Very Low" (< −20%) totalled 13,141.76 km², corresponding to 20.37% of the region, whereas the "Very High" class (> +20%) occupied 12,001.87 km², equivalent to 18.61% of the total area. The intermediate classes showed lower spatial representation, with 1,711.74 km² observed for the "Low" class (−20 to −10%) and 2,662.90 km² for the "High" class (+10 to +20%), corresponding to 2.65% and 4.13% of the analysed area, respectively.

This demonstrates that more than half of the region presents productivity values close to the mean observed for the municipalities participating in the project, whereas approximately 39% of the area is located within productivity extremes, distributed between classes considerably below and above the regional mean. Although the interpolation was performed using a limited number of points represented by municipal centroids, the results enabled the identification of spatial productivity trends and demonstrated the applicability of geoprocessing tools for exploratory analysis of conilon coffee production at a regional scale.

Overall, the results demonstrate that the delimitation of environmentally suitable areas, combined with the spatial analysis of productivity, constitutes a strategic tool for guiding the sustainable expansion of conilon coffee cultivation in north-western Minas Gerais. The identification of areas that combine favourable climatic and environmental conditions enables the reduction of establishment risks, optimisation of natural resource use, and the direction of technical assistance actions and territorial planning strategies. In this context, conilon coffee presents high potential as an alternative for diversifying regional family farming production systems, particularly in environmentally suitable areas, contributing to increased income generation, strengthening the resilience of rural properties, and promoting sustainable development in the region.

4. Conclusion

Based on the results presented, it can be concluded that the north-western region of Minas Gerais exhibits environmental potential for conilon coffee cultivation, although this potential is heterogeneous among the analysed municipalities. The analysis demonstrated that precipitation was the most restrictive factor for crop suitability, whereas temperature, elevation, and slope were more favourable across most of the territory. Only some municipalities met all the established criteria, particularly Arinos, Buritis, and Riachinho, which concentrated the largest extensions of suitable areas and presented the highest number of small areas of up to 3 hectares, in accordance with the funding criteria of the CAPUL Conilon Coffee Project.

Future prospects for conilon coffee cultivation in north-western Minas Gerais are promising, particularly considering the region's capacity to achieve productivity levels comparable to those of the country's main producing centres, as demonstrated by the results obtained in Buritis (up to 55 bags ha^{-1}). The strengthening of the CAPUL Conilon Coffee Project, through the expansion of the number of participating cooperative members and continuous technical training, may consolidate the crop as a viable alternative for productive diversification in family farming systems, reducing dependence on dairy cattle production and increasing the economic resilience of rural properties.

Future studies should advance the integration of prospective climate models, considering climate change scenarios, as well as the use of higher spatial resolution remote sensing techniques to improve the identification of suitable areas. The development of a participatory geospatial monitoring system, involving farmers themselves in the recording of production and phytosanitary data, could enhance the generation of local knowledge and contribute to the sustainability and long-term continuity of coffee cultivation in the region.

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