RBGF
ISSN:1984-2295

Revista Brasileira de Geografia Física

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

# Physical-Environmental Characterization of Areas for the Cultivation of Guaraná *(Paullinia cupana)* in Bahia, Brazil

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Artigo recebido em 20/06/2023 e aceito em 02/03/2024

**ABSTRACT**

Brazil is the world's leading producer of guarana and Bahia is the largest producing state, which suggests the need for cultivation planning. In this study, the physical-environmental factors of six municipalities in Lower Southern Bahia, Brazil were characterized to identify favorable areas for guarana cultivation. A database with the basic physical-environmental conditions was used to characterize and identify such areas. As described in the literature, the thresholds of conditioning factors for successful cultivation were selected using Structured Query Language (SQL) based on Geographic Information Systems (GIS), with logical operators and overlay tools. The factors considered in the analysis were soils (drainage and texture), climate (precipitation and temperature), and topography (slope). The results indicate the existence of favorable areas for guarana cultivation in Lower Southern Bahia, Brazil, which can significantly contribute to the planning and optimization of fruit cultivation in the region. A total of 23,489.7 hectares were considered favorable areas for guarana cultivation. This value is double the area allocated for cultivation in Brazil and more than four times the area allocated for harvesting in Bahia.

Key-words: Crop planning. Land use and occupation. Physical-environmental factors. SQL. GIS.

# Caracterização Físico-Ambiental de Áreas de Cultivo de Guaraná (Paullinia cupana) na Bahia, Brasil

**RESUMO**

O Brasil é o maior produtor mundial de guaraná e a Bahia é o maior estado produtor, o que sugere a necessidade de planejamento do cultivo. Neste estudo, foram caracterizados os fatores físico-ambientais de seis municípios do Baixo Sul da Bahia, Brasil, para identificar áreas favoráveis ao cultivo do guaraná. Foi utilizado um banco de dados com as condições físico-ambientais básicas para caracterizar e identificar tais áreas. Conforme descrito na literatura, os limites dos fatores condicionantes para o sucesso do cultivo foram selecionados utilizando Linguagem de Consulta Estruturada (SQL), baseada em Sistemas de Informação Geográfica (SIG), com operadores lógicos e ferramentas de sobreposição. Os fatores considerados na análise foram solos (drenagem e textura), clima (precipitação e temperatura) e topografia (declive). Os resultados indicam a existência de áreas favoráveis ao cultivo do guaraná no Baixo Sul da Bahia, o que pode contribuir significativamente para o planejamento e otimização da fruticultura na região. Um total de 23.489,7 hectares foram considerados áreas favoráveis ao cultivo do guaraná. Esse valor é o dobro da área destinada ao cultivo no Brasil e mais de quatro vezes a área destinada à colheita na Bahia.

Palavras-chave: Planejamento de culturas. Uso e ocupação do solo. Fatores físico-ambientais. SQL. SIG.

## Introduction

Fruit production plays a significant role in the Brazilian economy. According to data released by the Food and Agriculture Organization (FAO) for the year 2022, fruit production in Brazil was 41.7 million tons, accounting for 4.46% of global production, harvested from 2.31 million hectares (FAOSTAT - Statistics, 2024). In the specific case of guarana cultivation (*Paullinia cupana*), Brazil is the largest global supplier and virtually the sole commercial-scale producer, except for small producing areas in the Venezuelan Amazon (Marques et al., 2019; Silva et al., 2022a).

Data from the Brazilian Institute of Geography and Statistics (IBGE) for 2022 reported that 10,762 hectares were allocated for guarana cultivation, totaling 10,391 hectares of harvested area with a production of 2,460 tons of dried seeds and yield of 237 kilograms per $ha^{-1}$ (Ibge, 2024a). In Bahia, which has the highest concentration of production, the area allocated for cultivation was 5,538 hectares, with the entire area being harvested. A total of 1,554 tons of dried seeds were generated, accounting for 63.17% of the country's production, which represented a yield of 281 kilograms per $ha^{-1}$, which is higher than the national average (Ibge, 2024a).

The guarana plant is a low-growing shrub, native to the Amazon region of Brazil (Carciochi et al., 2021). The medicinal and stimulant properties of its fruit are recognized worldwide (Santos et al., 2019) and have attracted the interest of the pharmaceutical and food industries (Silva et al., 2022b). Guarana seeds have various pharmacological functions, such as neuroprotective activity (Roggia et al., 2020), antimicrobial and antioxidant properties, and anticancer effects. They also have stimulating and cognitive abilities, promote liver protection, and aid in weight loss (Marques et al., 2019). In the beverage industry, guarana seeds are widely used in the production of non-alcoholic drinks. Approximately 70% of Brazil's production is used for manufacturing juices and, more popularly, energy drinks and soft drinks (Silva et al., 2021). The properties of guarana have created a promising market for the agricultural producer due to the industrial interest, increasing demand, and a significant increment in planted areas (Marques et al., 2019).

Recent studies conducted on guarana have explored various approaches. These include investigation of the non-volatile chemical composition of methanolic extracts of nectar and whole guaraná flowers (de Oliveira et al, 2024), synthesis and characterization of silver nanoparticles using aqueous extract of guarana leaves (Lima et al, 2024), investigation of the antioxidant capacity of supercritical guarana extracts by different methods (Marques et al, 2024), evaluation of the damage caused by glyphosate to the development and quality of guaraná seedlings (Konrad et al, 2023), investigation of the effect of aqueous powder extract on cholesterol absorption mechanisms (Figueira et al., 2022), highlight for the potential anticancer effects of guarana against lung, colorectal, and breast cancer (Machado et al., 2022; Nascimento et al., 2022; Reguengo et al., 2022), evaluation of the co-encapsulation of probiotics and seed extract using complex coacervation (Silva et al., 2022b; Silva et al., 2022c), and assessment of the current importance of pollination services for major crops, including guarana, in Argentina, Brazil, Chile, Mexico, and Uruguay (Basualdo et al., 2022).

The studies that used guarana from Bahia followed the same trend, as they focused on chemical analyses (Silva et al., 2019; Mendes et al., 2019; Santos et al., 2019; Silva et al., 2021; Salles et al., 2022; Silva Junior et al., 2022; Farias et al., 2022).

The volume of research conducted on guarana has highlighted concerns regarding the physicochemical characteristics of the plant, particularly the seeds. However, the analysis of the physical environment components proves to be a fundamental tool for crop planning, as knowledge of plant requirements is a premise that assists in agricultural planning aiming for increased productivity, profitability, and reduced losses due to climatic factors (Duarte, Nunes, and Martins Filho, 2020). In other words, it is necessary to analyze the environmental conditions in terms of their suitability for the intended land use. The survey of the characteristics and properties of natural resources, as well as their distribution in the landscape, therefore, enables an analysis of favorable areas for cultivation.

Cultivating guarana in Lower Southern Bahia offers several advantages. However, there is still insufficient knowledge to fully maximize the planning of this crop. Areas are considered favorable when they simultaneously exhibit the physical-environmental characteristics recommended in the literature, which are known to contribute to successful cultivation locations in Brazil. These areas represent significant levels of suitability for cultivation. Information systematization and spatialization are important for control, organization, and land management, and require the use of tools and techniques that facilitate automated processing, such as those available in GIS.

In this context, the objective was to characterize the physical-environmental conditions in six municipalities of Lower Southern Bahia, Brazil, with the aim of identifying favorable areas for cultivating guarana. For this purpose, a database containing information on the physical-environmental conditions served as the basis for the characterization and recognition of these areas. As described in the literature, the thresholds of the conditioning factors for successful cultivation were selected using SQL based on GIS, applying logical operators and overlay tools.

## Materials and methods

*Study area*

The study area corresponds to the municipalities of Camamu, Igrapiúna, Ituberá, Nilo Peçanha, Taperoá, and Valença, totaling 381,033.6 hectares (Figure 1). Data from IBGE reveal that 181,294 people reside in the studied municipalities (Ibge, 2024b). These municipalities are the main producers of guarana in Bahia and are located on the east coast of the state, known as the “Costa do Dendê”. They are located approximately 100 km south of the state capital, Salvador. On a regional scale, they are part of a region known as the Lower South Identity Territory, which is composed of 15 municipalities (Bahia, 2018).

The relief of the area presents significant variations. Inland, some hills and valleys are utilized for diverse agricultural activities, as well as commercial and subsistence livestock farming (Bahia, 2018). In the coastal zone, there are low-lying areas characterized by marine plains, river-lagoon systems, and river-marine systems, where fishing and tourism activities prevail (D'alexandria, Silva & Souza, 2015). The construction of the new BA-001 highway, which connects the main coastal tourist zones of Bahia, has facilitated access to the municipalities, consolidating this territory as a tourist hotspot and an important economic hub.

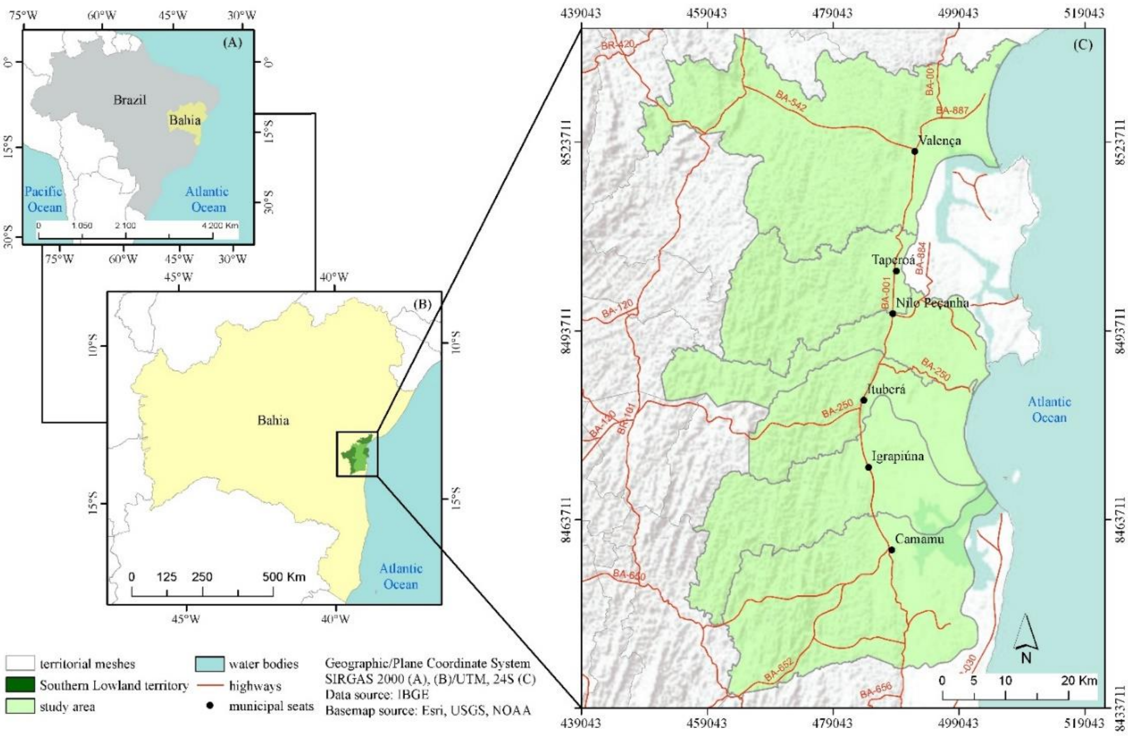


Figure 1. Location of the study area. (A) Borders of Brazil (gray) and the state of Bahia (light yellow). (B) Borders of the state of Bahia (light yellow), the Lower South Identity Territory (dark green), and the studied municipalities (light green). (C) Borders of the studied municipalities: Valença, Taperoá, Nilo Peçanha, Ituberá, Igrapiúna, and Camamu.
IBGE: Brazilian Institute of Geography and Statistics. Esri: Environmental Systems Research Institute. USGS: United States Geological Survey. NOAA: National Oceanic Atmospheric Administration.

*Study planning*

The work was organized into three stages, namely: I - Gathering information about the physical-environmental conditions for cultivation; II - Preparation of basic maps and physical-environmental characterization; and III - Identification of favorable areas for guarana cultivation. For this purpose, the *ArcGis®* 10 GIS software was used, starting from the organization of the geographic database to the production of map layouts. The data sources were government agencies, with information extracted directly from their websites, except for climatic data, which was obtained from Xavier (2022). The official data for calculating the areas of the municipality boundaries were the vector files available on the IBGE website. Considering the different data sources for various themes and the diverse indentations in the coastline shapes, all cartographic data were adjusted and clipped based on the municipal boundary file, with overlapping inconsistencies categorized as "Unclassified."

*Survey of information on physical-environmental conditions for cultivation*

The literature was reviewed to gather basic information on the physical-environmental factors that contribute to the interpretation of the landscape and constitute the conditions under which guarana has been successfully cultivated. The searches were conducted in the databases of Web of Science (WoS) and Science Direct (SD), as well as on official websites of the Brazilian government, using search terms such as "guarana," "Paullinia cupana," and "guarana cultivation." The results were organized according to the available digital data of the physical-environmental characteristics, considering existing thematic maps and the generation of additional information. From this survey, the attributes listed in Table 1 were obtained.

**Table 1.** Attributes used in the diagnosis of favorable areas for the cultivation of guarana

| Attributes | Data source | Procedures | Recommendation for cultivation |
|---|---|---|---|
| Soil drainage | IBGE (2022) | Shapefile manipulation with soil class characteristics and insertion of drainage data | Well-drained soil, no waterlogging problems (Poltronieri et al., 1995; Fundação Getúlio Vargas - FGV, 2003) |
| Soil texture | IBGE (2022) | Shapefile manipulation with soil class characteristics and insertion of texture data | Medium and clayey to very clayey textures (Poltronieri et al., 1995; Tavares et al., 2005) |
| Slope | INPE (2022) | DEM data manipulation of TOPODATA/SRTM images, 30 m resolution | Slightly sloping or flat if well drained (Tavares et al., 2005) |
| Precipitation | Xavier et al. (2022) | Interpolation of precipitation data and generation of rainfall map | Average annual precipitation : 1,500 mm – 3,000 mm (Tavares et al., 2005) |
| Temperature | Xavier et al. (2022) | Interpolation of temperature data and generation of thermal map | average annual temperature: 24 ºC – 27 ºC (Castro, 1992) |

EMBRAPA: Brazilian Agricultural Research Corporation. INPE: National Institute for Space Research. IBGE: Brazilian Institute of Geography and Statistics. DEM: Digital Elevation Model. TOPODA: Geomorphometric Database of Brazil. SRTM: Shuttle Radar Topography Mission.

*Preparation of basic maps and physical-environmental characterization*

The geo-referenced data of the physical-environmental attributes were organized through the construction of a Geographic Database (GD), which initially aimed to consolidate the area recognition base. Preexisting raster (orbital) and vector (point, line, and polygon) data were gathered, and primary data were also generated. The physical and environmental characterization was carried out through the interpretation of data from consolidated cartographic materials, basic maps generated from the GD, as well as additional non-graphical information from specialized literature and institutional sources.

The raster and vector data were adjusted to fit within the information plans (IPs). When necessary, they were transformed into the same cartographic reference system due to different coordinate systems and/or *Data* sources. Thus, reprojection was carried out to the coordinate system and *Datum* incorporated by the Brazilian Geodetic System, the Geocentric Reference System for the Americas 2000 (SIRGAS2000), using the Universal Transverse Mercator (UTM) projection. The data was clipped to fit within the boundaries of the study area using the official municipal boundary shapefiles provided on the official website of the IBGE. In the GIS environment, the clipping tools used were *Clip* for vector features and *Extract by Mask* for raster features. In the characterization of the physical-environmental factors, the original mapping scales were maintained. The lithological and soil data were kept at a scale of 1:250,000, while the other data were adjusted to a compatible scale of 1:100,000.

*Land use and occupation*

The adaptation of the MapBiomas Project for the year 2021, had obtained data on land use and occupation (MapBiomas, 2023). These data are from Collection 7, which had an overall mapping accuracy of 87.9%, based on the values from the confusion matrix provided by the institution. The mapping for the referenced year was performed using Land Remote Sensing Satellite (LANDSAT), Operational Land Imager (OLI) sensor.

Initially, the images were mosaicked, followed by classification, filtering, and integration of the data, leading to the creation of the land use and occupation map. Five major groups of land use and occupation for the study area, as shown in Table 2, were possible to identify with the mapping conducted by the institution.

**Table 2.** Land use groups and classes used by MapBiomas, for the year 2021

| Group | Class | Description |
|---|---|---|
| Forest (1) | Forest formation | encompasses the dense, open and mixed ombrophilous forest and semi-deciduous seasonal forest, besides the pioneer tree formation |
| | Mangrove | formation regularly inundated by the tide and related to the Mangrove ecosystem |
| | Wooded Sandbank Vegetation | present on sandy soils or on dunes in the coastal zone |
| Natural formation no forestry (2) | Wetland | vegetation with fluvial and/or lacustrine influence |
| | Other no forest formations | other non-categorized formations |
| | Salt flat | associated with the higher, hypersaline and less flooded mangrove zone, in the transition with the dry land |
| | Herbaceous Sandbank Vegetation | vegetation with fluviomarine influence |
| Agriculture and pasture (3) | Pasture | pasture areas, natural or planted, linked to cattle raising activity |
| | Mosaic of uses | areas where no distinction was made between agriculture and pasture |
| | Forest plantation | tree species planted for commercial purposes |
| Water bodies (4) | River, lake and ocean | continental water bodies (rivers, lakes, dams, reservoirs and other water bodies) |
| | Aquaculture | artificial lake area, with aquaculture or salt culture practices |
| -------- | No vegetated areas | areas without vegetation, such as exposed soil, mining, infrastructure and urban areas |

*Climate data*

The climate data were limited to a time series of 35 years (1985 – 2019), a period that allows a comprehensive knowledge of how temperature patterns evolve throughout the year over a long period, normally being considered at least 30 years (Serrano-Notivoli et al., 2020). According to the methodology proposed by Xavier et al. (2022), they were acquired from spatialized meteorological points. The authors considered available data from conventional and automatic rain gauges and rainfall stations for the compilation, sampling, and interpolation of data, generating a grid of daily information on meteorological variables in Brazil. The data were kindly provided by the first author in Microsoft Office Excel format (.xls).

The temperature and precipitation parameters were used to observe the favorable ranges for cultivating guarana. Additionally, data on relative humidity, solar radiation, evapotranspiration, and wind speed were included in the table, which assisted in synthesizing the climatic aspects. Initially, the daily data from the time series were grouped into months and then into years, resulting in accumulated data and annual averages for the tabulated parameters within the series, for each of the meteorological points.

It was possible to distribute 61 meteorological points around the study area within a bounding rectangle, in vector format. The Inverse Distance Weighted (IDW) interpolator - found in the Spatial Analyst module, and Interpolation toolbox - was used to generate rainfall and thermal maps, both in matrix format.

This interpolation method uses a weighted linear combination of sampling points to determine the values of the resulting cells, with greater weight assigned to points closer to the location of interest (Nistor et al., 2020; Yang et al., 2020). According to Ly, Charles, and Degré (2011), this interpolator was widely used with the exponent of two, which is commonly referred to as inverse-square distance (ISD). The use of IDW has shown good results (Xavier et al., 2016; 2022), which is why it was also employed in this study. Equation 1 determines how to calculate the values for the points.

$$Z_p = \frac{\sum_{i=1}^{n}\left(\frac{z_i}{d_i^p}\right)}{\sum_{i=1}^{n}\left(\frac{1}{d_i^p}\right)} \quad (1)$$

Where, $Z_p$: unsampled point value. = sum of points to interpolate. $Z_i$: sampled point value. $d_i$: distance from the sampled point to the unsampled point. p: power/exponent selected by the user.

*Types of relief*

The matrix data of relief used were obtained from the website of INPE (Inpe, 2022), where images from the Shuttle Radar Topography Mission (SRTM) sensor of the Geomorphometric Database of Brazil (TOPODATA) were acquired. Specifically, the data from sheets 13S39ZN, 14S39ZN, 13S405ZN, and 14S405ZN were used, with a spatial resolution of 30 meters. The hypsometric distribution and slope distribution were extracted from the Digital Elevation Model (DEM) of the radar images, using the Spatial Analyst module, and Surface and Reclassify toolboxes.

The hypsometry was obtained by observing the main patterns of the present relief forms, with the reclassification of the DEM into 4 classes. The slope classes were organized according to Santos et al. (2018), which classify the reliefs based on slope ranges as follows: flat (0-3%), gently undulating (3-8%), undulating (8-20%), hilly (20-45%), mountainous (45-75%), and steep (>75%).

*Rock substrates and soils*

Studies in the specialized literature have shown characteristics related to rock substrates and soil classes, which served as a basis for the characterization of these topics. Other studies were also considered with additional information on favorable drainage conditions and soil texture.

The digital lithology data used were obtained from the websites of the Basic Geological Surveys Program of Brazil, developed by the Geological Survey of Brazil (CPRM), and from data cataloged by IBGE (Ibge, 2022a). Based on the color palette used by CPRM, it was possible to manipulate the vector data and create the map of rock substrates, adapting the lithological information accordingly. The digital pedological data used were obtained from the website of IBGE (Ibge, 2022b), from which the vector information of soil classes was derived. The color palette was classified according to the tones found in the literature (Santos et al., 2018).

*Recognition of favorable areas for guarana cultivation*

In this stage, it was necessary to convert the data to compatible scales. Considering that the data of rock substrates and soils are in the 1:250,000 scale, the other data underwent a conversion process to match this scale. For this purpose, a cartographic generalization tool was employed, running the Douglas-Peucker algorithm

(Douglas & Peucker, 1973), which is widely used in this type of process (Tang et al., 2021a). This algorithm is located in the Cartography module, Generalization toolbox, and Simplify Polygon tool.The adopted Cartographic Accuracy Standard (CAS) was Class A (Brasil, 1984), considering the extrapolation of the generalized data.

Additionally, the Polynomial Approximation with Exponential Kernel (PAEK) polygon smoothing algorithm, developed by Bodansky, Gribov, and Pilouk (2002), was operationalized. This algorithm is found in the Cartography module, Generalization toolbox and Smooth Polygon tool. Its use after applying the Douglas and Peucker algorithm (1973) was recommended by Azevedo, Nascimento, and Candeias (2019) to achieve better spatially distributed results, thus modeling the vector line by adjusting the points to a smoothly curved surface (Zollini et al., 2019; Fedorca et al., 2021). PAEK calculates smoothed lines using the technique of parametric continuous averaging. The coordinates of the current point are calculated by the weighted average of the coordinates of all points in the original line. The weights of each point decrease with the distance along the line to the current point (Esri, 2022).

Next, the overlay of the IPs was performed to identify the favorable areas for cultivation based on the specialized literature (Table 1). For this purpose, SQL operators were used to manipulate the relational data. The selected data were exported, creating conditions for the use of the Overlay cartographic analysis tool, which calculates the geometric intersection of the input features. The features or parts of features that overlap in all layers and/or feature classes are recorded in the output feature class. In the end, polygons belonging to forests, non-forested natural formations, wetlands, bodies of water, and urban areas were excluded from the favorable areas, leaving only areas more suitable for cultivation.

## Results and discussion

The Physical-environmental characterization aimed to understand the arrangement of landscape components to identify favorable areas for guarana cultivation in the region, based on land use and land cover, climatic conditions (precipitation and temperature), relief (elevation and slope), rock substrates, and soils (Figure 2). The data on rock substrates and elevation, although not directly used for the delineation of favorable areas, are important components that contribute to the interpretation of the landscape; therefore, they were considered in the characterization process. Understanding this composition can contribute to the development of actions focused on environmental conservation and territorial planning in the region. By directing the cultivation, it is possible to optimize land use, whether by expanding cultivation to favorable regions or reducing the required land area. This allows for more efficient and sustainable use of agricultural resources.

*Land use and land occupation*

The non-anthropized areas indicated forest groups and non-forest natural formations, in addition to the *restinga* class, equivalent to 64.55% of the observed uses and occupations. The anthropized spaces comprised the groups of non-vegetated, agricultural and pasture areas, in addition to the aquaculture class, with 30.26% of the total mapped areas. The remaining 5.36% consisted of areas that were not classified or were occupied by bodies of water such as rivers, lakes, and the ocean (Figure 2A and Table 3).

Forest formations are distributed over an area that covers approximately 56% of the land surface. Following the geomorphological pattern of the region, these formations can be predominantly found in undulate to steep terrains, present in areas characterized by hills and ridges. In areas closer to the coast, their occurrence varies from flat to undulating terrain. Considering the ecological role and ecosystem services provided by forests, the conservation and/or preservation of these areas should be evaluated in any land planning scheme. Their clearance for cultivation purposes is not recommended as the first option. Among the ecosystem services provided, forests play a crucial role as carbon storage in above-ground biomass, energy providers, and regulators of water and climate (Mengist, Soramessa & Lugese, 2020, Van Der Hoff et al., 2022; Sultana et al., 2023).

In the eastern sector, along the coastal areas, the presence of coastal forest is evident, represented by mangroves. Mangroves are transitional ecosystems between terrestrial and marine environments, serving as a nursery for biodiversity and providing ecosystem services to local communities (Rodrigues et al., 2023). Therefore, they require attention and preservation efforts. There are also notable vegetation types such as arboreal *restinga* (wooded sandbank vegetation) and other non-forest formations, including herbaceous *restinga* (herbaceous sandbank vegetation), *apicum* (salt flats), wet grasslands, and swampy areas. All of these environments are sensitive to disturbance and have certain limitations and fragility due to soil salinity and drainage issues; therefore, their preservation is necessary.

Changes in land use and land cover alter surface-atmosphere interactions by modifying the timing and magnitude of energy fluxes, impacting the partitioning of available energy, and consequently, the climate and water balance (Caballero, Ruhoff & Biggs, 2022). Time series of satellite images indicate changes between 1985 and 2021, with agriculture and livestock expanding by over 25,000 hectares, representing a 28.78% increase in this activity in the study area (Mapbiomas, 2023). This reflects a reduction in natural formations and an expansion of pastures and cultivated areas. The research data indicate that these activities, including the cultivation of guarana, are primarily distributed in the interior of the study area, particularly in the central and western portions, with low occurrence near the coastal zone, thus confirming the logic of economic activities practiced in different parts of the territory, as mentioned by Bahia (2018) and D'alexandria, Silva & Souza (2015).

Among the municipalities, Valença is where the mosaic of land uses and pastures has the highest coverage (45,809.6 ha), with the pasture area value (18,139.4 ha) exceeding the sum of the other municipalities combined (16,514.7 ha). When assessing the scenario to suggest favorable areas for guarana cultivation, it is interesting to consider these spaces already occupied by anthropogenic activities as potential options for expanding cultivation, thus avoiding compromising the existing forest systems.

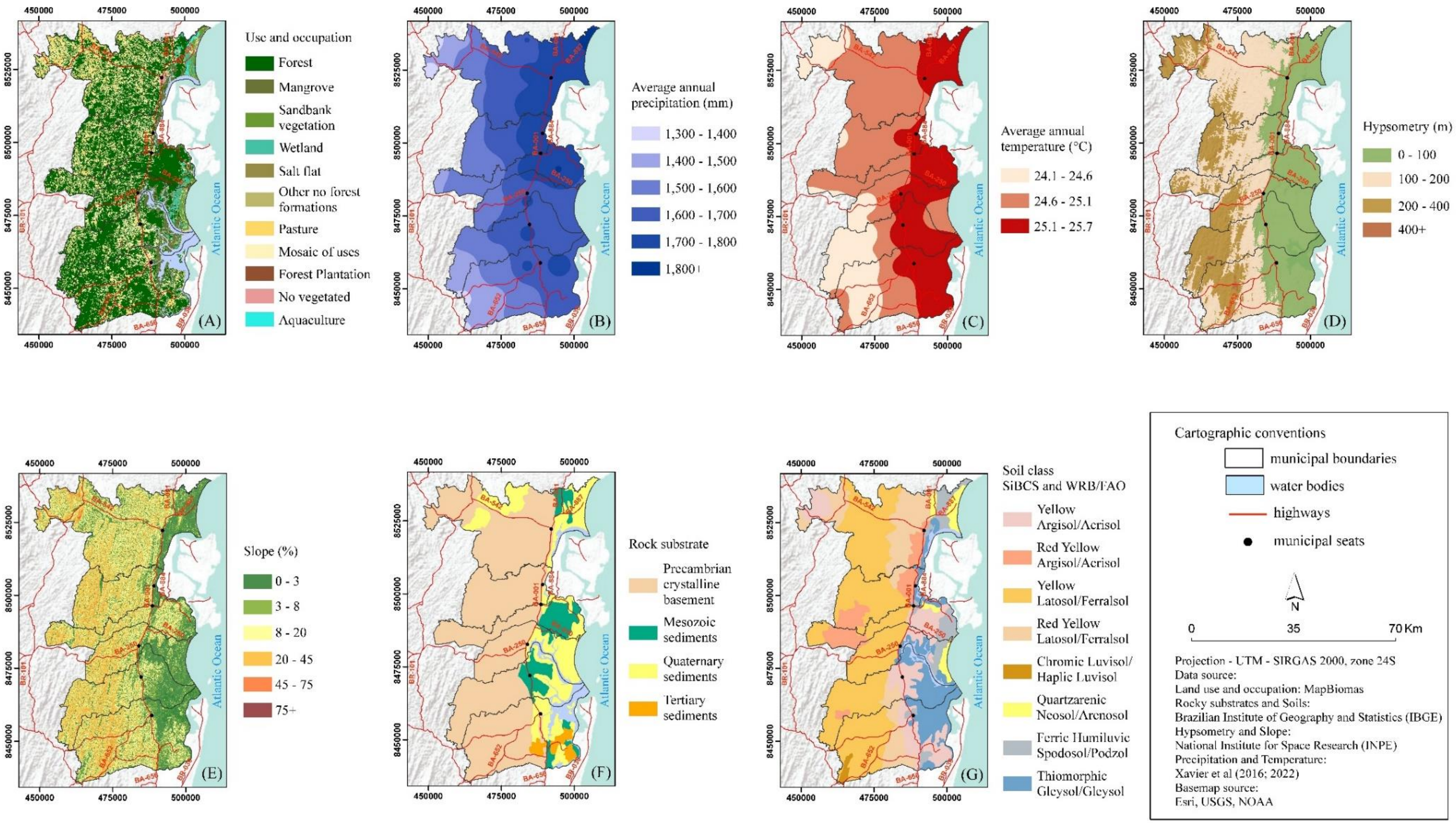


**Figure 2.** Physical-environmental attributes for characterizing the study area. (A) Land use and land cover. (B) Average annual precipitation. (C) Average annual temperature. (D) Hypsometric classes. (E) Slope classes. (F) Rock substrate. (G) Soil classes.
SiBCS: Brazilian Soil Classification System. WRB/FAO: World Reference Base for Soil Resources/ Food and Agriculture Organization of the United Nations. Esri: Environmental Systems Research Institute. USGS: United States Geological Survey. NOAA: National Oceanic Atmospheric Administration.

**Table 3.** Land use and occupation in the municipalities of Lower Southern, Bahia, Brazil, in the year 2021

| Groups | Classes | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|---|
| | | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| 1 | Forest | 49,981.6 | 32,074.3 | 22,439.8 | 27,285.4 | 27,641.4 | 53,858.4 | 213,280.9 |
| | Mangrove | 4,307.8 | 4,800.3 | 2,788.7 | 1,170.5 | 909.1 | 2,798.1 | 16,774.5 |
| 2 | Salt flat | 183.1 | 493.3 | 276.8 | 21.8 | 0.6 | 9.1 | 984.7 |
| | Wetland | 679.6 | 739.7 | 2,563.6 | 1,388.4 | 119.6 | 2,702.0 | 8,192.9 |
| | Other no forest formations | 53.4 | 39.4 | 9.0 | 36.1 | 15.1 | 16.1 | 169.1 |
| 3 | Mosaic of uses | 14,364.6 | 11,749.2 | 7,321.6 | 5,859.8 | 11,075.1 | 27,670.2 | 78,040.5 |
| | Pasture | 5,453.9 | 3,007.6 | 1,137.6 | 1,818.1 | 5,097.5 | 18,139.4 | 34,654.1 |
| | Forest plantation | 3.9 | 367.6 | 6.2 | 0.0 | 4.2 | 271.7 | 653.6 |
| 4 | Aquaculture | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 633.7 | 633.7 |
| | River, lake and ocean | 8,597.7 | 5,515.5 | 2,285.1 | 546.6 | 436.7 | 2,446.9 | 19,828.5 |
| | No Vegetated | 164.6 | 71.3 | 199.5 | 53.1 | 65.6 | 760.5 | 1,314.6 |
| | *Sandbank vegetation | 25.1 | 174.4 | 2,387.5 | 632.1 | 1.8 | 2,676.1 | 5,897.0 |
| | Unclassified | 78.6 | 52.3 | 94.5 | 51.2 | 5.8 | 327.1 | 609.5 |
| | Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

1: Florest. 2: Natural formation no forestry. 3: Agriculture and pasture. 4: Water bodies. * Sum of wooded and herbaceous sandbank vegetation.

*Climatic conditions*

The study area is located in a coastal strip where rainfall averages exceed 1,800 mm annually, gradually decreasing towards the inland areas, reaching around 1,300 mm. The highest rainfall occurs from April to July. The ranges of average annual rainfall were organized from 1,300 mm to greater than 1,800 mm, in increments of 100 mm (Table 4 and Figure 2B).

The range of highest average annual rainfall varies between 1,600 ─┤1,700 mm, accounting for 39.06% of the study area. This rainfall range predominantly occurs in the territories of Ituberá, Igrapiúna, and Camamu. Values between 1,700 ─┤1,800 mm are prominent in the territories of Nilo Peçanha and Valença, while the municipality of Taperoá has a greater representation of its area with average annual rainfall between 1,500 ─┤1,600 mm. Annual average rainfall exceeding 1,800 mm was found in Valença and Nilo Peçanha. All of these rainfall ranges are considered favorable for guarana cultivation, with only those below 1,500 mm being disregarded, following the favorable rainfall ranges indicated by Tavares et al. (2005).

The average annual temperature in the region is 24.9°C, with minimum values in July and August, and maximum values between January and March. The predominant range of average annual temperature is between 24.6 ─┤ 25.1 ºC, with greater representation in the municipalities of Taperoá, Valença, Ituberá, and Nilo Peçanha (Table 5 and Figure 2C).

The highest average annual temperatures, ranging from 25.1 ─┤ 25.7ºC, are predominantly found in Nilo Peçanha, accounting for 47.36% of its territory. On the other hand, the lowest temperatures, ranging from 24.1 ├─┤ 24.6ºC, are more prevalent in Igrapiúna, with approximately 42.15% of the area in that municipality. This small temperature variation makes all the temperature ranges favorable for guarana cultivation, according to the range suggested by Castro (1992).

According to the Köppen Classification, the climate of the study area is defined as Af - Tropical Rainforest climate without a drought, characterized by relatively abundant rainfall throughout the year. The average monthly rainfall is above 60 mm, the temperature of the coldest month is above 18°C and the summers are long and hot, with the average temperature of the hottest month being above 22°C. The relative humidity is around 80%, with peaks in June and July, coinciding with periods of low temperatures and a low number of sunshine hours, resulting in lower evapotranspiration rates (Xavier et al., 2022). The total accumulated solar radiation amounts to 6,600 MJ $m^{-2}$, and the evapotranspiration reaches 1,405 mm. The wind speed shows little variation, ranging from 1.57 to 1.73 m $s^{-1}$ on average annually, decreasing from the coastal area towards the inland area (Xavier et al., 2022).

**Table 4.** Average annual precipitation of the municipalities of Lower Southern, Bahia, Brazil, from 1985 to 2019

| Intervals (mm) | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| 1,300 ├─┤ 1,400 | 1,635.2 | 519.9 | 0.0 | 0.0 | 0.0 | 2,847.2 | 5,002.3 |
| 1,400 ─┤ 1,500 | 20,156.9 | 9,078.3 | 0.0 | 2,909.9 | 0.0 | 8,678.1 | 40,823.2 |
| 1,500 ─┤ 1,600 | 22,405.4 | 13,867.9 | 10,849.7 | 12,018.5 | 18,344.6 | 18,426.2 | 95,912.3 |
| 1,600 ─┤ 1,700 | 34,157.1 | 33,032.4 | 26,284.7 | 2,753.0 | 13,917.6 | 38,672.6 | 148,817.4 |
| 1,700 ─┤ 1,800 | 5,539.3 | 2,586.4 | 4,375.5 | 20,815.6 | 13,110.3 | 41,547.3 | 87,974.4 |
| > 1,800 | 0.0 | 0.0 | 0.0 | 366.1 | 0.0 | 2,137.9 | 2,504.0 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

**Table 5.** Average annual temperature of the municipalities of Lower Southern, Bahia, Brazil, from 1985 to 2019

| Intervals (ºC) | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| 24.1 ├─┤ 24.6 | 24,656.9 | 24,904.1 | 9,131.7 | 1,886.9 | 1,675.3 | 15,225.7 | 77,480.6 |
| 24.6 ─┤ 25.1 | 25,484.7 | 10,047.5 | 19,990.3 | 18,569.2 | 36,657.5 | 73,115.8 | 183,865.0 |
| 25.1 ─┤ 25.7 | 33,752.3 | 24,133.3 | 12,387.9 | 18,407.0 | 7,039.7 | 23,967.8 | 119,688.0 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

Precipitation and temperature are the main variables in the fields of climatology and hydrology that allow us to understand climate change and key hydrological metrics (Shigute et al., 2023). They also contribute to knowledge about agricultural requirements. Most climate indices show the overall climate behavior and are useful for establishing cultivation limits based on factors such as frost frequency (Serrano-Notivoli et al., 2020) or favorable rainfall and temperature ranges for specific crops.

Among several factors, precipitation and temperature play a crucial role in determining of agricultural productivity (Volenec & Belovsky, 2018; Sinore & Wang, 2024). The duration and amount of rainfall during the summer and winter seasons are crucial for agricultural practices (Weldegerima et al., 2018). Furthermore, average monthly and annual temperatures and precipitation assist in understanding crop requirements. For example, temperature and precipitation changes can affect clay content in soil (Zhang et al., 2023). In general, when there is an increase in temperature and precipitation, chemical weathering makes the soil sticky and heavy. On the other hand, physical weathering produces sandy soil when there is high-temperature fluctuation and low precipitation (Liu et al., 2020), which can affect soil conditions for certain crops.

*Topography: hypsometry and slope*

The different types of topography in the area facilitate the understanding of the three-dimensional arrangement of features and the dynamics of the physical environment. Attributes such as slope and hypsometry contributed to the characterization of landforms, allowing the definition of four altimetric classes and six slope classes (Tables 6-7 and Figures 2D-2E).

The analysis of slope allows us to highlight the distribution of the terrain's inclinations in the landscape, which is an important characteristic for the balance between morphogenesis and pedogenesis. The steepness of the terrain slopes contributes to the instability of the slopes, as it facilitates surface runoff and leads to erosive processes and material movement. It was observed that slopes ranging from flat terrain (0 ├─┤ 3%) to gently undulating terrain (3 ├─┤ 8%) are mainly found on hilltops, tabular surfaces, and valley bottoms, where depositional processes are dominant. These slope classes also represent areas of coastal plains with flat terrain, with or without associated hills. There are coastal deposits, floodplains, and mangroves settled in these areas. Together, they cover 39.7% of the mapped area.

**Table 6.** Hypsometric classes defined for the municipalities of Lower Southern, Bahia, Brazil

| Intervals (m) | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| 0 ├─┤ 100 | 37,116.9 | 25,480.4 | 18,333.8 | 19,330.8 | 9,641.0 | 30,351.0 | 140,253.9 |
| 100 ─┤ 200 | 29,444.6 | 11,406.5 | 12,477.2 | 14,369.5 | 21,294.7 | 62,043.3 | 151,035.8 |
| 200 ─┤ 400 | 16,764.8 | 21,861.9 | 10,687.5 | 5,162.8 | 14,341.0 | 19,251.4 | 88,069.4 |
| >400 | 567.6 | 336.1 | 11.4 | 0.0 | 95.8 | 663.6 | 1,674.5 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

**Table 7.** Slope classes and their representation in the municipalities of Lower Southern, Bahia, Brazil

| Intervals (%) | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| 0 ├─┤ 3 | 19,695.5 | 16,425.0 | 12,103.9 | 7,544.6 | 5,825.6 | 23,766.3 | 85,360.9 |
| 3 ─┤ 8 | 16,016.0 | 10,069.6 | 6,853.8 | 7,409.4 | 5,675.0 | 19,900.6 | 65,924.4 |
| 8 ─┤ 20 | 28,926.5 | 16,968.4 | 11,932.2 | 14,446.7 | 15,986.2 | 43,840.8 | 132,100.8 |
| 20 ─┤ 45 | 18,558.2 | 15,331.4 | 10,436.4 | 9,274.5 | 17,413.3 | 24,203.4 | 95,217.2 |
| 45 ─┤ 75 | 695.0 | 290.3 | 183.6 | 187.9 | 471.4 | 573.4 | 2,401.6 |
| > 75 | 2.7 | 0.2 | 0.0 | 0.0 | 1.0 | 24.8 | 28.7 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

Very steep topographic characteristics are not suitable for crop production and pasture due to the inaccessibility and fragility of the terrain, which tends to have greater soil loss due to precipitation (Birhanu et al., 2019; Mushtaq et al., 2023). In a study conducted in Ethiopia, the same authors argued that in addition to the steep areas, the soils had low fertility and low water retention capacity, which can compromise the availability of agricultural land. Similarly to the conditions in the African country, in the study area, steeper slopes can pose challenges to agricultural production, particularly for guarana cultivation, which has requirements for slopes lower than those found in the steep Ethiopian areas.

Among other important factors, slope and elevation can play a key role in the occurrence and prediction of erosion (Guan et al., 2021, Zhao et al., 2021), as well as influence the patterns and distribution of land use and land cover, considering that they interfere with the supply of water and heat to vegetation and the physical and chemical conditions of the soil (Birhanu et al., 2019; Wang & Cheng, 2023). Additionally, they provide ecosystem services related to their changing characteristics (Mirghaed & Souri, 2023).

As a general rule, the prevalence of agricultural activities in predominantly flat areas can be attributed to the ease of agricultural practices such as plowing and irrigation, as well as the proximity to human settlements, which can lead to significant deforestation. In gentler slopes, water flows more slowly and the soil remains moist during the rainy season, making it a favorable period for production (Birhanu et al., 2019). The recommended slopes for cultivating guarana fit precisely within these ranges, as long as there is no soil waterlogging (Tavares et al., 2005), due to the ease of mechanization, better deposition compared to dissection, and mitigation of erosion effects. However, the favorable areas for cultivation are recorded in terrains outside the coastal plain, mainly due to the drainage conditions and soil texture present.

*Rock substrates*

The rock substrates were divided into four units, namely Pre-Cambrian Crystalline Basement, Mesozoic Sediments, Tertiary Sediments, and Quaternary Sediments (Table 8 and Figure 2F).

The Pre-Cambrian Crystalline Basement Unit mainly consists of metamorphic rocks formed in the Archean and Proterozoic periods, located in the Itabuna-Salvador-Curaçá Belt, part of the São Francisco Craton. The most common lithotypes are tonalitic orthogneisses of granulite facies and trondhjemitic orthogneisses (Neves, 2021). It is also possible to find a set of rocks composed, with a felsic member consisting of underbites and charnoenderbitic rocks, and a mafic member composed of metamorphosed gabbro-diorite in granulite facies (Garcia et al., 2018). There is also the presence of dike-like bodies of undifferentiated rock materials, abundant in ferromagnesian compounds and relatively low in silica content, known as mafic bodies.

**Table 8.** Rock substrates present in the municipalities of Lower Southern, Bahia, Brazil

| Units | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| Precambrian crystalline basement | 51,609.0 | 35,204.6 | 24,102.0 | 21,277.0 | 43,627.5 | 78,081.7 | 253,901.8 |
| Mesozoic sediments | 3,710.0 | 9,553.7 | 1,450.0 | 11,547.4 | 0.0 | 4,682.8 | 30,943.9 |
| Tertiary Sediments | 7,200.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 7,200.1 |
| Quaternary sediments | 13,117.7 | 9,627.9 | 13,674.3 | 5,681.3 | 1,277.1 | 27,153.7 | 70,532.0 |
| Water bodies | 8,218.0 | 4,678.4 | 2,221.9 | 304.5 | 467.8 | 2,331.5 | 18,222.1 |
| Unclassified | 39.1 | 20.3 | 61.7 | 52.9 | 0.1 | 59.6 | 233.7 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

The findings of favorable areas for guarana cultivation indicate that this unit has the highest number of fragments, due to formation of well-drained soils with an acceptable texture range, as well as goodclimatic conditions - except in the extreme west of the municipalities of Camamu, Nilo Peçanha, and Valença. Distributed across all municipalities, the substrates of this unit represent nearly two-thirds of the study area, with Taperoá having the highest representation. Due to this factor, the territory of this municipality has a wide range of favorable areas for guarana cultivation, as the indicated physical-environmental factors are spread across the municipality's surface, in line with the presence of the crystalline basement.

The Mesozoic Sediments Unit is characterized by two groups. The first consists of reddish sandstones, shale, and mudstones, including fluvial and aeolian sandstones (Magnavita, Silva & Sanches, 2005), found in the municipalities, except for Taperoá, which did not impact the composition of the favorable areas for guarana cultivation in that locality, as they were concentrated in areas of crystalline basement, as mentioned. The second group consists of materials composed of sandstones, conglomeratic sandstones, and shales, with additional records of dolomitic, oolitic, and pisolitic limestones, as well as calcilutites, present in the municipalities of Camamu and Nilo Peçanha (Souza, 2015).

The sum of all Mesozoic sediments reaches 8.12% of the analyzed surface, with Nilo Peçanha being the municipality with the highest representation. There are no implications of this unit in the constitution of favorable areas for cultivation, as they consist of poorly drained swampy environments and/or soils with moderate drainage, despite having favorable climatic conditions.

The Tertiary Sediments unit is primarily represented by the Barreiras Group. This group is characterized by a discordant arrangement with crystalline rocks, consisting of sands, clays, and pebbles, with sediments predominantly of continental origin but with marine influence in sedimentation (Souza et al., 2020). Its sediments are confined to plateaus distributed over the crystalline rocks or over Mesozoic sediments of the Camamu Basin. It corresponds to only 1.27% of the entire area, being found only in Camamu and covering 5.79% of the municipality.

The presence of detrital-lateritic coverings formed in the Tertiary was also observed, comprising material originating from the modification of underlying rocks. These surfaces represent only a patch after the Barreiras Group, in the inland direction. The substrates present in this unit have resulted in soils with moderate drainage, which has contributed to their absence in the composition of favorable areas for guarana cultivation.

The Quaternary Sediments Unit is represented by substrates that occupy the lower areas of the relief, bordering the coastline and extending into the valleys of the coastal basin domain until the contact zone with the Pre-Cambrian basement. The sum of all these sediments occupies 18.51% of the study area. In Ituberá, they cover approximately 32.94% of the surface area, the highest proportion among the analyzed municipalities. Originating in the Pleistocene and Holocene, the Quaternary sediments comprise coastal deposits, lagoon plain deposits, and mangroves and swamps. The sandy nature of the former contributes to excessive drainage, while the latter exhibits poor drainage, making them unsuitable for cultivation (Poltronieri et al., 1995; Tavares et al., 2005).

There are also detrital-lateritic land surfaces formed in the Pleistocene, concentrated in the northwest direction of Valença. These surfaces are confined outside the coastal boundaries, with their materials deposited in the crystalline basement. They have given rise to soils with drainage and texture suitable for favorable cultivation areas, in addition to favorable climatic conditions, and cover approximately 12.78% of the municipality or 3.76% of the entire study area.

*Soils*

The soils are distributed into six classes, considering the 1st hierarchical level of the Brazilian Soil Classification System (Santos et al., 2018). This classification has five additional categorical levels, but due to the scale, only the first two levels are presented (Table 9 and Figure 2G).
The soils with significant clay content found in the study area are argisols, latosols, and luvisols. Clayey soils influence plant phenology, they are rich in minerals, has lower leaching potential and have greater stability in organic matter compared to sandy soils (Riaz & Marschner, 2020; Nath et al, 2024). The variation in clay content at different depths influences water repellency, soil fertility, and crop growth (Zhang et al., 2023).

Argisols are soils with a textural B horizon (Bt), with low clay activity or high activity combined with low base saturation and aluminum characteristics (Santos et al., 2018). Yellow Argisol occurs in the studied municipalities, except in Taperoá. It extends along the coastal strip behind the Gleysols, with its occurrence being different only in Valença, where it appears inland, associated with the mountainous terrain in the western part of the municipality. On the other hand, Red-Yellow Argisol is found behind the swampy terrains of Taperoá and Valença, as well as in patches to the west of the other municipalities. Both types have medium to clayey textures, which is favorable for the cultivation of guarana. Regarding drainage, while Red-Yellow Argisol has good conditions, Yellow Argisol has moderate drainage, which does not make in the most favorable for cultivation.

Latosols require intense and persistent chemical weathering for their formation, exhibiting morphologically homogeneous profiles that are deep and leached (Martinez & Souza, 2020; Benedet et al., 2022). Two variations were observed: yellow and red yellow. Yellow Latosol occupies a larger area in the studied surface, with a representativeness of 44.54%, distributed across all municipalities. Red-Yellow Latosol, on the other hand, covers a little over 14% of the analyzed area, with significant allocation in Valença, accounting for 31.59% of its territory. With clayey to very clayey textures, these soils are found on terrains ranging from gently undulating to mountainous. When they have good aeration and drainage conditions, and variations in clayey textures, they provide favorable conditions for the cultivation (Poltronieri et al., 1995; Tavares et al., 2005).

Luvisols are composed of mineral material, exhibiting a Bt horizon with high clay activity, high base saturation, and chromic characteristics (Santos et al., 2018; Santos et al., 2022). This soil covers an area corresponding to 2.59% of the Camamu territory, with predominantly gently undulating to undulating terrains, characterized by a medium to clayey texture and drainage ranging from moderate to good. These parameters are considered acceptable for guarana cultivation.

Clayey soils have a stronger bond than sandy soils, thus preventing the loose structural development found in the latter (Zhang et al., 2023). Sandy soils commonly have low cation exchange capacity (CEC), base saturation, and fertility. Under crops, the fraction of evaporation to precipitation is higher in sandy soils (74%) compared to other soils (68%), while the proportions of evapotranspiration are similar, indicating a need for irrigation (Huang & Hartemink, 2020). According to the authors, leaching is higher in sandy soils compared to fine-textured soils, except when the soils are compacted or have textural discontinuity in the profile, which contributes to the attenuation of percolation.

**Table 9.** Soil classes of the municipalities of Lower Southern, Bahia, Brazil

| Soils (SiBCS and WRB/FAO) | Municipalities (area in ha) | | | | | | Total |
|---|---|---|---|---|---|---|---|
| | Camamu | Igrapiúna | Ituberá | Nilo Peçanha | Taperoá | Valença | |
| Yellow Argisol/Acrisol | 16,367.8 | 10,296.6 | 3,776.6 | 9,126.9 | 0.0 | 7,286.1 | 46,854.0 |
| Red Yellow Argisol/Acrisol | 61.7 | 1,263.8 | 733.1 | 8,109.7 | 12,464.1 | 5,754.4 | 28,386.8 |
| Ferric Humiluvic Spodosol/ Podzol | 2,714.3 | 0.0 | 3,662.4 | 6,086.4 | 588.6 | 7,538.5 | 20,590.2 |
| Thiomorphic Gleysol/Gleysol | 16,876.3 | 13,020.2 | 5,446.6 | 1,742.1 | 1,546.3 | 2,697.1 | 41,328.6 |
| Yellow Latosol/Ferralsol | 32,988.9 | 28,775.8 | 23,098.2 | 12,110.4 | 28,007.9 | 44,741.4 | 169,722.6 |
| Red Yellow Latosol/Ferralsol | 12,670.8 | 3,536.8 | 0.0 | 0.0 | 2,265.6 | 35,478.1 | 53,951.3 |
| Chromic Luvisol/ Haplic Luvisol | 2,175.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2,175.0 |
| Quartzarenic Neosol/ Arenosol | 0.0 | 0.0 | 2,768.5 | 1,265.7 | 0.0 | 6,433.9 | 10,468.1 |
| Water bodies | 0.0 | 2,171.5 | 1,962.8 | 368.9 | 500.0 | 2,320.2 | 7,323.4 |
| Unclassified | 39.1 | 20.2 | 61.7 | 53.0 | 0.0 | 59.6 | 233.6 |
| Total | 83,893.9 | 59,084.9 | 41,509.9 | 38,863.1 | 45,372.5 | 112,309.3 | 381,033.6 |

SiBCS - Brazilian Soil Classification System. WRB/FAO - World Reference Base for Soil Resources/Food and Agriculture Organization of the United Nations.

Neosols and Spodosols possess these characteristics. The first soils are poorly developed, composed of thin mineral and/or organic material, without a diagnostic B horizon (Santos et al., 2018). They appear in the form of Quartzarenic Neosol in the coastal lowland areas, represented by beach sands in the municipalities of Ituberá, Nilo Peçanha, and Valença. The latter municipality has the largest area expression (6,433.9 ha), however, the highest percentage representation is observed in Ituberá (6.67%).

Spodosols are generally nutrient-poor soils that exhibit significant differentiation between horizons, characterized by the presence of an illuvial horizon or histic horizon (Santos et al., 2018). In the studied area, the Spodosols are found on predominantly flat terrain, followed by Quartzarenic Neosols moving inland. Additionally, they are found intermingled with Argisols in the municipality of Camamu, along the coastal strip. With sandy texture and imperfect drainage, Spodosols represent 5.40% of the municipalities, especially Valença, where they cover over 7,000 hectares. Despite having promising topographic and climatic characteristics, these soils have a sandy texture and excessive drainage (Neosols) or imperfect drainage (Spodosols), which are undesirable conditions for cultivating guarana.

The soil moisture content increases as drainage decreases, while the soil temperature tends to be higher during winter in poorly drained soils due to the low thermal diffusivity of soils with high water content (Arkhangelskaya & Lukyashchenko, 2018). Hydromorphic soils are characterized by chemical reduction and localized iron segregation due to transient or permanent waterlogging of the soil pores, which leads to long-term oxygen deprivation (Shirzaditabar & Heck, 2021).

With a similar profile, Gleysols are characteristic of waterlogged areas or areas prone to flooding (Santos et al., 2018), where primarily poor drainage conditions limit their use. In the study area, Gleysols can be found near the estuaries of brackish water bodies, concentrated in the municipalities of Camamu and Igrapiúna, representing 20.12% and 22.04% of their areas, respectively. Located on flat terrain, Gleysols have poor drainage and considerable saline content due to the composition of the environment where they are located. Despite their notable topographic and climatic conditions, the poor drainage of Gleysols hinders the cultivation of guarana.

*Favorable Areas for guarana cultivation*

Suitable climatic conditions for guarana cultivation encompass a rainfall range between 1,500 mm to 3,000 mm annually (Tavares et al., 2005). The precipitation amounts that fall within these conditions represent 87.99% of the mapped surface, with rainfall intensifying from the inland areas toward the coast. The values below the favorable minimum limit are distributed in the westernmost part of the municipalities of Camamu, Igrapiúna, Nilo Peçanha, and Valença, accounting for the remaining 12.01%.

Among the meteorological factors that are crucial for crop development, temperature is possibly the most important, interfere as its variations determine the limits of plant development stages, with small changes above ideal bringing important effects on growth and reproduction (Serrano-Notivoli et al., 2020; Timlin & Han, 2024). Regarding temperature conditions, the recommended average annual range for guarana cultivation is between 24ºC and 27ºC (Castro, 1992). These temperatures contribute to the process of evapotranspiration, which enhances the relative humidity conditions and should be around 80% or higher for guarana cultivars (Castro, 1992; Poltronieri et al., 1995).

The favorable conditions of average annual temperature are found throughout the studied surface, with the highest scores concentrated closer to the coastal area, in line with rainfall patterns. In the specific case of average annual temperatures, the variation in values is low, not exceeding a range of 1.6ºC from the inland areas to the coast. It is worth mentioning that the observed climatic parameters, although considered favorable, do not prevent fruit production under milder conditions, as evidenced by planting records in the state of São Paulo (Nascimento Filho et al., 2004). The state of São Paulo, located in Southeast Brazil, has lower temperature and rainfall conditions compared to the North and Northeast regions, where the largest guarana-producing areas in the country are concentrated.

Climate indices can be calculated based on the requirements of a particular species, considering the phenological periods from planting to harvest and their potential inherent climatic impacts (Serrano-Notivoli et al., 2020). Unfavorable climatic conditions can indeed pose challenges to agricultural production (Chen, Cui & Gao, 2023). In summer, occasional extreme temperatures or prolonged exposure to heat are not favorable for winter grain crops as their growing season is outside that period. However, they can be beneficial for vineyards as the fruit is produced during this time (Serrano-Notivoli et al., 2020). Winter rains can indeed impact the production of long-cycle crops, with disabling consequences for agricultural production (Gladys, 2017). For example, in the Lake Tana basin in Africa, precipitation is one of the most significant climatic factors affecting the natural environment and agricultural production (Weldegerima et al., 2018).

In agricultural areas, natural drainage is another important factor. When adequate, it can prevent soil waterlogging. In the studied area, the soils with the most favorable drainage conditions for cultivation are the latosols, red-yellow argisols, and luvisols. Together, they make up an area corresponding to 66.72% of the analyzed surface. In contrast, soils in the coastal strip, namely, the Neosol and Spodosol, exhibit excessive or imperfect drainage, respectively, while the Gleysols exhibit poor drainage. Therefore, they present problems related to low water retention and waterlogging, respectively. In the specific case of areas covered by yellow argisols, they were not included in the map of favorable areas for guarana cultivation due to the moderate drainage characteristic of these soils. The other parameters were met in part of the areas mapped with this class, such as their texture, which is predominantly clayey.

The recommended drainage for guarana cultivation is attributed to soils with good drainage, without waterlogging issues (Castro, 1992; Poltronieri et al., 1995; Fgv, 2003). Good drainage conditions will help remove excess water from the field, which is fundamental for guarana cultivation.

Waterlogging stress affects the plant and inhibits the development of its root system. The guarana crop is particularly sensitive to water accumulation, which can lead to plant mortality (Tavares et al., 2005). On the other hand, excessively drained soils are seemingly not recommended, as they hinder the retention of desirable amounts of water for carrying out the necessary metabolic processes for plant development. Understanding the influences of water in the environment requires the observance of drainage conditions, which are controlled by the physical characteristics of the soil throughout a profile, taking into account the frequency and duration of wet cycles under conditions similar to those in which the soil was formed (Shirzaditabar & Heck, 2021).

Soil texture was another observed parameter. The favorable soil texture patterns for guarana production range from medium to clayey and very clayey, with good aeration and drainage, as observed by Tavares et al. (2005) and Poltronieri et al. (1995). The aforementioned authors note that 54% of guarana crops in the Amazon region were grown in soils with a very clayey texture. In the study area, the soils that meet the favorable texture conditions are the latosols (clayey to very clayey - 58.70%), the argisols (medium-clayey to clayey - 19.74%), and the luvisols (medium-clayey - 0.005%). In contrast to the recommended conditions, the Spodosol and neosol have a sandy texture, while gleysol has an indiscriminate texture.

Indeed, soil texture is one of the most important properties for agricultural activities, food security, soil productivity, and various other environmental practices (Taghizadeh-Mehrjardi et al., 2020). Soil texture controls the characteristics of water release and, therefore, the moisture retention capacities, distinguishing soils based on their physical properties, such as porosity and aeration (Obayomi et al., 2019; Cui et al., 2023).

Soil texture also affects important processes such as evapotranspiration, water infiltration and retention, cation exchange capacity, nutrient transport, organic carbon capacity, soil erodibility, pollutant retention, and plant root growth (Minasny & Mcbratney, 2018; Tümsavaş et al., 2019).

Soil texture is critical for root growth and is a determinant of the occurrence and distribution of soil microbiota (Ruger et al., 2023). The authors manipulated the soil texture by gradually adding quartz sand to agricultural clay in maize plantations and observed compensatory root growth and a linear change in the structure of the microbial community with the changes in soil texture. It is so crucial in ecological processes that even in Antarctica, ice-free areas are dependent on this property (Siqueira et al., 2023).

Another factor that influences the implementation of crops is slope, as it impacts both surface water flows and the associated erosive processes, as well as the mechanization conditions of arable areas. For guarana cultivation, the chosen terrain should be flat or slightly inclined, as long as it is well-drained, as advised by Tavares et al. (2005). The authors also suggest avoiding steeper slopes due to potential erosion issues. Slope analysis started with the selection of flat areas (0% - 3%) and gently undulating areas (3% - 8%), which accounted for 41.95% of the analyzed surface as favorable for guarana cultivation.

The rate of soil detachment and sediment transport capacity varies with slope position (Tang et al., 2021b). Intense detachment occurs in areas with steep slopes, while deposition occurs in locations with low slope gradients, depending on land use type and slope position (Wang et al., 2023). The differences in soil erosion intensity among different slope positions are considered one of the main reasons for changes in soil function (Mandal et al., 2021).

Other examples include the influence of slope on the attenuation of pesticide toxicity in surface runoff, with land use and vegetation playing a role (Yorlano, Demetrio & Rimoldi, 2022). On the slope, the spatial patterns of soil nutrients are linked to land use and topographic orientation, which influences the loss of soil nutrients (such as nitrogen and phosphorus) in cultivated areas (Zhang et al., 2020; Zhou et al, 2024).

Based on the overlay of physical parameters, 56,988.2 hectares of favorable areas for guarana cultivation were mapped. The composition primarily included the following factors: rainfall exceeding 1,500 mm, a range of temperature conditions, substrates associated with crystalline bedrock and Quaternary detrital-lateritic land surfaces, slopes ranging from 0% to 8%, elevations between 100 m and 200 m, corresponding to the contact between the coastal plain and the crystalline basement, extending inland areas, and the presence of yellow and red-yellow latosols and red-yellow argisols.

However, it was observed that 58.78% of the favorable areas for cultivation, totaling 33,498.5 hectares, are located in urban areas and/or non-forest natural formations. In addition, there are forested areas within this context, which should raise concerns about limitations in planning plantations. It is crucial to prioritize the conservation and preservation of these areas. Based on the analysis, the cultivation of guarana should be given priority in areas where it is possible to replace existing crops and/or pastures. When combined, these areas accounted for 41.22% of the mapped areas with favorable conditions for guarana cultivation, resulting in an effective area of 23,489.7 hectares, as shown in Figure 3. The favorable areas mapped in this study represent more than double the areas designated for guarana cultivation in Brazil and more than quadruple the areas designated in the state of Bahia.

Among the favorable areas for guarana cultivation, Valença had the highest score, with 12,855.9 hectares, representing 54.73% of the total. The largest mapped areas were concentrated in the northern, northwestern, and west-northwestern orientations of the municipality, predominantly present on rocky substrates associated with detrital-lateritic surfaces over the crystalline basement, where yellow latosols are notably located. In the other municipalities, the favorable areas for cultivation are scattered as follows: in the central regions of Igrapiúna and Camamu, totaling 3,794.0 hectares; west of Ituberá, with 1,464.1 hectares; and from the west to the vicinity of the coastal areas in Nilo Peçanha and Taperoá, totaling 5,375.7 hectares.

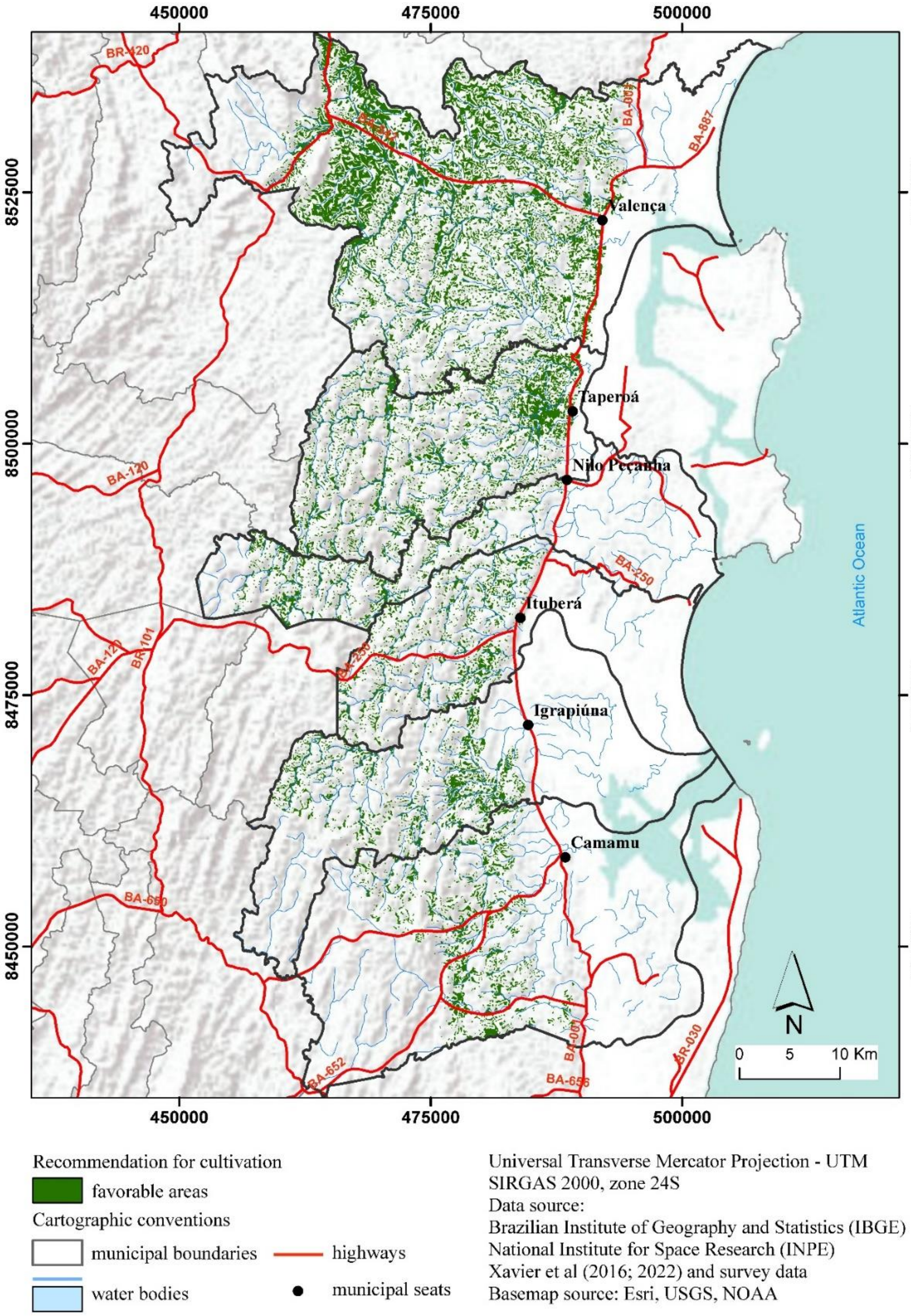


**Figure 3.** Favorable areas for guarana cultivation in the municipalities of Valença, Taperoá, Ituberá, Nilo Peçanha, Igrapiúna, and Camamu in the year 2021.
Esri: Environmental Systems Research Institute. USGS: United States Geological Survey. NOAA: National Oceanic Atmospheric Administration.

## Conclusion

The results indicate favorable areas for guarana cultivation in Lower Southern Bahia, Brazil, which can significantly contribute to the planning and optimization of fruit cultivation in the region. A total of 23,489.7 hectares of favorable areas were identified for guarana cultivation. This value represents a score that is more than double the area designated for guarana cultivation in Brazil and more than four times the area designated for guarana cultivation in Bahia. A high percentage of the municipalities within the study area have a higher percentage of their territories located on crystalline bedrock, with a strong occurrence of metamorphic rocks. In this configuration, combined with favorable climatic conditions, soils with better texture and drainage conditions were observed for guarana cultivation, notably the latosols and red-yellow argisols. These areas are concentrated in a more undulating relief of hills and plateaus, varying in characteristics from flat to gently undulating, associated with valley bottoms between the interfluves of hills and mountains. In these areas, the altitude ranged from 100 m to 400 m.

In the areas considered favorable for guarana cultivation, the presence of forested areas and non-forest natural formations was significant. This highlights the need for careful planning of plantations, taking into consideration the preference for preservation in many of these areas, as outlined in environmental legislation. This condition stresses the need for further studies to identify areas suitable for cultivation beyond the physical and environmental limits indicated in this study. Furthermore, a wide dispersion of recommended cultivation areas was observed, with a low incidence of significant or concentrated patches.

It is worth noting that the data presented here are initial findings - a first approximation - for analyzing the suitability of guarana cultivation and its distribution in the analyzed area. It is important to conduct further mappings that complement and justify the distribution and allocation of crops in different geographical areas, demonstrating a gradation of suitability, with zones adjacent to areas where guarana has been successfully cultivated.

This is justified as an alternative to cultivation in areas that would require the clearing of forest fragments. In this regard, it is suggested that future analyses include other physical-environmental factors as well as anthropogenic factors, which should be taken into account when assessing cultivation suitability in a particular location. Examples of such factors to be considered in a more refined analysis include water deficit, soil erodibility, distances to water bodies, transportation routes, processing facilities, and physical and legal constraints, which can influence cultivation conditions, supply, and commercialization of the fruit.

## Acknowledgements

The authors acknowledge the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), 313993/2021-1 and the Santa Cruz State University.

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