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# GEOTECHNIC ZONING OF SLOPE BY REMOTE SENSING FOR PHYSICAL ENVIRONMENT PLANNING: ANALYSIS OF THE AGRO-ENVIRONMENTAL POTENTIAL AND MECHANIZATION OF SUGARCANE

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**Abstract:** Part of the sugarcane cultivation in the state of São Paulo has a great predominance in the Administrative region of Ribeirão Preto - SP, composed of 25 municipalities in the northeast region of the state that represent 60% of the sugarcane in São Paulo. The Region has a high valuation of its lands due to the good conditions of climate, location and productivity, however, studies that address agricultural and environmental aspects in agricultural management are incipient. Thus, the objective of this study was to identify the agricultural, agroclimatic and agro-environmental potential of sugarcane in the Administrative Region of Ribeirão Preto, and the aptitude for the mechanized production system with a view to an adequate and efficient territorial planning. The region has 91.9% of its area with adequate climatic suitability and 89.3% of land suitable for mechanization, with slopes ranging from 0 to 12%. The agro-environmental zoning of adequate planting occupies 39%, but with the crossing between environmentally fragile and vulnerable zones, adequate planting followed by environmental restrictions of use extends to 44% of the areas and with environmental limitations of use in 12.5%, use inadequate extends by only 4.4%. The city of Jaboticabal has the largest area under the criteria for sugarcane cultivation, 596.5 $km^2$ (84.3%). Geographic information systems are powerful tools in these analyses, assisting in the zoning and quantification of areas, allowing knowledge and assistance to managers in decision-making on land use policy.
**Keywords:** Geographic Information System, biofuel, agricultural production, climate zoning.

## INTRODUCTION

The cultivation of sugarcane is an important agent of the Brazilian energy economy and security, with great emphasis on the production of ethanol and sugar (Santoro et al., 2017). Brazil is the largest producer of sugarcane in the world, responsible for approximately 20% of sugar production and 40% of total world trade (COLIN, 2009; IBGE, 2010). At the national level, the territory of São Paulo stands out, which accounts for 55% of the planted area in the country and exceeds about 442 million tons produced (IBGE 2016). The development of this sector was driven by Brazilian government projects such as Proálcool due to the need for alternative fuel sources to oil (Única, 2016). However, while ethanol is beneficial for the environment and the search for renewable sources is fundamental for more sustainable agricultural production systems; the traditional sugarcane production chain relies on the harvesting process carried out manually with the practice of burning the cane before harvesting (Segato et al., 2006). This strategy caused many negative impacts on the environment (emission of polluting gases) and on human health ( Cançado , et al., 2006; Martinelli et al., 2007), so that the practice of burning sugarcane has been gradually eliminated with its replacement by mechanized harvesting.

In pursuit of environmental adequacy and reduction of greenhouse gases agreed in international treaties, the Brazilian government incorporated the mechanization of harvest, "green harvest", to promote sustainable practices of sugarcane production in the State of São Paulo ( Lucon and Goldenberg, 2010). Thus, the Agroecological Zoning of Sugarcane was established as an aid to effective and sustainable planning of sugarcane farming ( Granco et al., 2019). Due to the potential of agricultural exploitation with a view to mitigating greenhouse gases in Brazil (LOTZE-CAMPEN et al., 2014), the spatialization of areas suitable for mechanization in hydrographic basins makes agricultural management decision-making a land use policy system aimed at environmental sustainability, in line with agroecological zoning and the conservation of natural resources (PISSARRA et al., 2013). ; PACHECO et al., 2014).

The sustainable development planning of the sugar-energy sector also has an agroecological foundation in the State of São Paulo, which considers the hydrographic, physical, topographic and climatic aspects of the areas and establishes criteria for the licensing of new ethanol plants in São Paulo (MANZATTO et al. al., 2009). With this, the advent of Precision Agriculture - AP, is an important tool for the management of the crop implantation system, as it considers the great variability of soil attributes and slope and crop development, improving the quality of management to from the adoption of new techniques (CORÁ et al., 2004; COELHO et al, 2004; MANTOVANI et al., 2005 ; MOLIN et al, 2015).

In the agricultural activities management system, Precision Agriculture - AP helps to monitor the phenomena that occur, as the localized information improves productivity, environmental preservation and rural producers' income. This technology can be used in the production chain and offers tools for optimizing the use of inputs and permanent innovation in the field (MOLIN et al., 2015; BALASTREIRE, 2001) and also to assist in the decision-making of land use policies. In this work, the application of geoprocessing techniques as a component of the PA, was carried out to identify the potential for exploitation of the sugarcane crop in terms of soil and climatic, agroecological parameters and aspects of environmental sustainability for the Administrative Region of Ribeirão Preto. With the objective of identifying and determining agricultural areas for the implementation of sugarcane production systems in line with environmental protection activities in hydrographic basins.

## MATERIAL AND METHODS

### STUDY AREA

The study area used for the analysis of sugarcane cultivation has a great predominance in the Administrative Region of Ribeirão Preto - SP (60% of Cana Paulista), which includes 25 municipalities: Altinópolis, Barrinha, Brodowski, Cajuru, Cássia dos Coqueiros, Cravinhos, Dumont, Guariba, Guatapará, Jaboticabal, Jardinópolis, Luís Antônio, Monte Alto, Pitangueiras, Pontal, Pradópolis, Ribeirão Preto, Santa Cruz da Esperança, Santa Rosa de Viterbo, Santo Antônio da Alegria, São Simão, Serra Azul, Serrana, Sertãozinho and Taquaral (FIGURE 1).

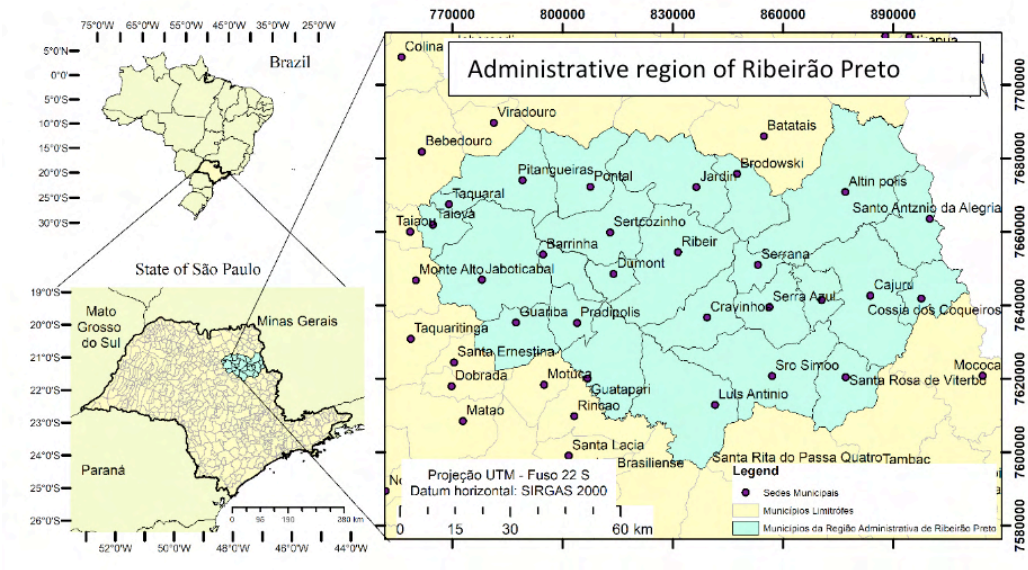


Figure 1. Map of the 25 municipalities in the Administrative Region of Ribeirão Preto and their host cities.

These municipalities occupy an area of 931.9 thousand hectares, of which 357 thousand hectares are destined for the production of sugarcane. The 25 municipalities in the Administrative Region of Ribeirão (RA15) have rural areas that are valued for their good weather conditions, location and productivity. Due to these characteristics, the region has a high valuation of the average price per hectare, reaching 39% higher than the state average.

## DATABASE

To achieve the objective proposed in this work, it was necessary to create a georeferenced database with files and images representing plans of information of interest from the maps of the studied region (Table 1). All maps in shapefile format were produced with a resolution of 30 × 30 m, re-projected in Datum SIRGAS 2000, Fuso 22, south. The administrative region of Ribeirão Preto was used to carry out the cuts and analysis of the aptitude for mechanization and in line with the agro-environmental zoning and edaphoclimatic aptitude.

| Database | Description | site |
|---|---|---|
| Administrative Region of Ribeirão Preto (RARP) | Municipalities and administrative headquarters of RARP | http://datageo.ambiente.sp.gov.br/app/?ctx=DATAGEO |
| Digital Elevation Model (DEM) | Image with terrain altitude data. | http://www.webmapit.com.br/inpe/topodata/ |
| Agro-environmental Zoning SMA/SAA | Map with the classification of classes for sugarcane cultivation | http://www.ciiagro.sp.gov.br/Zoneamento_Agroambiental |
| Edaphoclimatic Aptitude SAA/IAC | Map with climatic suitability for sugarcane cultivation | https://www.infraestruturameioambiente.sp.gov.br/etanolverde/zoneamento-agroambiental/ |

Table 1. Database

## SLOPE

- Step 1: Definition and processing of the digital elevation model

All land use capacity modeling was done from the orbital image of the SRTM - Shuttle Radar

Topography Mission project, where the world altitude topographic database was modeled. The MDE raster image – Digital Elevation Model of spatial resolution ~ 90 m, was processed by INPE, by the TOPODATA Project, Geomorphometric Database of Brazil, for a resolution of ~ 30 m (BRASIL, 2008). After defining the grids of interest, the grids were exported to the geographic information system – GIS, ArcGIS 10.1 software, for processing and standardization.

- Step 2: Slope Modeling

The slope consists of the slope of the land surface in relation to the horizontal, this topographic unevenness is shown between two points along the horizontal distance (GRANELL-PÉREZ, 2004; IBGE, 1999). The slope map was generated in ArcGIS software (ERSI, 2010), using the Digital Elevation Model – MDE database. The study was generated using the percentage pattern ( percent_rise ), for this the input matrix file, MDE, was processed for the plane coordinate system. MDE has been redesigned for UTM Coordinate System. The slope calculation in the GIS was performed based on the altimetric values of adjacent pixels, making a total of 8 pixels (DUNN; HICKEY, 1998).

The slope of the slope is output as percentage values with values from 0 to essentially infinity. A flat surface is 0 percent and a 45 degree surface is 100 percent, and as the surface becomes more vertical, the percentage increase becomes larger and larger (SANTOS, MELO, ROVANI, 2017). The definitions of each class followed the precepts of the work carried out on the soil slope classes, which were classified according to the potential for mechanization, (0 - 12 %) mechanized, (12.1 - 19 %) mechanized with restrictions, (> 19.1 %) not mechanized.

## AGRO-ENVIRONMENTAL ZONING

The Agroenvironmental Zoning (ZAA) of the region was carried out using the databases available in the database of the Integrated Center for Agrometeorological Information (CIIAGRO). The classification of the areas followed the criteria established by the Resolution SMA 88/2008 (SÃO PAULO, 2008), which determines the suitability of areas for sugarcane cultivation, considering climatic (temperature, precipitation), agricultural (soil attributes, relief, quality and water availability) and environmental aspects ( areas of environmental protection and preservation):

- **suitable areas** : correspond to the territory with favorable soil and climatic aptitude for the development of the sugarcane culture and without specific environmental restrictions;
- **suitable areas with environmental limitations** : correspond to the territory with favorable soil and climatic aptitude for sugarcane cultivation and incidence of Environmental Protection Areas (APA); medium priority areas for increasing connectivity, as indicated by the BIOTA-FAPESP Project; and the hydrographic basins considered critical;
- **suitable areas with environmental restrictions** : correspond to the territory with favorable soil and climatic aptitude for the cultivation of sugarcane and with incidence of buffer zones of the Conservation Units of Integral Protection – UCPI; the high priority areas for increasing connectivity indicated by the BIOTA-FAPESP Project; and areas of high groundwater vulnerability in the State of São Paulo.
- **unsuitable areas** : correspond to Full Protection Conservation Units – State and Federal UCPI; the fragments classified as of extreme biological importance for conservation, indicated by the BIOTA-FAPESP project for the creation of Full Protection Conservation

Units – UCPI; the Wildlife Zones of the Environmental Protection Areas – APAs ; to areas with edaphoclimatic restrictions for sugarcane cultivation and to areas with a slope greater than 20%.

The characteristics of soils in the State of São Paulo, aiming to know the agricultural aptitude (good, regular or restricted) were evaluated considering their aspects of natural fertility (high, medium or low), depth for the exploration of roots (favorable, unfavorable) and stoniness (present or absent) ( Brunini et al., 2008).

Agroclimatic suitability and edaphoclimatic zoning are according to:

1) Quantification of the region's physical resources;

2) Quantification of water balance terms;

3) Quantification of the climatic requirements of crops;

4) Interaction between the parameters described in items one to three: definition of agroclimatic ranges for cultivation. These bands or climatic zones are basically three, as follows:

Apt Zone – when there are no climatic restrictions for cultivation, and the associated climatic risks are negligible.

Marginal Zone – when, from the climatic point of view, at some stage of the crop there may be, or there is a certain non-high probability, water deficiency, low temperatures or heavy rains at harvest.

Unsuitable Zone – when, from the climatic point of view, anomalies occur with high frequency that make commercial exploitation unfeasible.

From the combination of the three climatic zones with the soil attributes, we have the soil and climate zoning for a given crop:

Edaphoclimatic aptitude the thermal and water deficit ranges were used.

The thermal ranges considered were the following:

a) Average annual temperature below 20 ºC – considered unsuitable for growing on a commercial scale with maturation problems and risks of frost;

b) Average annual temperature between 20 and 21 ºC considered marginal;

c) Average annual temperature above 21 ºC considered optimal for the crop.

It must be noted that the average annual air temperature presented here is about 1.0 to 1.2ºC above the average compensated air temperature, since the arithmetic mean between the maximum and minimum values of air temperature was worked out.

In the case of annual water deficit, the limits used were:

a) annual water deficit of less than 5 ( five) mm – Unfit;

b) annual water deficit between 5 (five) and 10 mm – Marginal;

c) annual water deficit greater than 10 and less than 250 mm – Apt.

For the water index, the established ranges were:

a) annual water index greater than 80 – Unsuitable, excess moisture;

b) water index between 60 and 80 – Marginal;

c) water index below 60 and above -20 – Apt.

## RESULTS AND DISCUSSION

In this work, the areas of the RARP region that cannot be mechanized (3.6% - 326 km²) are dispersed mainly in the western region, in the cities of Altinópolis (56 km²), Cajuru (49 km²) and São Simão (41 km²). These municipalities have some regions with more rugged relief, preventing the entry of machinery and making mechanization in the area unfeasible. This way, conservation practices must follow the risk qualification of the most sloping areas as a basis and aid for soil conservation planning. The recommendations indicate that soil type and relief must be considered as dependent factors in determining soil erodibility or susceptibility to erosion , and the association of the slope of these municipalities may have contributed to processes of gravitational transport of soil particles, which correspond directly to surface runoff processes and erosion processes (De Maria, 2016).

The data show that RARP follows the mechanization potential found in the State of São Paulo, the region has a high mechanization potential that exceeds 96%. The mechanized class corresponded to 89.3% (8,125 $km^2$) of the RARP region, and the restricted mechanized class represented 7.1% (642 $km^2$). The regions with restrictions on the adaptation of machinery must present a differentiated management due to the intensity of the slopes, being necessary to adopt more sustainable agricultural practices that improve soil and water conservation ( Giboshi et al., 2006). The three main cities with the largest mechanized areas are: Altinópolis (749 $km^2$), Jaboticabal (649 $km^2$) and Ribeirão Preto (607 $km^2$). In the RARP region, the cities that have their reliefs 100% mechanized are Pitangueiras and Pontal.

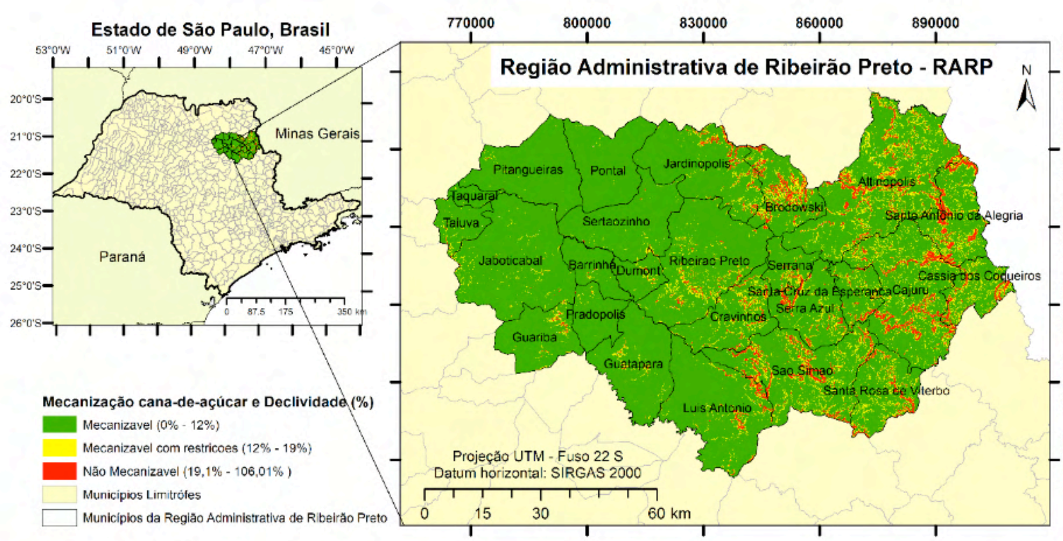


Figure 2. Distribution of sugarcane mechanization in the Administrative Region of Ribeirão Preto, SP. Source: Processed MDE (Brazil, 2008).

As we can see in Figure 3, the mechanization potential found among the RARP municipalities was above 74%. The lowest percentages of mechanized areas were found in the cities of Santo Antônio da Alegria and Brodowski, which have sloping relief. The slope of the land for proper management is one of the main geomorphological features ( Florenzando , 2008), limiting the use of agricultural machinery (Höfig ; Araujo -Junior, 2015; Francisco et al. 2013; Lepsch , et al., 1996).

The slope of the land is an important landscape variable for management and territorial planning, being defined for several applications and adopted in the Brazilian soil classification system, classification of land use capacity, occupation of permanent preservation areas, areas subject to to flooding, areas with possibilities for mechanization of agriculture, in addition to defining the limits for subdivision and land use (SANTOS, MELO, ROVANI, 2017).

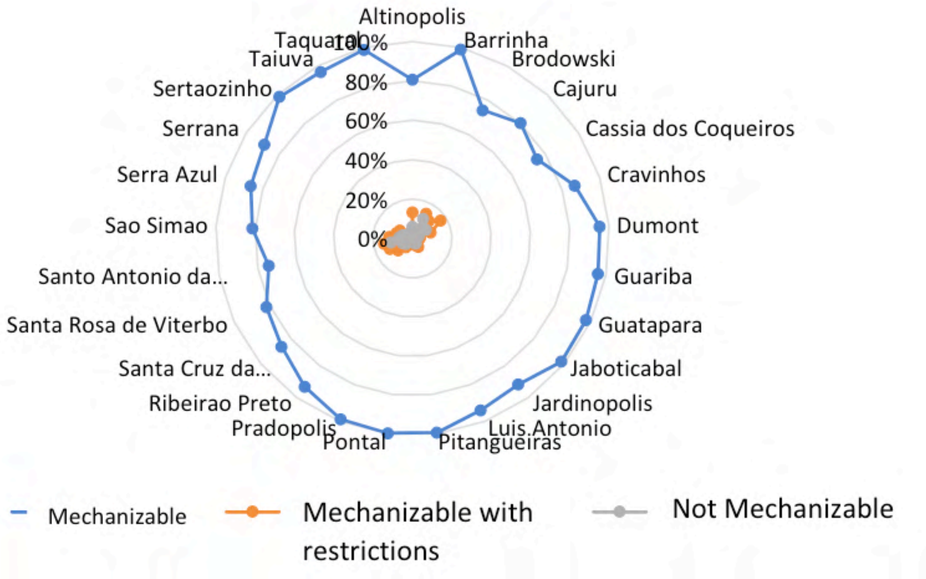


FIGURE 3. Distribution of the percentage of mechanization classes among the cities of the Administrative Region of Ribeirão Preto. Source: author.

According to Dias & Sentelhas (2018), the sugarcane crop has a wide territorial distribution in the state due to annual weather patterns, temperature and precipitation, which provide favorable thermal and water ranges for the development of this crop. Based on the thermal requirements of the crop and the characteristics of the annual rainfall distribution of the State, the soil and climate suitability for the cultivation of sugarcane was determined ( Brunini , 2008). The agro-environmental zoning for the sugar-alcohol sector in the State of São Paulo was defined observing suitable or restricted areas for the expansion of the cultivation of the culture and the installation of a new industrial unit.

The establishment of agro-environmental zoning for the cultivation of sugarcane relied on studies of soil and climate suitability and an agro-environmental analysis that included aspects of biodiversity preservation, environmental connectivity and soil management (DE MARIA et al., 2016). The planting area of the sugarcane system in Brazil is expected to reach 8.5 million hectares in 2012, to about 14 million hectares in 2030, according to data from the Sugarcane Technology Center (CTC, 2018). Therefore, the mechanization system of soil preparation and management must be considered in environments such as hydrographic basins and managers must rethink significant changes to bring the activity to adequate levels of sustainability.

Suitable agricultural suitability covers soils with high natural fertility, favorable depth and absence of stoniness, medium agricultural suitability, dystrophic and/or unfavorable depth soils, and restricted suitability comprises soils with two or more unfavorable conditions (Brunini et al., 2008).


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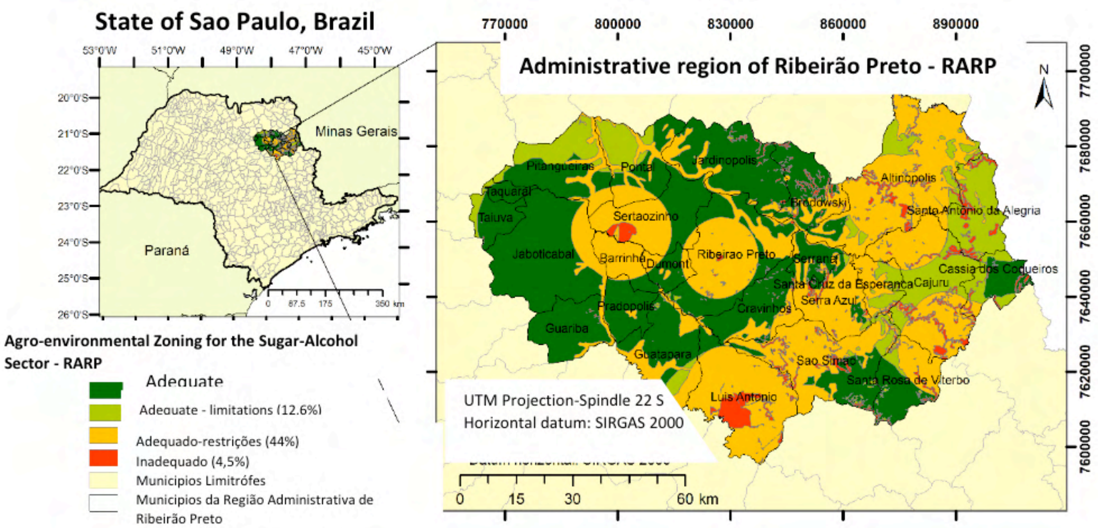


Figure 4. Agro-environmental Zoning for the Sugar-Alcohol Sector in the Administrative Region of Ribeirão Preto. Source:

The suitable region with environmental restrictions has the highest representation, 44% (3,999 km²), as can be seen in Figure 4, and corresponds to territories with favorable soil and climatic aptitude for sugarcane cultivation, including regions with buffer zones of Protection Conservation Units (UCPI). UCPIs are high priority areas for increasing the connectivity of biological flows between habitat fragments ( Met-zerg , 2001 ). The UCPIs also constitute regions of high vulnerability to groundwater in the State of São Paulo, according to the publication IG/CETESB/DAEE – 1997, and demand more complex measures for the preservation and protection of fauna and flora. The cities with the greatest representation in this class are Altinópolis and Luís Antônio, but with areas of 718 km² and 487 km², respectively. (Figure 5).

The region with adequate zoning for sugarcane cultivation extends over 39% of the area (3,550 km²). The most representative cities are Jaboticabal (608 km²), Jardinópolis (406 km²), Guariba (244 km²) and Ribeirão Preto (233 km²), regions further west. These areas correspond to the territories that present favorable soil and climatic aptitude for the development of the sugarcane culture and without specific environmental restrictions. According to Marin et al. (2008), the region of Ribeirão Preto presents soil, water and climatic conditions favorable to an efficient productivity, allowing the economic exploitation of the culture in the region as long as the agricultural management processes are correctly used.

Appropriate areas with slight environmental limitation occupy 12.5% (1,140 km²) of the region, these areas correspond to territories with favorable soil and climatic aptitude for sugarcane cultivation, however, part of them are found in regions with an incidence of Environmental Protection Areas (APA) and Natural Reserves of Private Heritage (RPPN). This pattern is also observed in the other regions of the state (Teófilo et al., 2015) and indicates the need to adopt measures of environmental control and agricultural management, since these areas are of medium priority for increasing the connectivity of the landscape ( Flynn et al., 2015; Oliveira and Costa, 2018). The most representative cities are Santo Antônio da Alegria (247 km²) and Cajuru (215 km²).

In relation to the total area of the State of São Paulo in which the sugarcane activity is effectively carried out, this study identified that 26% of the cultivated area occurs in suitable areas, 45%

in suitable areas with environmental limitations, 28% in suitable areas with environmental restrictions. and; although specific resolutions were created in 2008 determining suitable and unsuitable areas for sugarcane cultivation ( Brunini et al., 2008), sugarcane cultivation was found in inappropriate areas (1 % of the cultivated area).

These results underscore the need for attention to cultivation in areas intended for environmental protection, which are essential for the conservation of ecosystems and biodiversity (Lobato et al. 2017). Thus , the disorderly occupation of these areas can cause several environmental impacts and compromise in the short and medium term the sustainability of arable areas (MÜLLER, et al., 2008).

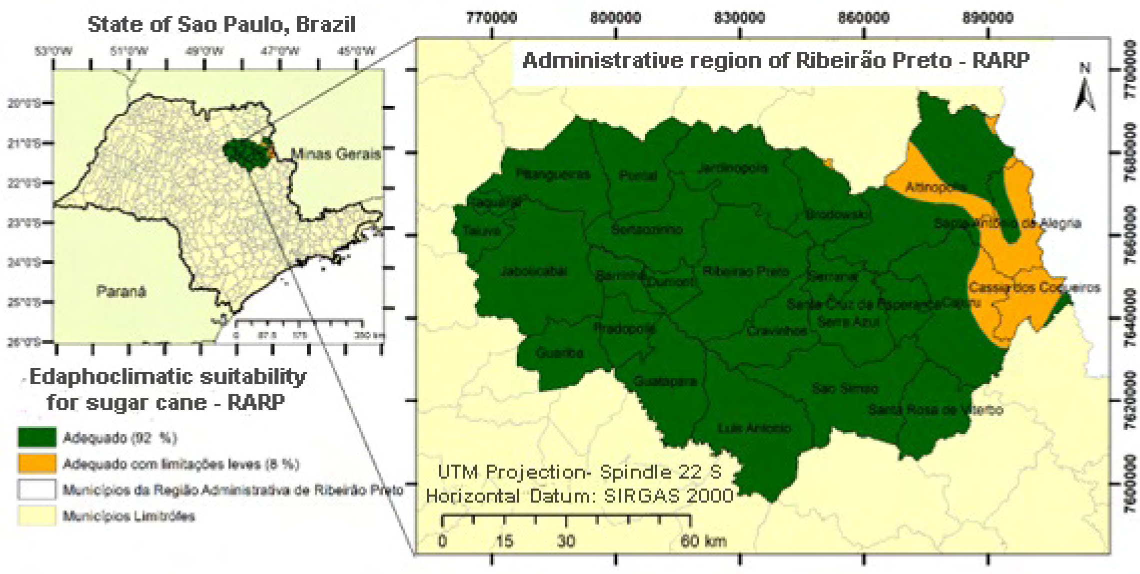


Figure 5. Edaphoclimatic Aptitude Zoning for the Sugar-Alcohol Sector in the Administrative Region of Ribeirão Preto. Source:

The agro-environmental zoning for the sugar-alcohol sector based on soil and climatic aptitude for sugarcane has four classes in the state of São Paulo (adequate, adequate with mild limitations, adequate with moderate limitations and inadequate). In the study area, only the first two classes were found, about 92% (8,361 km²) , indicating that the region can be considered an area of high climatic suitability due to low water deficit or thermal amplitude (Maluf et al., 2007) and, highlighting the importance of zoning based on the environmental and climatic characteristics of the region (Figure 5).

| | Mechanizable | | Mechanizable with restrictions | | N o t mechanisable | | **Grand total** | |
|---|---|---|---|---|---|---|---|---|
| | km² | % | km² | % | km² | % | **km²** | **%** |
| **Agro-environmental Zoning** | | | | | | | | |
| Adequate | 3304.0 | 36% | 179.5 | two% | 66.9 | 1% | **3550.4** | **39%** |
| Adequate - limitations | 988.7 | 11% | 105.4 | 1% | 45.9 | 1% | **1140.0** | **13%** |
| Suitable - restrictions | 3581.4 | 39% | 287.1 | 3% | 130.9 | 1% | **3999.4** | **44%** |
| Inappropriate | 251.1 | 3% | 70.3 | 1% | 83.2 | 1% | **404.6** | **4%** |
| Grand total | 8125.2 | 89% | 642.3 | 7% | 326.9 | 4% | **9094.4** | **100%** |
| **Edaphoclimatic Aptitude** | | | | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Adequate | 7589.6 | 83% | 523.7 | 6% | 248.6 | 3% | **8361.9** | **92%** |
| Suitable with mild limitations | 535.6 | 6% | 118.6 | 1% | 78.2 | 1% | **732.5** | **8%** |
| Grand total | 8125.2 | 89% | 642.3 | 7% | 326.9 | 4% | **9094.4** | **100%** |

Table 2: Spatial distribution of mechanization classes in the face of agro-environmental zoning and soil and climatic aptitude.

The mechanisable region extends mainly in the appropriate agro-environmental zoning classes with restrictions (39% - 3581 km²) and adequate (36% - 3304 km²), for the adequate edaphoclimatic aptitude reaches 83% (7589 km²). A favorable percentage, given the prospects of climate change and trends in water stress conditions for the region (Marin and Nassif, 2012).

In general, the potential for mechanization in the municipalities of the RARP was above 60% throughout the area, these results collaborate with the percentage of mechanized harvesting in Ribeirão Preto and its surroundings, which according to Aguiar et al. (2011) corresponds to 50% of the sugarcane harvest in the region. The combined climatic and edaphic analysis of the region showed that the exploration and expansion of the culture is viable.

As the PA is a management system that considers crops in all their aspects ( Tschiedel ; Ferreira, 2002), technology must be considered as a tool for use in land use policies (Ramalho Filho; Beek , 1995; Lepsch , et al., 1996). The greater the amount of data collected, the more accurate the diagnosis will be about the variability present in the crops analyzed, with the taking of measures regarding the most diverse aspects of an agricultural area ( Srbinovska et al., 2015).

This way, the AP allows small, medium and large producers to manage the property, in the right place and in the right amount, promoting increased productivity and sustainability. The geographic information system concept adds value to precision agriculture in the spatialization of the set of points in the traditional field-objective dichotomy of interest representing the situation of entity and location. Thus, there is localized information, which brings the possibility of a more adequate management in agricultural production systems.

## CONCLUSION

For the precision agriculture system, the spatialization of areas suitable for mechanization is extremely important in terms of land use policy based on the conflict methodology. The methodology proves the great potential of geographic information systems in the integration of geocoded data and makes it possible to obtain data when obtaining specialized maps of the slope and the potential of areas for mechanization. The slope is an important factor for soil management, being a limiting factor for the occupation and implementation of productive systems in a sustainable way. This way, the digital elevation model and geographic information systems make it possible to scale slope maps quickly and with acceptable resolution for environmental management at the scale of hydrographic basins. This way, the study of slope must be an instrument considered for the monitoring of soil degradation and in the strategic planning of land use policy plans. The project supports bio-energy programs and the reduction of polluting gases, as it analyzes the agro-environmental zoning based on the climatic and edaphic potential of sugarcane in the administrative region of Ribeirão Preto.

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