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ORIGINAL ARTICLE

Determining regions for installing flex-biomass sugar-ethanol plants: a multicriteria approach for location

Determinação de regiões para instalação de usinas sucroalcooleiras flex: uma abordagem multicritério para localização

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Abstract: The development of sugarcane varieties has allowed Brazilian ethanol plants to operate longer during the harvest, however, in the off-season they remain idle due to the absence of biomass. To increase energy safety and guarantee supply in critical periods, it has been proposed to adapt ethanol plants to the flex-biomass model, allowing the production of biofuel from corn as well. Considering the costs of building or adapting a plant, strategically defining the location is essential for optimizing ethanol production. The aim of this study is to verify whether the combination of location criteria can identify the most suitable regions for the construction of new plants and map them. The method consists of the Analytical Hierarchical Process (AHP) with GIS techniques. We found two large continuous regions suitable for the construction of new flex ethanol plants, corresponding together to 11% of the study area. However, in these two suitable regions, only 0.33% of the territory has more than 90% suitability. Therefore, we confirmed the existence of more suitable regions and concluded that the mapping of these areas enhances the resources application, avoiding installation in inappropriate areas.

Keywords: Flex ethanol plant; Sugarcane off-season; Corn; Location problem; GIS tools.

Resumo: O desenvolvimento de novas variedades de cana-de-açúcar tem permitido que as usinas brasileiras de etanol operem por mais tempo durante a safra, porém, na entressafra elas permanecem ociosas devido à ausência de biomassa. A fim de aumentar a segurança energética e garantir o abastecimento em períodos críticos, tem sido proposta a adaptação das usinas de etanol para o modelo flex, permitindo também a produção de biocombustível a partir do milho. Considerando os custos para construção ou adaptação de uma usina, definir estrategicamente a localização é fundamental para otimizar a produção de etanol. O objetivo deste estudo é verificar se a combinação de critérios de localização permite identificar regiões mais adequadas para a construção de novas usinas flex e mapeá-las. O método consiste na análise hierárquica multicritério AHP

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em conjunto com técnicas de geoprocessamento. Encontramos duas grandes regiões contínuas adequadas para usinas flex, correspondendo juntas a 11% da área de estudo. No entanto, nessas duas regiões aptas, somente 0,33% do território tem mais de 90% de adequação. Portanto, confirmamos a existência de regiões mais adequadas e concluímos que o mapeamento dessas áreas potencializa o uso de recursos, evitando a instalação em áreas inapropriadas.

Palavras-chave: Usinas flex; Entressafra de cana-de-açúcar; Milho; Problema de localização; Ferramentas SIG.

1 Introduction

Sugarcane ethanol was introduced in the Brazilian market as an alternative fuel to minimize the crisis in the sugar sector and reduce dependence on oil (Grassi & Pereira, 2019). The 1973 oil crisis forced Brazil to develop a program to replace fossil fuels with renewable biofuels (Nitsch, 1991), which created the Brazilian Alcohol Program (Proalcool) in 1975. However, it was only after the launch of flex fuel vehicles in 2003 that ethanol production received new incentives and began to increase its commercial importance (Bernardo et al., 2019). With heavy investments for the specialization in the production of sugar and alcohol (Paiva & Morabito, 2007), Brazil has become the world's largest sugarcane producer and set the benchmark for fossil fuel replacement with bioethanol (Rossi et al., 2021).

Improvements in industrial processes along with the development of new sugarcane varieties adapted to different climates and regions allow the operation of sugarcane plants for up to eight months in the harvest period (Matsuoka et al., 2009; Milanez et al., 2014). However, in the off-season, the plants remain idle, generating an unbalance between supply and demand in production cycles. In order to increase the country's energy security and ensure supply in critical periods, studies have proposed an adaptation of Brazilian ethanol plants to the flex-biomass model, allowing ethanol production from different biomasses. According to Milanez et al. (2014), among all possible raw materials, corn is the alternative with the greatest potential.

Sugarcane is a semi-perennial crop with a production cycle of up to 6 years (Silva et al., 2017) and its off-season in Brazil occurs between December and March. The corn crop in Brazil has up to three planting seasons over the year, and in the study area, there are often two. The second crop is usually cultivated in rotation with the soybean (Milanez et al., 2014). The corn ethanol production process is less efficient in terms of energy and economic balance when compared to ethanol produced from sugarcane (Hoffmann, 2015). However, the corn grain, as raw material for ethanol production, has the advantage of storage throughout the year, thus allowing the processing during sugarcane off-season.

The Brazilian Development Bank (BNDES) created a policy to fund projects for the adaptation of national sugar-ethanol plants to the flex model, given the great productive potential of corn and sugarcane in Brazil. However, according to data from Brazilian National Bioenergy Union (UDOP, 2020) and Brazilian National Union of Corn Ethanol (UNEM, 2020), of all 176 plants in the states of São Paulo and Mato Grosso, only 8 (less than 5%) currently operate with the flex model.

The logistics structure of ethanol distribution in Brazil, as well as the centers analyzed by Guazzelli & Cunha (2015), is organized in a hierarchical structure. In this sense, the plants supply the distribution centers, which in turn supply the resellers, who finally sell the product to the final consumer. Thus, as noted by the authors, several characteristics can influence decision-making on the location of flex-biomass plants.

Then, a strategic definition of locations for new flex plants based on factors that influence the decision-making process is essential for improving ethanol production in both sugarcane harvest and off-season periods. Aspects related to the distribution and spatialization of agricultural production have an impact on the decision about where to build ethanol plants because they can increase product competitiveness in the market and create a relationship between specialized production and interregional trade (Bargos et al., 2016; Coleti & Oliveira, 2019).

Location analysis seeks to choose suitable locations in the geographic space, considering the discrete point and its surroundings to ensure minimal investment and low operating costs. Attractive and repulsive factors of the region (Schettini & Azzoni, 2013; Sharma et al., 2017; Souza et al., 2020), elements such as time and space (Barquette, 2002), cost and quality (Rosa et al., 2015), accessibility to transport (Durmuş & Turk, 2014), land rent (Verhetsel et al., 2015) and the triple bottom line (Kheybari et al., 2019) can also be considered in these analyses. In this sense, the Analytic Hierarchy Process (AHP) proposed by Saaty (1990) can support to address spatial components in a Geographic Information System (GIS), allowing the definition of appropriate geographic locations (Alves & Alves, 2015; Al Garni & Awasthi, 2017).This combination (AHP+GIS) enables the manipulation of spatially distributed large data volumes (Furlanetto et al., 2020), simplifying the decision-making process (Gonçalves et al., 2020) and generating a tool to support planning (Rosa et al., 2015; Valladares et al., 2012).

The site selection for establishing flex-biomass sugar-ethanol plants is a complicated process of Multi-Criteria Decision Making (MCDM). This paper considers relief, road proximity, and water availability as the 3 most important criteria that have influence on biofuel plant location selection. We limited the criteria to three and divided them into 6 sub-criteria to avoid the emergence of consistency concerns (Asadabadi et al., 2019; Piengang et al., 2019). The consistency concern arises because humans are not capable of keeping consistent pairwise judgments when the number of elements increases (Miller, 1956).

Assuming that, given locational factors, it is possible to establish more suitable areas for the construction of new plants, this study aimed to map and analyze whether a combination of location criteria can identify such regions. Then, AHP was used in combination with geoprocessing techniques, considering qualitative and quantitative criteria. There are several studies for the solution of location problems, which present several effective solution techniques (Bargos et al., 2016). The article's contribution is offering an AHP+GIS method for location problems, which generates a large number of locational alternatives while taking care to exclude restricted territories. Then, the results were evaluated in a proximity analysis with relevant criteria not included in the AHP to validate the indicated regions. The AHP+GIS combined with territory restrictions and proximity analysis led to a prompting discussion about area suitability.

2 Materials and methods

This study was conducted in an area of 2,640,424 km^2 (Figure 1), covering the states of São Paulo (SP), Minas Gerais (MG), Paraná (PR), Mato Grosso (MT), Mato Grosso do Sul (MS), Goiás (GO), and the Federal District (DF). São Paulo and Mato Grosso are major producers of sugarcane and corn, respectively, and the other states were included in the study because they are neighboring states and important producers of these two raw materials for the sugar-ethanol plants. According to the climate classification by Köppen & Geiger (1928), the predominant climate types in this area are Am (tropical monsoon) and Aw (tropical with dry winter). The average annual precipitation ranges from 1000 to 3100 mm and the average temperature, from 20 to 24 ºC (Alvares et al., 2013). According to the Geological Survey of Brazil (CPRM, 2010), the region is mostly flat (0 to 3%), slightly undulating (3 to 8%), and undulating (8 to 20%). Oxisol and Acrisol are the main soil orders in the area, corresponding to 38.33% and 24.13%, respectively (EMBRAPA, 2020).

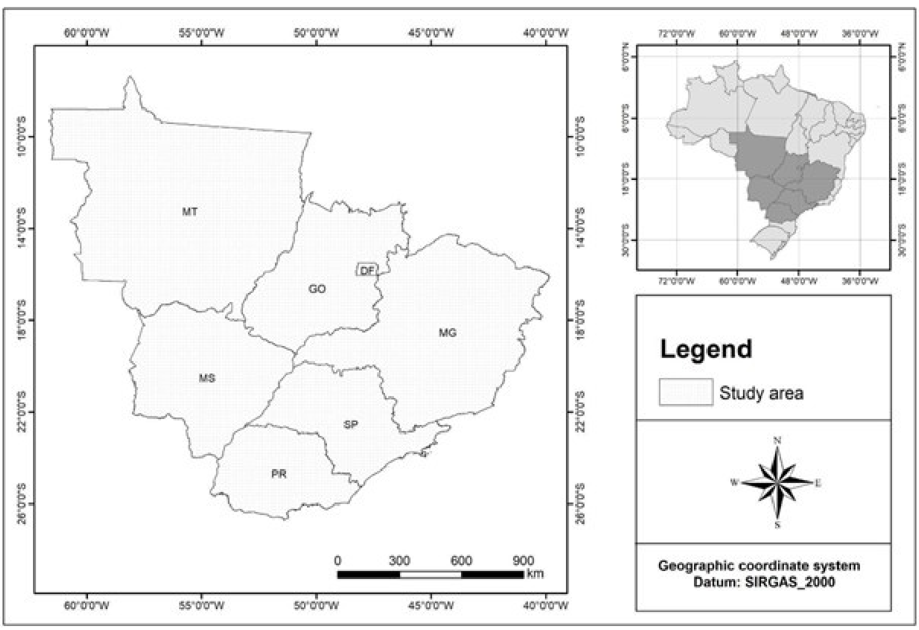

Figure 1. Location of the study area.

The method used in this study comprised 5 main steps (Figure 2) to identify the appropriate areas for the construction of flex plants. AHP was applied according to the model developed by Saaty (1990) to determine the weights of each criterion and then data processing was performed. We chose AHP because despite being a knowledge-driven method (Moura & Jankowski, 2016), subjected to expert bias, AHP is one of the most consolidated MCDM methods (Chen et al., 2010; Ramík, 2020). The AHP has been widely applied since the 1970s (Zamani-Sabzi et al., 2016) and may be more human-understandable than other methods due to the hierarchical structure (Ramík, 2020; Rosa et al., 2015). In the methods for defining the weights by consulting experts, the intention is to receive opinions from people who understand the investigated question, according to their experience and knowledge of the State-of-the-Art. It is particularly interesting when we don’t have sufficient field data, or when the problem considerably varies from one condition to another. The choice of weights must be very well documented, justified, and open to revision. At this stage, system calibrations usually take place (Moura & Jankowski, 2016).

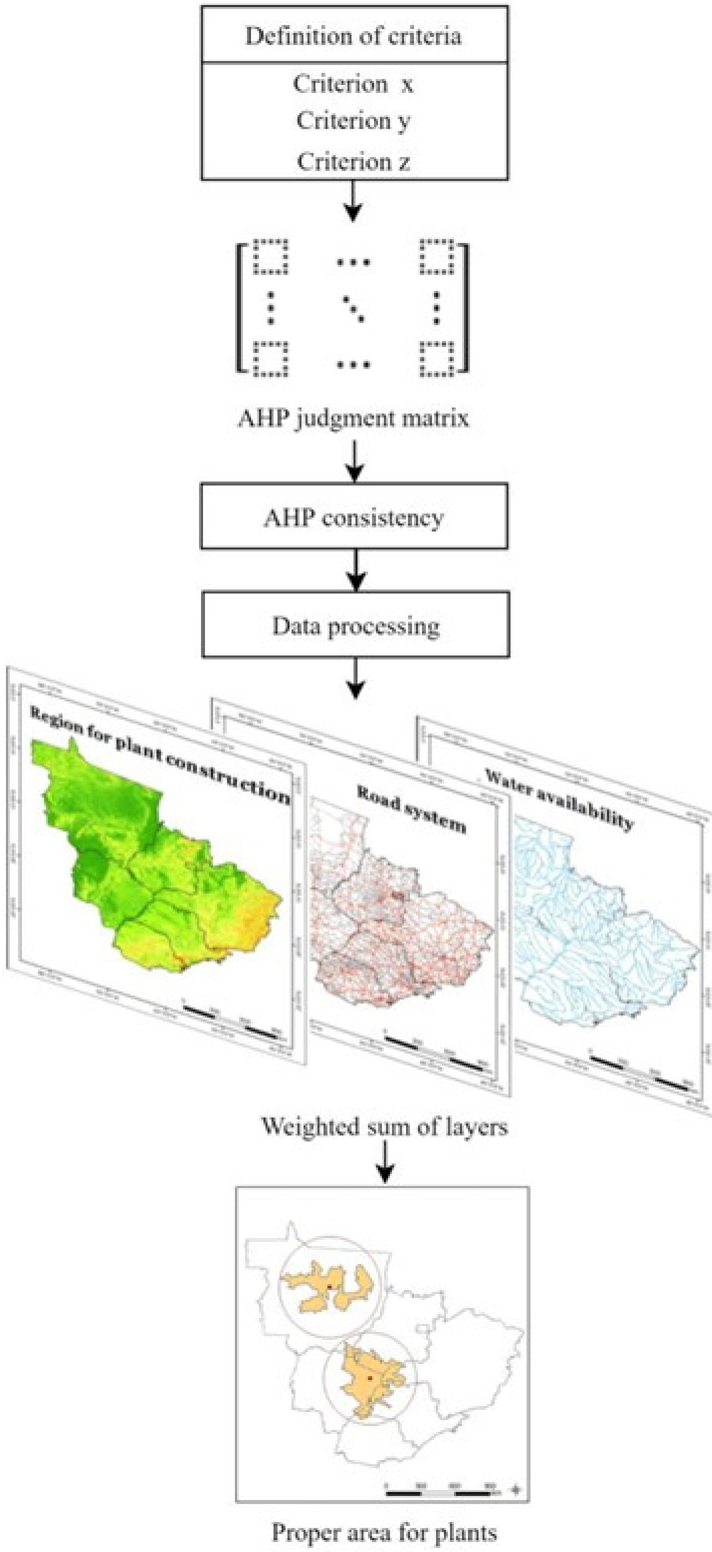

Figure 2. Method scheme.

In step 1, based on Alves & Alves (2015), Sahoo et al. (2016), and Sharma et al. (2017), we identified the criteria that can influence flex ethanol plants' location. The three adopted criteria - relief (x), road proximity (y), and water availability (z) - were hierarchically split into sub-criteria (Table 1). The relief has only one sub-criterion, the slope (x1). The road proximity was subdivided into proximity to federal (y1) and state (y2) roadways. Water availability, includes quantity and quality (z1), resilience (z2), and available surface water (z3). Where resilience is the groundwater recharge capacity by precipitation. This third criterion assesses the water available for industrial consumption (ANA, 2019).

Table 1. Criteria adopted in decision making for the construction of a flex plant.

Criteria	Relief	Road proximity	Water availability
	Slope (x_1)	Proximity to federal highway (y_1)	Quantity and quality (z_1)
Sub-criteria	-	Proximity to state highway (y_2)	Resilience (z_2)
	-	-	Surface water availability (z_3)

Source: Developed by the authors based on CPRM (2010), ANA (2019), and Brasil (2020a).

In step 2, using the AHP method (Saaty, 1990) and interviews with specialists and stakeholders who work directly in the bioethanol area[1], weights ranging from 1 to 9 were assigned to the pairwise comparison of the criteria according to the level of importance to represent the impact they have on decision-making. To enable a global analysis of the system, a square judgment matrix was generated (Figure 3) based on the comparisons of the criteria listed in Table 1.

$$
\begin{array}{c}
 \\ x_1 \\ y_1 \\ y_2 \\ z_1 \\ z_2 \\ z_3
\end{array}
\begin{array}{c}
\begin{array}{cccccc} x_1 & y_1 & y_2 & z_1 & z_2 & z_3 \end{array} \\
\begin{bmatrix}
1 & 1 & 1 & 1/7 & 1/5 & 1/7 \\
1 & 1 & 1 & 1/3 & 1/3 & 1/5 \\
1 & 1 & 1 & 1/3 & 1/3 & 1/5 \\
7 & 3 & 3 & 1 & 1 & 1 \\
5 & 3 & 3 & 1 & 1 & 1 \\
7 & 5 & 5 & 1 & 1 & 1
\end{bmatrix}
\end{array}
$$

Figure 3. AHP judgment matrix.

In step 3, with the aid of GIS techniques, the AHP consistency was assessed by the parameters of Consistency Ratio (0.016), Consistency Index (0.02), and by the proximity of the calculated eigenvalue (6.099) to the matrix dimension. For futher information about AHP methodology and consistency parameters, see Saaty (1990),

[1]Names and positions of the consulted specialists are not disclosed due to confidentiality, but they are linked to the following organizations: Sugarcane and Bioenergy Industry Union (União da Indústria de Cana-de-Açúcar e Bioenergia - Unica), Brazilian National Center for Research in Energy and Materials (Centro Nacional de Pesquisa em Energia e Materiais - CNPEM), and Raízen.

Freitas et al. (2009) and Oliveira & Martins (2015). The Consistency Ratio was below the limit value of 0.10 used in different AHP applications (Chen et al., 2010; Souza et al., 2020; Gonçalves et al., 2020). The layers combination was done through the weighted sum of the criteria (Equation 1).

$$\Sigma = 0.053x_1 + 0.070y_1 + 0.070y_2 + 0.258z_1 + 0.243z_2 + 0.306z_3 \quad (1)$$

Step 4 consisted of data processing and preparation. First, the Euclidean distance was applied to the vectors to prioritize the neighboring areas. Then, conversion of layers was performed, changing vector to raster formats, and all input files were reprojected to a conical projection system (South America Albers Equal Area Conic).

Table 2 shows data collected to establish the sub-criteria. In step 5, the weighted sum of layers consisted of pixel superposition of the matrices using a GIS tool, according to Equation 1. Urban areas (EMBRAPA, 2017), indigenous areas (FUNAI, 2020), and conservation units (Brasil, 2020b) were rated as inadequate for the construction of biofuel plants, and were removed from the resulting layer.

Table 2. Source of data to establish sub-criteria adopted in AHP.

Data	Area utilization	Source
Urban areas	Inadequate area	EMBRAPA (2017)
Location of indigenous areas	Inadequate area	FUNAI (2020)
Conservation units	Inadequate area	Brasil (2020b)
Slope	AHP sub-criterion	CPRM (2010)
State and federal highways	AHP sub-criterion	Brasil (2020a)
Resilience dimension	AHP sub-criterion	ANA (2019)
Surface water availability	AHP sub-criterion	ANA (2019)
Quantity and quality (Ecosystem dimension)	AHP sub-criterion	ANA (2019)
Ethanol distributors	Proximity analysis	ANP (2020)
Consumer market (Vehicle fleet)	Proximity analysis	Brasil (2020c)
Location of warehouses	Proximity analysis	CONAB (2020)
Agricultural production	Proximity analysis	IBGE (2020)
Transfer stations	Proximity analysis	EPL (2020)

In order to validate the results obtained, proximity analyses were performed with relevant criteria that were not included in the AHP, such as the location of agricultural production (IBGE, 2020), grain storage units (CONAB, 2020), intermodal transfer stations (EPL, 2020), and ethanol market (Brasil, 2020c).

3 Results and discussion

Pixel-based classification of the whole study area is illustrated in Figure 4. Two large continuous areas were rated as Good and Excellent (Figure 4) and are highlighted and identified in Figure 5. Both are close to biomass production and logistics infrastructure, such as grain warehouses and ethanol distributors.

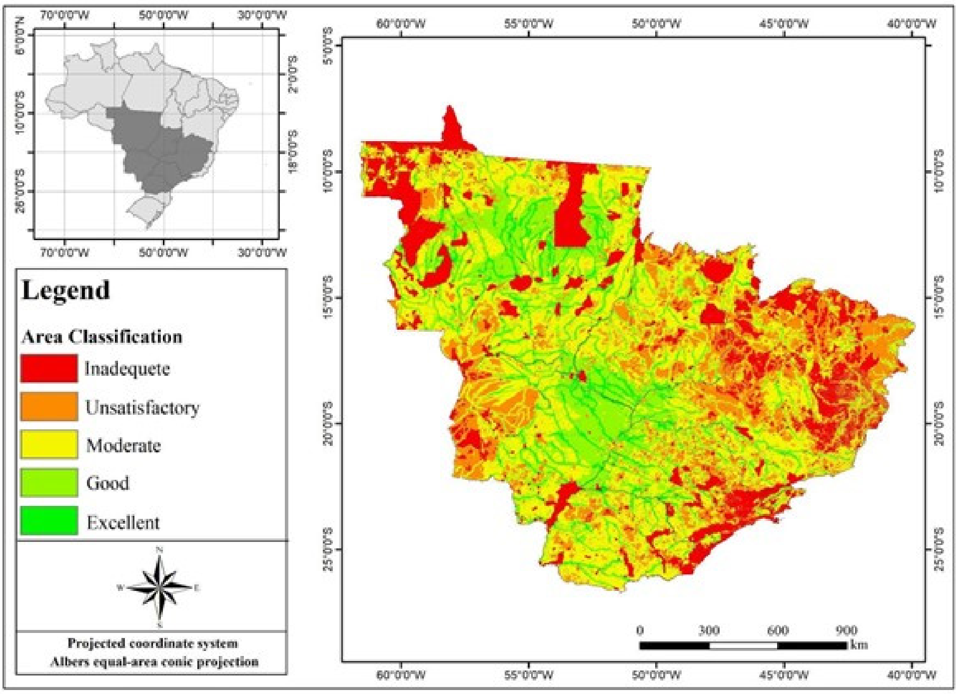

Figure 4. Suitability of areas for the construction of flex plants.

Continuous areas with many locational alternatives are interesting, as it allows concurrent search for various suitable terrains. This creates efficient results with the adaptability of changing the location due to land price negotiation or tax incentives. Unlike the study by Rosa et al. (2015), who applied AHP to select a distribution center from a limited number of alternatives, with AHP+GIS our result presents pixel-based location classification considering a very large number of possibilities. Serving the intention of classifying the regions in terms of suitability for installing a flex-biomass ethanol plant.

Operations research approaches with Linear Programming (LP) techniques are the most used in midsize localization problems. However, as the problem size increases, approaching the solution with LP becomes unpractical (Bargos et al., 2016). AHP+GIS is a less complex alternative to solve location problems when compared to the most applied methodologies of LP and its variations, mainly in large-scale problems. Zamani-Sabzi et al. (2016) state that simple MCDMs match the performance of complicated MCDMs, making it possible to optimize results while minimizing computational effort.

The area named A1 is located in the state of Mato Grosso, while A2 covers the borders of MT, GO, MS, MG, SP, and PR (Figure 5), and together they represent 11.74% of the total study area. Al Garni & Awasthi (2017) rated 80% of the areas as moderate and high suitability. A significant difference when compared to our study, showing the criteria of each study has different characteristics and suggesting the adequacy of parameters adopted. Our study area has continental dimensions, being larger than many countries. Although 11.74% is a low percentage, A1 has 45 municipalities and 13 microregions. A2 has 193 municipalities and 30 microregions. Table 3 shows the microregions of both A1 and A2.

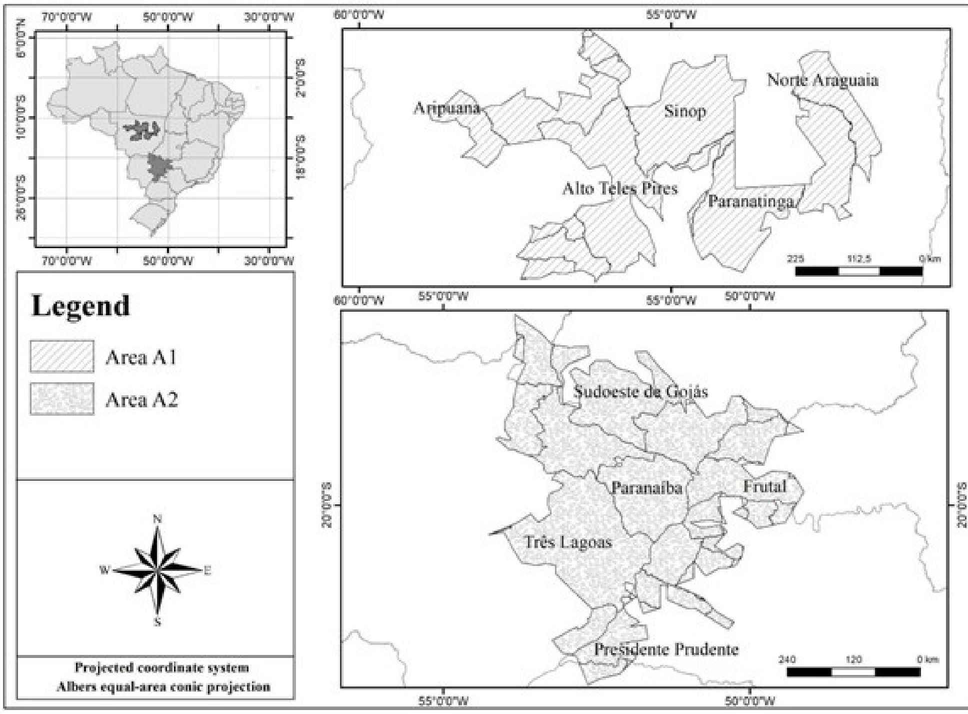

Figure 5. Identification of suitable areas for the construction of flex plants with the microregions located in each one.

Furthermore, only 0.33% of these adequate areas (A1 + A2) present over 90% suitability for the construction of flex plants. That is, only in 0.33% of pixels the criteria combination in the map algebra of Equation 1 was greater than 0.9. The AHP+GIS does not produce only optimal results. Contrariwise, the goal is to create reasonable and equilibrate results when the decision must contemplate multiple criteria, sometimes conflicting (Saaty, 1990). The applied technique excluded inappropriate areas and offers several location alternatives based on the combination of criteria. Thus, depending on the problem, it is expected that only a small percentage of the study area has high suitability.

The areas rated as good and excellent are located close to regions with a high road density. A similar condition is observed in Santos et al. (2019) when considering the proximity to highways. These areas are also located in regions with a large supply of quality water available for industrial consumption (quantity and quality), in addition to water storage that can be renewed through precipitation (resilience). Through AHP, Alves & Alves (2015) obtained a similar result when considering factors such as availability of raw material and water, and proximity to consumer markets.

The prominent role of logistics as a localization criterion was also presented by Gonçalves et al. (2020). They used AHP to determine the most promising regions of the State of Rio de Janeiro for the implementation of wind farms for electricity generation. The criteria used considered economic, technical and logistical aspects.

Table 3. Microregions of areas A1 and A2 adequate for the construction of flex plants.

Area	Microregions (UF)		
A1	Alta Floresta (MT)	Canarana (MT)	Rosário Oeste (MT)
	Alto Paraguai (MT)	Colíder (MT)	Sinop (MT)
	Alto Teles Pires (MT)	Norte Araguaia (MT)	Tangará da Serra (MT)
	Arinos (MT)	Paranatinga (MT)	
	Aripuanã (MT)	Parecis (MT)	
A2	Adamantina (SP)	Dracena (SP)	Paranavaí (PR)
	Alto Araguaia (MT)	Fernandópolis (SP)	Presidente Prudente (SP)
	Alto Taquari (MS)	Frutal (MG)	Quirinópolis (GO)
	Andradina (SP)	Ituiutaba (MG)	Rondonópolis (MT)
	Araçatuba (SP)	Jales (SP)	São José do Rio Preto (SP)
	Astorga (PR)	Marília (SP)	Sudoeste de Goiás (GO)
	Auriflama (SP)	Meia Ponte (GO)	Três Lagoas (MS)
	Birigui (SP)	Nhandeara (SP)	Tupã (SP)
	Campo Grande (MS)	Nova Andradina (MS)	Uberlândia (MG)
	Cassilândia (MS)	Paranaíba (MS)	Votuporanga (SP)

Figure 6 shows a proximity analysis with the criteria that were not used in AHP. According to Kanoli et al. (2007), in large-scale location problems, efficiency and adaptability of the model are essential for application to real-world problems. A1 and A2 have production characteristics according to the agricultural profile of the states where they are inserted, based on soil and climate aspects, with predominance of corn production in A1 (Figure 6a) and sugarcane production in A2 (Figure 6b).

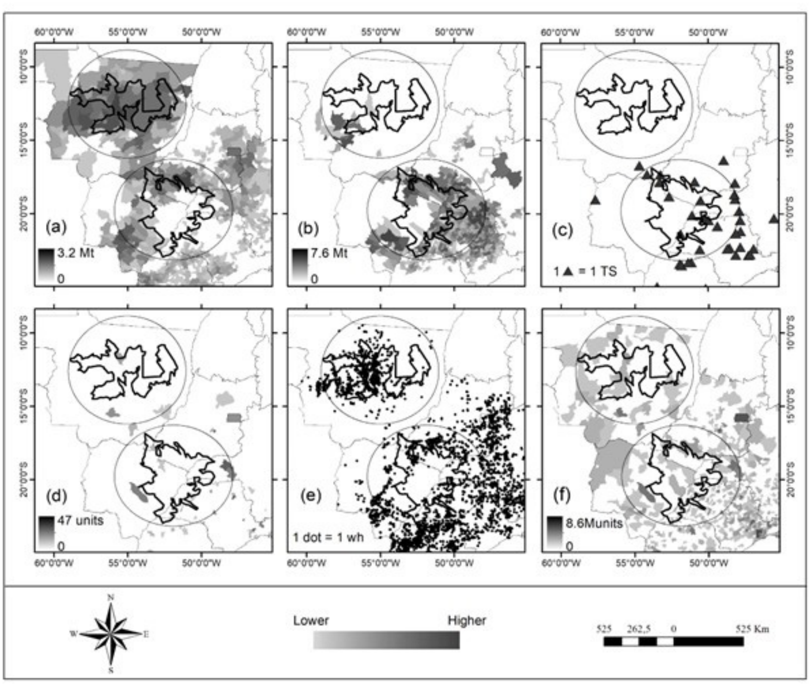

Figure 6. Proximity analysis. Circles centered on the centroid of each region for the following criteria: (a) Total municipal corn production (1st and 2nd harvest in tons); (b) Total municipal sugarcane production (in tons); (c) Transfer stations; (d) Fuel distributors; (e) Grain warehouses and (f) Consumer market (vehicle fleets by municipality).

Both A1 and A2 are located far from seaports and major consumer centers. Therefore, intermodal integration is required, allowing the shift from road transport to a more efficient mode (Coleti & Oliveira, 2019) and less harmful to the environment (Souza et al., 2020). These characteristics can be identified in Figure 6c, as it shows a greater concentration of transfer stations within and near A2. Despite a smaller presence of transfer stations near A1, this area is in corn-producing regions (Figure 6a) and close to some ethanol distributors (Figure 6d), a fact that minimizes the impact on the transportation of raw materials and finished products.

Figure 6e shows many warehouses located in both A1 and A2, particularly in A1. The A2 shows a greater spatial concentration at the edges. This abundant supply of warehouses is important, given the need to store a large amount of grain during the corn harvest for ethanol production in the sugarcane off-season. According to Mardaneh et al. (2021) and Oliveira & Alvim (2017), the storage capacity also assists grain distribution reducing transportation costs.

Finally, A2 is closer to ethanol markets than A1, represented in Figure 6f by the volume of municipal vehicle fleet. This is a strategic location considering the states of São Paulo, Goiás, and Minas Gerais are the main consumers of biofuel in the country (UDOP, 2020). Since the number of vehicles in a municipality is directly related to its population density, Hosseini & Mir Hassani (2015), when analyzing a problem of location of electric vehicle charging stations, obtained a similar result that prioritized areas with higher population density for fixed stations.

The sugar-ethanol sector in Brazil is electrically self-sufficient, as it generates electricity from bagasse and still sells the surplus to distribution concessionaires (Furlan et al., 2012; Castiñeiras & Pradelle, 2020; Dias et al., 2015). In the U.S. experience, they recur to fossil sources and the power grid to attend to heat and electrical demands in the ethanol conversion (Shapouri et al., 2003). However, it is necessary to assess whether these sugarcane residues would be sufficient to meet the energy demand of the plants in the generation of ethanol from corn. If the residue does not meet the cogeneration of energy for the continuous production of sugar and alcohol, we must consider the location of energy sources among the locational criteria. In addition, it is necessary to consider the possibility of increasing the production of second-generation ethanol from bagasse (Bechara et al., 2018; Castiñeiras & Pradelle, 2020; Palacios-Bereche et al., 2018). The technology is not yet extensively employed in the Brazilian industry (Castiñeiras & Pradelle, 2020), but a venture such as a flex plant must remain operating in the same location for several years.

Furlanetto et al. (2020) evidenced the complexity of the Brazilian taxation system. The authors concluded that this factor is essential for generating solid and resilient operating strategies, demanding a good assessment of taxes to avoid tax losses. An important aspect to be considered in location problems are taxes. This forces us to suggest that, despite the visual power and great value of the presented method, additional analyzes are necessary.

4 Conclusions

The mapping of areas enhances the use of resources and prevents the construction of flex plants in places classified as inadequate, unsatisfactory or moderate in relation to the necessary resources.

We confirm that AHP is effective in aiding decision-making, as it compares elements of different magnitudes and dimensions simultaneously. It is very uncommon in real-world problems to have all demanded supplies with quantity, quality, and low cost. So that, the decision-maker usually reduces the requirement of some criterion to minimally meet another. Since the data can be repulsive or attractive, all the criteria are normalized, pairwise compared, and weighted. The AHP enables handling multiple criteria in a reasonable equation. Combined with GIS, it allows the solving of complex large-scale location problems with efficiency and adaptability.

Within the same region, it is still possible to choose specific places that offer incentives such as tax reduction and simplified taxation. Taxation is a difficult aspect to map and optimize. In addition to there being significant variations throughout the Brazilian national territory, companies often negotiate directly with local governments and administrations, creating special regimes for which there is no general rule.

The comparison and complementation of structured specialists' opinion-based methods with optimization methods (both exact and heuristics solutions) should be further explored in future works. As well as the consideration of more variables and spatial-temporal uncertainty. The assessment of energy demand for ethanol production and the location of possible energy sources should also be considered in future studies.

Authors' contribution letter

Cristiane Andressa de Oliveira and Andrea Leda Ramos de Oliveira worked on the conceptualization and theoretical-methodological approach. The theoretical review was conducted by Cristiane Andressa de Oliveira and Marlon Fernandes de Souza. Data collection was coordinated by Cristiane Andressa de Oliveira. Data analysis included Cristiane Andressa de Oliveira, Andrea Leda Ramos de Oliveira e Marlon Fernandes de Souza. All authors worked together in the writing and final revision of the manuscript.

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