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Fuzzy logic and topographic data: susceptibility to soil salinization in the municipality of Jeremoabo, Bahia[1]

Lógica fuzzy e dados topográficos: susceptibilidade à salinização dos solos no município de Jeremoabo-BA

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ABSTRACT - Topographic data extracted from a digital terrain model (DTM) make it possible to analyze factors associated with various phenomena arising on the earth's surface. The aim of this study was to evaluate environmental susceptibility to soil salinization using the modeling of topographic data in the semiarid region of Brazil. The municipality of Jeremoabo, Bahia, was defined as the spatial scale for the analysis due to the climate characteristics and signs of environmental deterioration. The fuzzy gamma operator was applied to integrate the slope, plan and profile curvature, and topographic wetness index, and to configure scenarios of susceptibility to salinization. Together, the classes of high and severe susceptibility to soil salinization occur in around 22.29% of the total area. They are associated with low slopes, high topographic wetness indices, a concave curvature profile, and the planar class of plan curvature of the terrain. The data show the need to carry out effective land use planning for agriculture, such as the use of irrigation, to minimize the process of soil salinization, which is associated with the phenomenon of desertification.

Key words: Environmental analysis. Geoprocessing. Fuzzy logic. Salinity.

RESUMO - Os dados topográficos extraídos do modelo digital de terreno (MDT) possibilitam analisar fatores associados a diversos fenômenos decorrentes na superfície terrestre. Este estudo teve como objetivo avaliar a susceptibilidade ambiental à salinização do solo por meio da modelagem de dados topográficos no Semiárido brasileiro. Definiu-se o município de Jeremoabo-BA como escala espacial de análise devido às características climáticas e aos indícios de deterioração ambiental. Aplicou-se a lógica *fuzzy*, operador *gamma*, para integrar a declividade, plano de curvatura, perfil de curvatura e índice topográfico de umidade e configurar cenários de susceptibilidade à salinização. A ocorrência das classes de alta e severa susceptibilidade à salinização do solo decorrem, juntas, em cerca de 22,29% da área total. Elas estão associadas às baixas declividades, altos índices topográficos de umidade, perfil de curvatura côncavo e à classe planar do plano de curvatura do relevo. Os dados indicam a necessidade de realizar um planejamento eficaz do uso da terra pela agricultura, como o do emprego da irrigação, para minimizar o processo de salinização do solo, que estão associados ao fenômeno da desertificação.

Palavras-chave: Análise ambiental. Geoprocessamento. Lógica *fuzzy*. Salinidade.

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INTRODUCTION

The semiarid tropics in Brazil are characterized by the occurrence of a dry period of between six and eight months, that can extend up to eleven months with no rain in areas of extreme aridity (CUNHA *et al*., 2010). When rainfall values are significantly lower than normal during the year, especially during the rainy season, the phenomenon of drought occurs, bringing hydrological, agricultural and socioeconomic consequences (TEIXEIRA, 2016). The availability of fertile soils and water in certain areas, such as agricultural hubs, points to irrigation as one of the alternatives for agriculture and development in the semiarid region. It is estimated that irrigation hubs or irrigated perimeters can be found in more than 69 municipalities in the states of northeastern Brazil, with the exception of Maranhão (BUAINAIN; GARCIA, 2015). Some of these are found in areas with a semiarid tropical climate, where the production systems are capital, technology and knowledge intensive (BUAINAIN; GARCIA, 2015).

The climate conditions, quality of the groundwater, quality of the surface water, and topographic and pedological characteristics are intrinsic to the environmental dynamics of the semiarid tropics, and must be considered in land management in order to increase production and avoid the processes of salinization and degradation. Primary or natural salinization occurs through the integration of various components, such as topographic elements, by favoring salt deposition in flat terrain due to surface runoff (GUEVARA-LUNA *et al*., 2020). Other situations also play a part: the restrictions on drainage in low areas, where transported water and salts accumulate; the low permeability of the soil, that makes it difficult for the salts to be washed out; a high water table and the high rates of evapotranspiration, by contributing to capillary rise (VASCONCELOS, 2014).

Secondary salinization is induced through human activity, most often related to irrigation, due to the use of saline and/or sodic water; the lack of efficient drainage; and incorrect irrigation management, with the application of excessive irrigation depths, which raises the water table to the surface and causes salt deposition (GUEVARA-LUNA *et al*., 2020). Added to this is the exaggerated use of fertilizers with high levels of salts, such as ammonium nitrate (ANDRADE JÚNIOR *et al*., 2011), potassium chloride and other commercial products. All this results in changes in the physical and chemical properties of the soil, with a resulting loss of productive capacity (CASTRO; SANTOS, 2020; PEDROTTI *et al*., 2015; VASCONCELOS, 2014). The accumulation of salts in the root area reduces osmotic potential and water availability, generates ion toxicity in plants, reduces the percentage of germination, and inhibits crop growth (GKIOUGKIS *et al*., 2015; PEDROTTI *et al*., 2015).

On the scale of the semiarid region, soil salinization is one of the indicators of desertification, in addition to its association with land abandonment (CASTRO; SANTOS, 2020). Aspects of the terrain are important in demonstrating environmental fragility and factors that are prone to salinization, as they influence hydrological processes and spatially restrict the areas where moisture accumulates on the surface. From the perspective of this analysis, susceptibility refers to the probability of a process, such as soil salinization, occurring due to natural characteristics (PEREIRA; OLIVEIRA JUNIOR; LOBÃO, 2020). As such, the aim of this study was to develop an environmental model of susceptibility to soil salinization through the integration of topographic data, as an aid in defining indicators for land management in the semiarid tropics.

MATERIAL AND METHODS

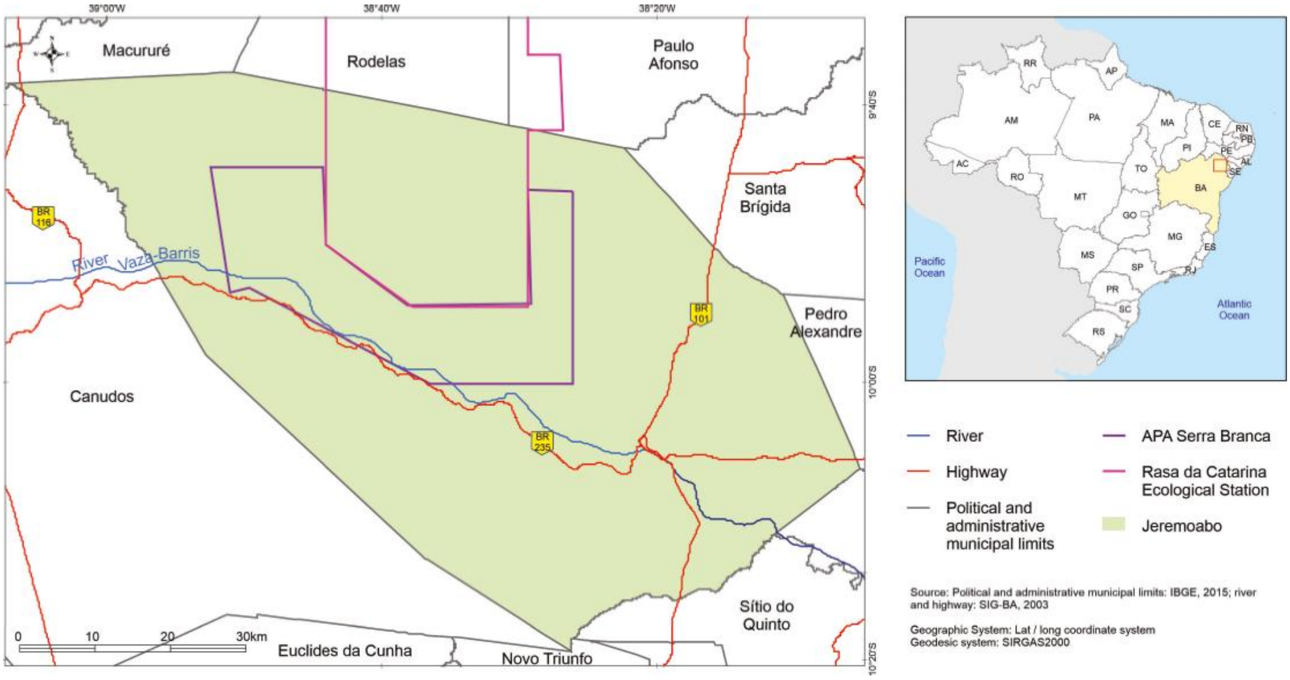
The study area comprises the municipality of Jeremoabo, located in an Area Susceptible to Desertification (ASD) in the north of the state of Bahia (Figure 1). The area is 4,267,488 km^2 in size, and includes advanced stages of environmental deterioration, which show a high propensity for desertification (LOBÃO; VALE, 2013; OLIVEIRA JUNIOR *et al*., 2018, 2020). Droughts occur frequently (NASCIMENTO, 2015; SÃO JOSÉ *et al*., 2020), there is no water surplus in any month, and the climate is characterized by an annual water deficit of around 822.9 mm (SUPERINTENDÊNCIA DE ESTUDOS ECONÔMICOS E SOCIAIS DA BAHIA, 1999), demonstrating the severity of the climate.

Sedimentary rocks are the largest extensions, largely made up of sandstones corresponding to 74.46% of the total found in the area. The geomorphology comprises three units that are notable, in order of area, due to the formations of embedded dissections and levelling, tablelands and pediments, both functional and modeled by incipient drainage (GEOREFERENCED INFORMATION SYSTEM – SIG-BA, 2003).

The altitude varies between 212 m and 741 m, with the lower altitudes comprising the valley of the Vaza-Barris river and the higher altitudes the peaks of the tablelands. The formations where the highest altitudes are found correspond to the slopes of the tablelands.

The predominant plant features are the woody Caatinga and park Caatinga, which especially thrive on the tablelands. The woody Caatinga is characterized by a composition of floristically heterogeneous, deciduous and thorny, small-leaved species; the density is continuous and semi-continuous, with the structure largely comprising two woody strata, an upper stratum with an average height of 5 m, and a shrub layer, of less than 3 m (OLIVEIRA

Figure 1 - Location of the municipality of Jeremoabo, in the state of Bahia



JUNIOR *et al*., 2020). The park Caatinga consists of a shrub layer with spaces between the individuals, which show woody, thorny, deciduous, semideciduous and small-leaved characteristics; and an herbaceous layer, composed of grasses (*Aristida sp.*), which densely cover the soil during the rainy season (OLIVEIRA JUNIOR *et al*., 2020).

Farming is noticeably developed in the formations of embedded dissections and levelling, and characterized by extensive livestock farming and rainfed agriculture. Irrigated agriculture takes place in the Vaza-Barris river valley, with the production of fruit and maize (OLIVEIRA JUNIOR *et al*., 2020).

In developing the study, information planes were elaborated, maps of the terrain variables, such as slope, plan curvature, profile curvature and the topographic wetness index. These were extracted from the digital terrain model (DTM) of the Shuttle Radar Topography Mission (SRTM), with a resolution of 30 m, by applying geoprocessing techniques. The slope was classified into six levels, which met the intervals in degrees and the nomenclature defined by the Empresa Brasileira de Pesquisa Agropecuária – EMBRAPA (1979).

The profile curvature was elaborated considering null values for the rectilinear slopes, positive values for the concave slopes and negative values for the convex slopes (VALERIANO; CARVALHO JÚNIOR, 2003). A transition zone was seen when classifying the profile curvature, and intervals between -0.4 and 0.4 were established for the rectilinear slope, negative values below -0.4 for the convex, and positive values greater than 0.4 for the concave.

The plan curvature was extracted by defining positive values for divergent terrain, negative for convergent terrain and close to zero for planar terrain, adjusted by a transition zone (VALERIANO; CARVALHO JÚNIOR, 2003). A space of -0.4 to 0.4 was therefore stipulated for the planar curvature, values below -0.4 for the convergent curvatures and greater than 0.4 for the divergent curvatures.

The topographic wetness index was elaborated by extracting the slope and contribution area of the DTM using the SAGA extension of the QGIS 3.16.0 software. Classes were defined based on Lin *et al*. (2006), supported by data collected in the field during August, when the annual period with the highest rainfall index comes to an end. The HidroFarm HFM2010/HFM2030 electronic soil moisture meter was used for direct analysis of the soil moisture content at a maximum depth of 20 cm. The choice of depth was based on the pedological conditions of the study area, consisting of shallow soils that are often difficult to penetrate.

The geographic coordinates were obtained for each recorded measurement to integrate the data into the Geographic Information System (GIS) used in the research and help establish the classes for the topographic wetness index. The lower soil moisture indices were predominant along the pedimented areas, which coincided with the low and medium classes of the topographic wetness index. In the Vaza-Barris river valley, the highest values found in the field were recorded for soil moisture, which together with the lower values constituted a parameter for establishing the intervals of the four classes of the topographic wetness index.

For modeling the susceptibility to salinization, the information planes regarding slope, profile curvature, plan curvature and topographic wetness index were integrated into a GIS environment using the fuzzy gamma operator, as specified by equation 1.

$$\text{Fuzzy model} = (\text{algebraic sum})^{g} \times (\text{algebraic product})^{1-g} \quad (1)$$

where the constant g varies from 0 to 1. When close to zero, this indicates an optimistic scenario, while values close to 1 indicate a pessimistic scenario, since they approach, respectively, the algebraic sum and algebraic product (BONHAM-CARTER, 1994).

The characteristics of each class of information plane were analyzed to attribute levels of fuzzy set inclusion, which consisted of values between zero and one, with one indicating the greatest susceptibility to salinization. The levels of inclusion can be explained by the degree of influence of each class of information plane on the process under investigation. Similar methods for setting up environmental scenarios were used by Ilanloo (2011), Leonardia, Palamaraa and Ciriannia (2016), Lobão and Vale (2013), Pereira, Oliveira Junior and Lobão (2020) and Silva *et al*. (2013).

Each class of information plane was individually appraised by an analysis of the literature on soil salinization in dry areas (BRADY; WEIL, 2013; EMPRESA BRASILEIRA DE RESEARCH AGRICULTURAL, 2006; GKIOUGKIS *et al*., 2015; LANNETTA; COLONNA, 2013; 2010; PEDROTTI *et al*., 2015). For this, the classes were associated with data identified in the field in relation to the characteristics of the terrain, such as the forms of the modeled accumulation, denudation, valleys, slopes and escarpments that were integrated into the GIS used in the research.

The modeling resulted in a map with a cartographic scale of 1/90,000, which was used to carry out cross-tabulation using the soil maps (GEOREFERENCED INFORMATION SYSTEM – SIG-BA, 2003), and land-use and cover maps (OLIVEIRA JUNIOR *et al*., 2020). Quantitative descriptions of the simultaneity between the soil modeling and land-use and cover modeling were then produced on two spreadsheets to identify the classes of interest of the information planes associated with the scenarios of susceptibility to soil salinization. It is important here to outline a more efficient agricultural plan in order to increase productivity and environmental conservation.

RESULTS AND DISCUSSION

Some of the terrain variables had hierarchical importance in configuring the models, as they influence the processes of water accumulation and surface runoff, which are relevant to analyzing the susceptibility of the environment to soil salinization. There was a predominance of the gently undulating class of slope, as this represents 43.68% of the area (Figure 2). In decreasing order of magnitude, this is accompanied by the undulating (26.22%), flat (25.23%) and strongly undulating (4.33%) classes. A small proportion is formed by mountainous and steeply mountainous slopes.

The profile curvature refers to the concave, convex or rectilinear character of the terrain when analyzed in profile, and conditions the process of migration and the accumulation of water, minerals and organic matter on the surface (SILVA NETO, 2013; VALERIANO, 2003). The concave class is more evident, as it corresponds to 38.63% of the total area, followed by the convex and rectilinear slopes, with 37.84% and 23.53% respectively (Figure 2).

The plan curvature is associated with the divergent, convergent, or planar aspects of matter flows on the surface when analyzed in a horizontal projection (SILVA NETO, 2013; VALERIANO, 2003). In Jeremoabo, the divergent slopes predominate, as they occur in 36.18% of the area, convergent slopes correspond to 35.37%, and planar slopes to 28.45% (Figure 2).

The topographic wetness index characterizes the distribution of saturation zones and the topographical control over the water variation on the surface (VALERIANO, 2003). The environmental features specific to the area allowed four classes of topographic wetness index to be defined. The high index was prevalent, as it represents 41.20% of the study area (Figure 2). This is followed by the medium (37.77%), low (15.85%) and very high (5.18%) indices.

The information planes were integrated using the fuzzy gamma operator with an exponent of 7, as that is the most appropriate based on what can be seen in the field, meeting the criteria specified in Figure 3. High levels of fuzzy set inclusion were seen for the concave profile curvature, the rectilinear plane curvature, the flat slope, and the very high topographic wetness index.

The result of the modeling is shown in Figure 4. The class with the greatest coverage matches that with low susceptibility to salinization, as it represents 67.52% of the municipality, followed by high and medium susceptibility, which occur in 15.65% and 10.19%, respectively. Severe susceptibility to salinization occurs in 6.64% of the area, which corresponds to around 283.36 km^2. This is mainly distributed on the peaks of the tablelands and in the

Figure 2 - Topographic characteristics: slope, profile curvature, plan curvature and topographic wetness index, Jeremoabo, Bahia

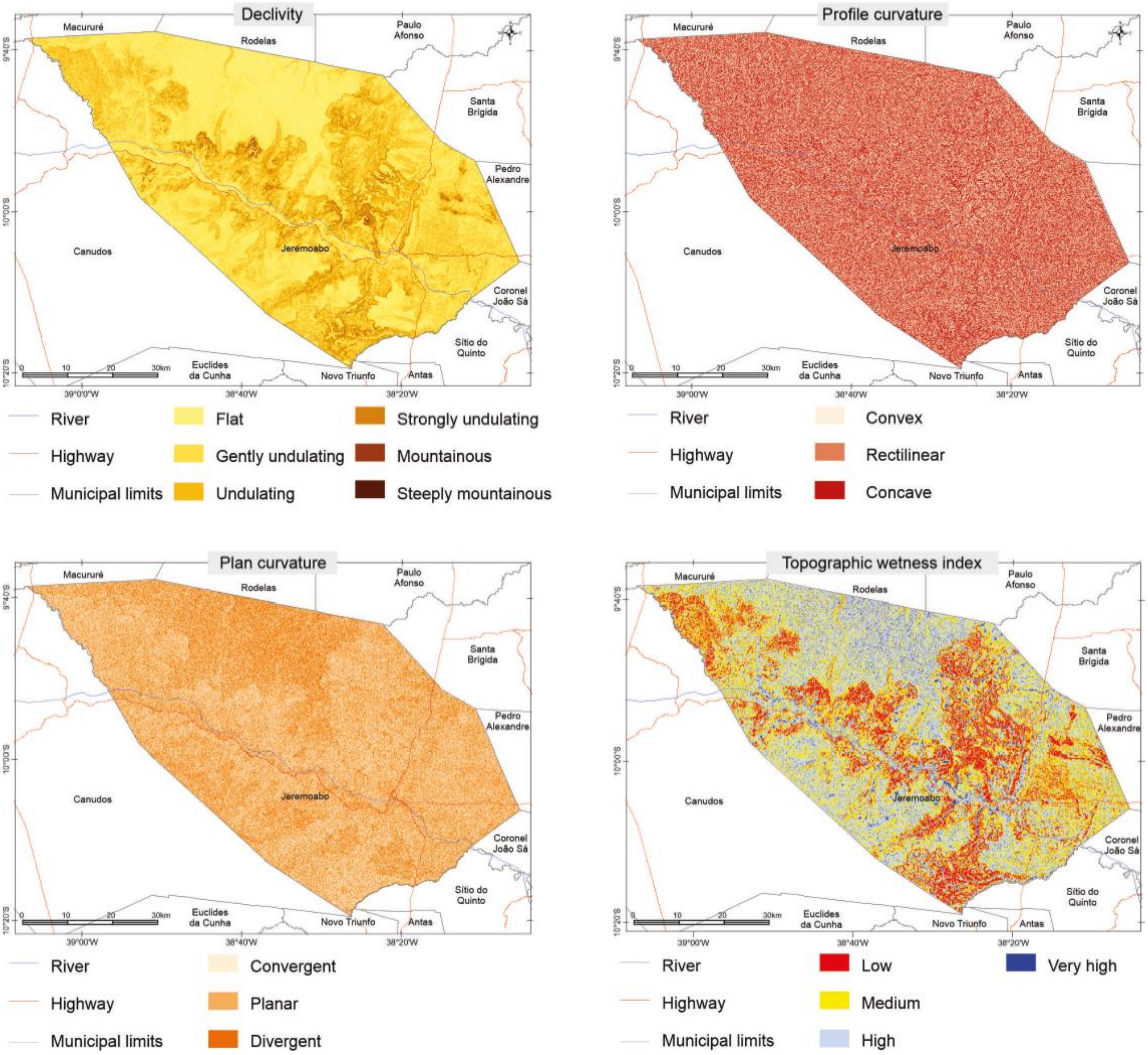


Figure 3 - Information planes and levels of fuzzy set inclusion: criteria established for modeling environmental susceptibility to soil salinization

Profile curvature	Convex	0.5
	Concave	1.0
	Rectilinear	0.7

Plan curvature	Divergent	0.6
	Planar	0.9
	Convergent	0.3

Declivity	Flat	1.0
	Gently undulating	0.9
	Undulating	0.5
	Strongly undulating	0.2
	Mountainous	0.1
	Steeply mountainous	0.0

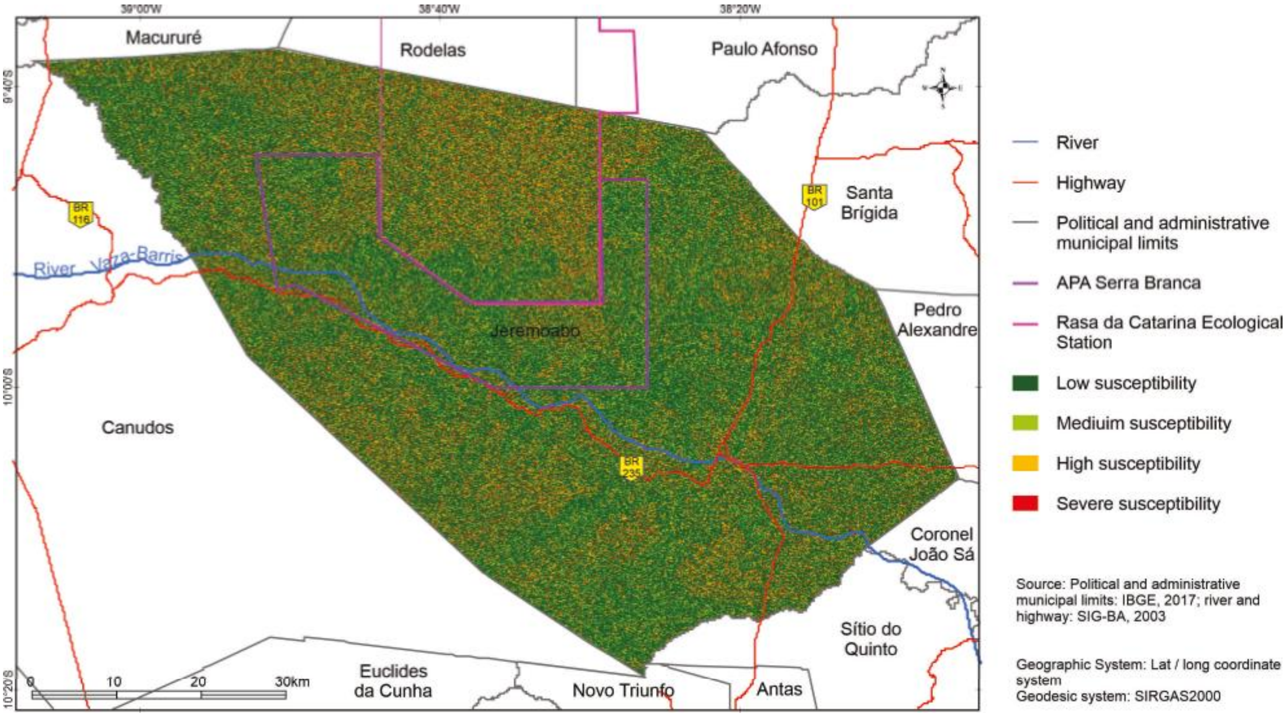
TWI*	Low	0.3
	Medium	0.5
	High	0.8
	Very high	1.0

* Topographic wetness index

Vaza-Barris river valley, precisely where flat terrain and the highest classes of the topographic wetness index are found, and the rectilinear and concave slopes disperse.

In the municipality of Jeremoabo, the most common soils are the Quartzarenic Neosols and Litholic Neosols, corresponding to 53.38% and 34.1% respectively (GEOREFERENCED INFORMATION SYSTEM – SIG-BA, 2003). When analyzed in isolation, they are soils with low susceptibility to salinization, characterized by a difficulty in accumulating water and salts (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA, 2006). However, the topographic conditions considered in the fuzzy modeling can favor the deposition of water and sediment, including

Figure 4 - Environmental susceptibility to soil salinization, Jeremoabo, Bahia



the possibility of salinization. About 14.09% of the extent of these soils is distributed over areas of high and severe susceptibility to salinization, around 526.01 km^2, as shown by the modeling (Figure 4).

Attention is now focused on the Luvisols, Planosols and Vertisols, as they are naturally prone to salinization due to the characteristics of the source materials and characteristics specific to the profile (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA, 2006; IBGE, 2007). Luvisols are relatively shallow, have a solodic and sodic nature, and are formed from a highly active clay fraction. Planosols are shallow soils, generally dense due to the accumulation of clay in the subsurface and have imperfect drainage and permeability. Vertisols are characterized by having little permeability, as 2:1 clays expand when wet and afford poor drainage. From the cross-tabulation data, it was found that most Vertisols develop in areas of high and severe susceptibility to salinization, resulting in a total of 61.45 km^2.

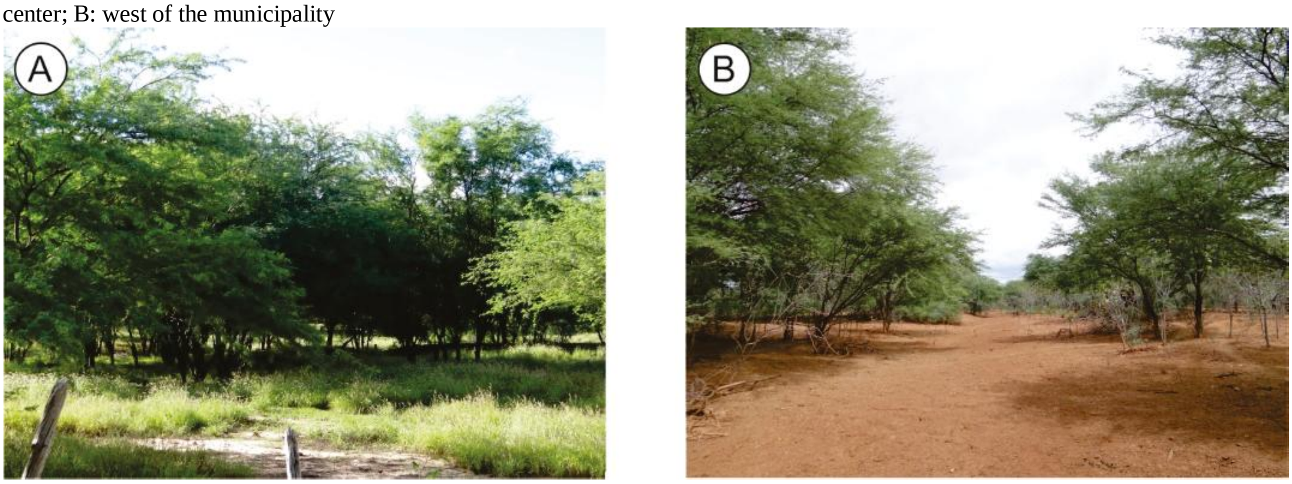
Farming is found in 24.89% of the area (OLIVEIRA JUNIOR *et al*., 2020), with around 20.53% of the total for this class taking place in areas of high and severe susceptibility to soil salinization, equivalent to 243.29 km^2 of the municipal area. In these places, in addition to the natural topographic characteristics, are human activities, including the process of irrigation, common in the Vaza-Barris river valley. It is therefore necessary to pay attention to the quality of the water, so as to prevent the process of degradation from being triggered, e.g. soil salinity, and to select the most appropriate irrigation method based on the environmental characteristics and the crops being grown.

Furthermore, there has been an advance in the agricultural use of land in some areas of the tablelands, as was seen when manipulating the GIS data from the surveys carried out in the field. At some of these points, a concentration of high and severe indices of susceptibility to soil salinization was found using fuzzy modeling of the topographic data.

In the field, the spread of *Prosopis juliflora* was seen in pastures located in areas of the Vaza-Barris river valley, especially in the center-west of the municipality (Figure 5). The species is resistant to drought and can therefore be used as an alternative for feeding animals during periods of drought. Some of the points of greatest density coincided with the highest levels of susceptibility to soil salinization.

The above data show the necessity of carrying out land use planning to avoid the processes of soil salinization, which are directly linked to environmental degradation in dry areas. This shows the importance of conservation practices to prevent actions that can trigger desertification in the Caatinga biome, with harmful repercussions on the economy, and a reduction in agricultural productivity.

Figure 5 – Development of *Prosopis juliflora* in areas of severe susceptibility to salinization, Vaza-Barris River valley. A: municipal center; B: west of the municipality



CONCLUSIONS

The integration of topographical variables using fuzzy logic demonstrated the extent of the classes with high susceptibility to soil salinization. The severe class is distributed over approximately 283.36 km^2, while the high class over 667.86 km^2. These are factors that need to be considered in managing the irrigation water, so as not to trigger the phenomenon of salinization. Soil salinization susceptibility maps can help select more suitable irrigation methods. It is therefore important to associate them with other information, such as drainage capacity, pedological characteristics and water quality.

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