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Papers

Methodological proposal for evaluation of susceptibility to environmental degradation

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Abstract

Land use and occupation is a research theme that contributes to the analysis of the territory dynamics, reflected in the relationships between society and nature that modify the landscape. These relationships include environmental, spatial, cultural, and socioeconomic factors that integrate the environment from a systemic point of view and perform functions and activities capable of maintaining or disturbing the natural balance of the environment. Thus, knowing the limits of environmental systems is a way to live rationally with the exploitation of natural resources for the development of the various human activities. Therefore, this study aimed to propose a method to assess the degree of susceptibility to environmental degradation, using geoprocessing techniques, in the Immediate Geographical Region of "Princesa Isabel" (IGRPI), located in the semi-arid region of Paraíba. Geology, pedology, geomorphology, rainfall, vegetation cover, and land use and occupation data were integrated into the Geographic Information System to compute the Biophysical Index of Susceptibility to Environmental Degradation (BISED) in the IGRPI. The analyzed factors were more fragile in rural areas because of natural factors, since in urban areas there are more intense anthropogenic activities, and the BISED ranged from low to high, especially in municipal seats, indicating that the region, even being little developed, has the opportunity to plan the environment for a future with sustainable exploitation.

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INTRODUCTION

Land use and occupation is a research subject of geography that contributes to the accurate analysis of space and social, economic, cultural, political, and environmental processes of a territory. It was developed over the different phases of geographical thinking, highlighting (1) the concepts of area and integration, formulated by Hartshorne in the so-called corological school in the early 20th century; (2) the quantitative revolution in geography in the post-World War II, which contributed to developing the study of space towards conceptual and geometric delimitation of spaces and differentiation of areas, according to the integration of heterogeneous elements of the earth's surface, strongly contributing to the emergence of Geographic Information Systems (GIS) and techniques that improved the process of map production and analysis of dynamics in land use and occupation; and (3) the postmodern geography, which derives from radical geography and seeks to discuss the production of the social environment from spatial relationships (IBGE, 2013).

Land use and occupation are understood from the elements that constitute the landscape, which can be comprehended as a synthesis of the physical and social aspects and processes of a territory and studied from a systemic approach, making possible its analysis from the integration of its components. The variables that structure the landscape and form bio-geophysical subsystems are susceptible to diagnosis, giving an interdisciplinary character to environmental analysis that seeks to understand the interconnectivity of these variables, which are intrinsic to geological, pedological, geomorphological, climatic, phytogeographic, and land use and occupation aspects (TEIXEIRA et al., 2021).

The environmental analysis can be performed by considering the fragility of the environment, which can be understood as the ease with which environmental systems can be destroyed or poorly durable as human interventions intensify (emerging fragility) or by natural processes (potential fragility) (TEIXEIRA et al., 2021; MACEDO et al., 2021).

The intensification of non-planned anthropogenic activities on fragile environmental systems compromises the stability of these systems and this imbalance leads, for example, to processes of environmental degradation and desertification, which compromises the subsistence of the community itself that depends on natural resources. Therefore, by assessing the environmental degradation susceptibility of a territory, we can obtain information to subsidize environmental planning, focusing on sustainability in the processes of exploitation of resources, and respecting environmental limits.

In this sense, geotechnologies are an important technical and technological resource for the study of spatial phenomena, with the advantages of covering large geographical scales, integrating data from different areas of knowledge, and automating the production of maps, which are a way to communicate geographical information.

The assessment of environmental degradation susceptibility or environmental fragility, using remote sensing products (satellite images and vegetation indices) and geospatial analysis techniques implemented in GIS, has been a recurring strategy in the scientific literature (CREPANI et al., 2001; SANTOS et al., 2016; SANTOS et al., 2021, MACEDO et al., 2021; TEIXEIRA et al., 2021). In this context, the hierarchical process analysis (HPA) stands out, which considers multiple criteria weighted by the degree of contribution of the variables to the analyzed processes.

Thus, especially in rural areas, it is elementary that the exploitation of natural resources translates into anthropogenic interference activities for the transformation or deepening of a technified geographical space, although this interference has more rudimentary characteristics than that in urbanized areas. For their future sustainability, these activities need to be based on the limits of environmental systems, especially if the territory has tourist potential and aims to develop tourist activities, such as the immediate geographical region of Princesa Isabel. Therefore, it is necessary to know what these limits are and evaluate them so that it is possible to obtain information to subsidize environmental planning and management, based on the development of instruments such as environmental zoning.

Given the above, this study aimed to propose a method to assess the degree of susceptibility to environmental degradation in the immediate geographical region of Princesa Isabel, based on spatialized biophysical indicators.

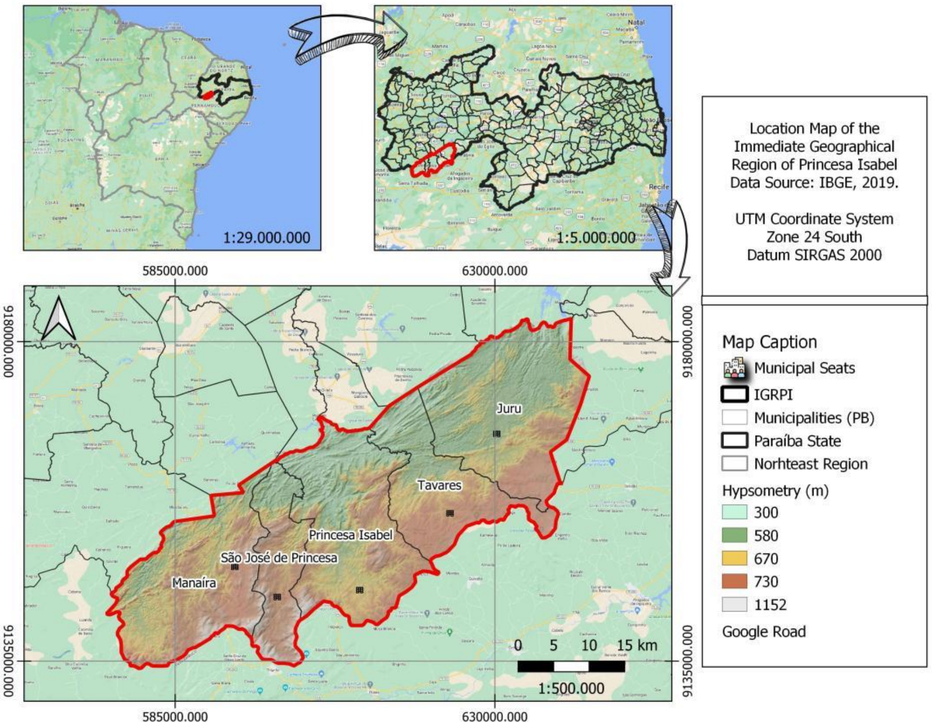
METHOD

Study area

The geographical region of Princesa Isabel (IGRPI) is located in southwestern Paraíba, in the Serra de Teixeira microregion. The IGRPI includes five municipalities (from east to west), as follows: Juru, Tavares, Princesa Isabel, São José de Princesa, and Manaíra. This region borders the state of Pernambuco to the south and the municipalities of Paraíba to the north, east, and west (Figure 1). The IGRPI has an average altitude of 690 meters and, among their municipalities, São José de Princesa has the highest altitude (720 meters). The presence of mountains is very common in the region, which is located on the Borborema plateau and reaches temperatures between 12ºC, in the rainy season, and 35ºC in the dry season. The rainfall is characterized by approximately 789 mm annually, occurring mostly between March and July, typical of the semi-arid region of Brazil. Small-size vegetation predominates in the region, with xerophyte species, typical of the Caatinga biome.

Data regarding the total, urban, rural (IBGE, 2010), and estimated population for 2021 (IBGE, 2017), including demographic density, and MHDI (2010) in the municipalities of IGRPI can be observed in Table 1.

Figure 1 - Location of the immediate geographical region of Princesa Isabel.



Source: The authors (2021).

Table 1 - Data summary on population, MHDI, and demographic density in the IGRPI.

Municipality	Total Population (2010)	Urban Population (2010)	Rural Population (2010)	Estimated Total Population (2021)	Demographic Density (2010)	MHDI (2010)
Juru	9,826	4,359	5,467	9,831	24.57	0.570
Tavares	14,759	6,616	7,487	14,791	59.42	0.586
Princesa Isabel	21,283	14,528	6,755	23,749	57.84	0.606
São José de Princesa	4,219	695	3,524	3,898	26.70	0.565
Manaíra	10,759	6,027	4,732	10,988	30.52	0.543
IGRPI (Total)	60,846	32,2255	27,965	63,257	Mean 39.8	0.574

Source: IBGE (2010) and IBGE (2017).

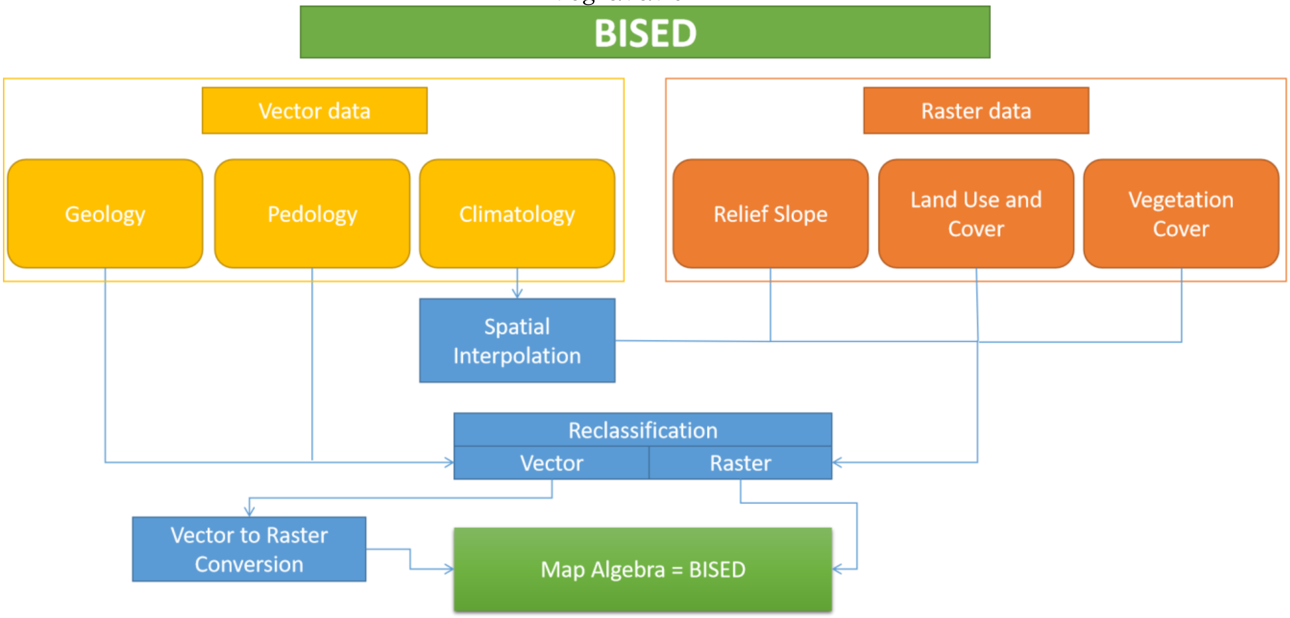
Among the above-mentioned municipalities, Princesa Isabel is the most developed and populous, in addition to having the highest per capita income (R$ 334.74) in comparison with Tavares (R$ 260.75), Juru (R$ 247.78), Manaíra (R$ 225.93) and São José de Princesa (R$ 221.16), and is therefore considered the center of the region (IBGE, 2010). It is noteworthy that in 2010 the rural population of Juru, Tavares, and São José de Princesa was larger than the urban population, which indicates that the occupation of that space provides a predominant development of activities related to that geographical context, such as agriculture and animal breeding.

Regarding the occupation of the territory, very low demographic densities are evident in all municipalities, especially in comparison with the most populous ones of the state, such as João Pessoa (3,421.28 hab./km²) and Campina Grande (648.31 hab./km²). In addition, the region has unexplored tourist potential, based mainly on natural and historical aspects.

Method

To verify the degree of susceptibility to environmental degradation in the IGRPI, we proposed a combined method from those developed by Crepani et al. (2001), Oliveira (2011), Franco et al. (2012), Santos et al. (2016), Valle et al. (2016), França et al. (2017), and Silva and Souza (2020). For this, indicators of geology (resistance to physical weathering), pedology (vulnerability to erosion), geomorphology (relief slope), climate (rainfall intensity), vegetation cover (vegetation index), and land use and occupation were considered, which received scores from 1 to 6, from the lightest to the most serious, according to their degree of contribution to environmental degradation. Finally, a simple sum of these indicators (Figure 2) was calculated.

Figure 2 - Flowchart for obtaining the biophysical index of susceptibility to environmental degradation



Source: The authors (2021).

Geology Indicator (Lithotypes)

The geology data, whose theme is geodiversity, were obtained using the GeoSGB, the database of the Geological Service of Brazil (CPRM, 2021). One of the attributes is the resistance to the physical weathering of each type or set of rocks, with the following classes in the IGRPI: "low to high" and "moderate to high". Considering that high resistance has weight 1 in the contribution to environmental degradation, low resistance has weight 5, i.e., the greatest chance of degrading. Then, simple means were calculated to represent the weight of the classes, resulting in weight 2 for the class from moderate (3) to high (1) and weight 3 for the class from low (5) to high (1) (Chart 1).

Chart 1 - Lithotypes and their respective weights for the calculation of susceptibility to environmental degradation.

Lithotypes	Resistance to Physical Weathering	Weight
Diorite, granite, granodiorite, monzonite	Moderate to high	2
Granite, porphyry granite	Moderate to high	2
Alkali-feldspar granite, quartz alkali-feldspar syenite	Moderate to high	2
Metabasalt, metadacite, metagabbro, metagrauvaca, metarriodacite, metavolcanoclastic, paragneisse, metachert	Low to high	3
Metarhythmite, metagrauvaca, metachert, banded iron formation, metatufo, felsic metavolcanic rock, carbonite schist, intermediate to mafic metavolcanic, metavolcanoclastic, schist, and phyllite.	Low to high	3
Migmatite, metagranite, metamonzogranite, metasyenite, metasyenogranite	Low to high	3
Mafic metavolcanic rock, felsic metavolcanic rock, metaconglomerate, metagrauvaca, metapyroclastic, lithic metarenite, metarrhythmite	Low to high	3
Polymitic metaconglomerate, metagrauvaca, metarenite	Moderate to high	2

Source: The authors (2021).

Geomorphology indicator (slope)

The geomorphology data of the study area were obtained in the matrix format, specifically from the ALOS DEM satellite (ASF Alaska/NASA), which is a digital elevation model with a spatial resolution of 12.5 m, whose pixels have values of the relief altitude. These data were subjected to pre-processing operations in GIS, using QGIS such as geographic cut to the study area and the application of filter for the removal of noisy pixels (Fill Sinks algorithm), and to processing operations to obtain the slope (percentage) and for the reclassification of the pixels, assigning them the corresponding weights (Chart 2).

Chart 2 - Weights attributed to the relief slope classes.

Relief	Range	Weight
Flat	0 - 3 %	1
Smooth wavy	3 - 8 %	2
Wavy	8 - 20 %	3
Strong wavy	20 - 45 %	4
Mountainous	45 - 75 %	5
Steep	> 75%	6

Source: The authors (2021).

The scale used in this research is referenced in Embrapa (2018) and considers that the steeper the slope, the greater the chance of environmental degradation, especially if combined with other factors, such as the lack of vegetation cover, type of soil or developed activity, such as pasture, deforested areas or ore exploitation areas.

Climate indicator (rain intensity)

The monthly rainfall data, from 2009 to 2019, were obtained on the Meteorological Data Portal of the Agência Executiva de Gestão das Águas do Estado da Paraíba (AESA, sd), which is the state agency responsible for the implementation of water resources management in the Paraíba state, in alphanumeric format, arranged in several spreadsheets. No gaps were identified.

From these data, we calculated the monthly rainfall incidence in the region, which is the division between the monthly average of each year, considering only the months when rainfall was higher than 50 mm – considered by Crepani et al. (2001) as a minimum value that contributes to environmental degradation – and the annual average accumulated rainfall. Thus, in the regions where the rainfall is concentrated in short periods, such as in the semi-arid region of Brazil, the intensity of rainfall is higher and provides more susceptibility to environmental degradation. The classes used by the above-mentioned authors were adapted to the study area in our research, assigning weights only to the existing classes in the data set for the municipalities of the IGRPI, reclassifying the values for the 1 – 6 interval (Chart 3).

Chart 3 - Attribution of weights to rainfall intensity in the IGRPI.

Rainfall Intensity / Month	Weight
< 50 mm	1
50 - 75 mm	2
75 - 100 mm	3
100 - 125 mm	4
125 - 150 mm	5
> 150 mm	6

Source: The authors (2021).

The monthly rainfall values were incorporated into the geographical data of the IGRPI's territorial limits, through a simple table combination, thus making possible the spatialization of this indicator. Then, the vector data generated were converted to the matrix format, in which each pixel contained the weight attributed to its respective class of monthly rainfall intensity.

Soil indicator (erosion vulnerability)

The geographical data on soil types, of vector structure (polygons), compatible with a level of detail on a scale of 1:5,000,000, generated in 2006, were obtained from the IBGE Geosciences Portal (sd). The field containing the name of the soils was observed to identify and weigh the different soil types in the region (Chart 4). Weighting was performed based on the scale of the vulnerability of soils proposed by Crepani et al. (2001), converting the values to a scale ranging from 1 to 5, by a simple "rule of three" calculation.

Chart 4 - Types of soil and their weights according to their vulnerability.

Soil type	Weight
Red-yellow argisol	3
Chromic luvisol	3
Haplic cambisol	4
Litholic neosol	5

Source: The authors (2021).

In the GIS, these data, which covered the entire national territory, were geographically cut to the study area and reclassified so that each type of soil received the corresponding weight and was then converted to the matrix format, in which the pixels contained the values of the weights.

Vegetation cover indicator (NDVI)

The vegetation cover data were obtained by computing the Normalized Difference Vegetation Index (NDVI) from the Landsat-8 satellite images (NASA), whose spatial resolution is 30 m. The images were obtained using Google Earth Engine, through commands written in the JavaScript programming language. On this platform, an algorithm was created to select images in the red and near-infrared spectral ranges, with a percentage of cloud cover less than 10%, atmospheric correction and radiance conversion to surface reflectance already applied. This algorithm was also used to generate images of the median of each pixel of 2019, aiming at minimizing the influence of seasonality, typical of the semi-arid region, on vegetation behavior. Finally, median images were used to compute the NDVI.

The weights applied to the vegetation cover classes were defined according to Oliveira (2011). Then, the NDVI image was reclassified so that each pixel showed the weight value following the logic that the higher the vegetation cover, the lower the susceptibility to environmental degradation (Chart 5).

Chart 5 - Weights corresponding to vegetation cover levels in the region.

NDVI	Soil cover	Weight
< 0.0	Water	0
0.0 - 0.2	Exposed soil	5
0.2 - 0.4	Low shrub vegetation	4
0.4 - 0.6	Medium shrub vegetation	3
0.6 - 0.8	Medium-high tree vegetation	2
0.8 - 1.0	Tree vegetation	1

Source: The authors (2021).

Land use and occupation

Land use and occupation were also considered as a factor that contributes to environmental degradation. Through images classified by the MapBiomas platform (2019), land use classes were identified in the municipalities of the IGRPI. The products consisted of 6 macro-classes: forest, non-forest natural formation, agriculture and livestock farming, non-vegetated area, water body, and not observed. Thus, a generalization was applied to these macro-classes to directly include them in the BISED, i.e., two large groups were established: anthropogenic activity and natural cover (Chart 6).

Chart 6 - Classes and weights attributed to land use and occupation.

New Class	Macro-Classes	Weight
Anthropogenic activity	Agriculture and livestock farming (agriculture and pasture) and non-vegetated areas (urban infrastructure).	3
Natural cover	Forests, natural formations, and water bodies.	0

Source: The authors (2021).

Finally, an Algebra of Maps was performed in the QGIS, using the raster calculator tool, fed by the raster data resulting from the processing of each indicator, calculating the simple sum as representative of the BISED, according to equation 1. The minimum and maximum possible values for this index in the IGRPI were 7 and 28, respectively.

$$BISED = \sum_{i=1}^{n=6} Indicator_i \qquad \text{(Eq. 1)}$$

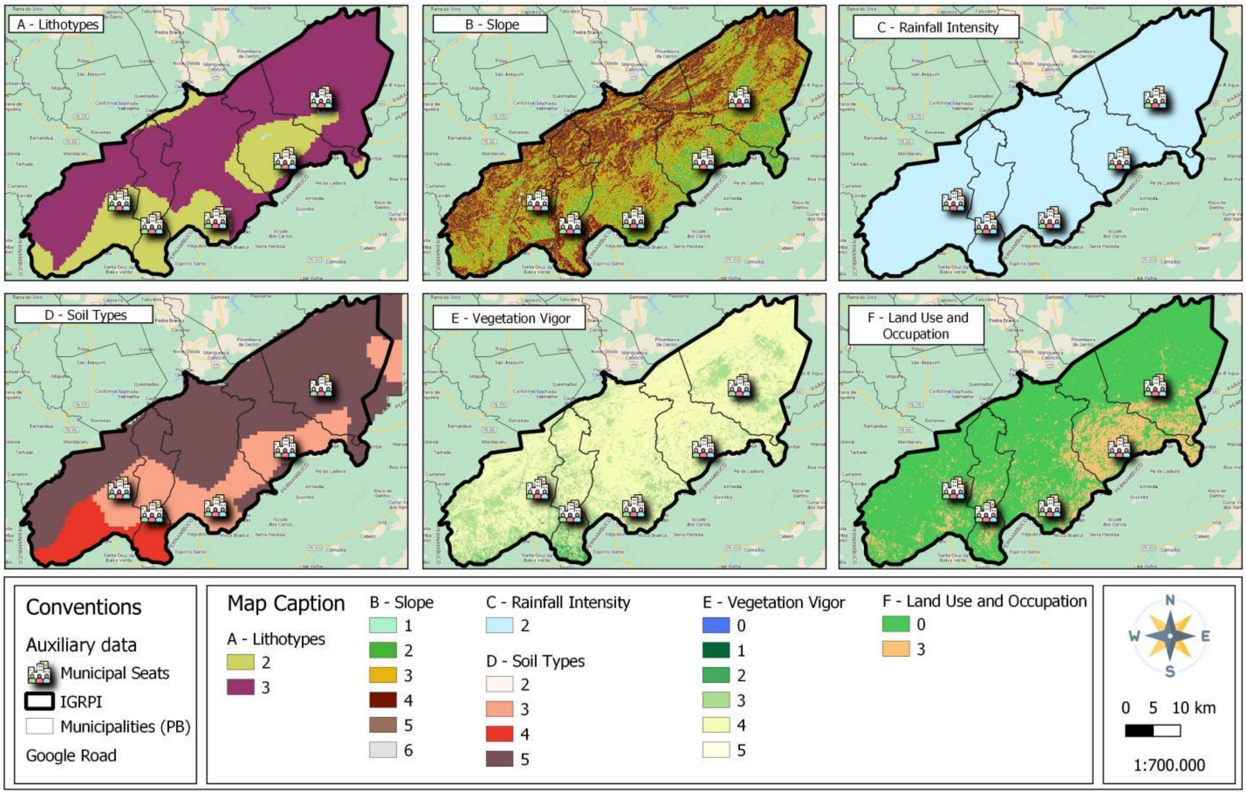
Where: indicator 1 = lithotype; indicator 2 = slope; indicator 3 = rainfall intensity; indicator 4 = soil vulnerability to erosion; indicator 5 = vegetation cover; indicator 6 = land use; and n = number of indicators, equal to 6.

RESULTS AND DISCUSSION

Thematic maps of lithotypes, relief slope, rainfall, soil types, vegetation vigor, and land use and occupation (Figure 3) provide a spatial view of the variability of these variables in the IGRPI. The way maps are shown (Figure 3), they can be analyzed individually, considering each variable, and by making associations between maps, as well as by location, previously identifying the municipalities with higher susceptibility to environmental degradation based on the values of the reclassified variables presented in the captions. The higher the value, the greater its contribution.

Regarding lithotypes, rocks with low to high resistance to physical weathering (value 3) predominate in the IGRPI, especially in the rural area of the municipalities. Under the municipal seats, we can observe the occurrence of rocks less susceptible to environmental degradation (value 2), except for Juru. The relief is steeper (values 4 and 5) in the extension from the west to the northeast and in the limits with Pernambuco, i.e., predominantly in the rural area.

Figure 3 - Contribution of biophysical variables to environmental degradation susceptibility



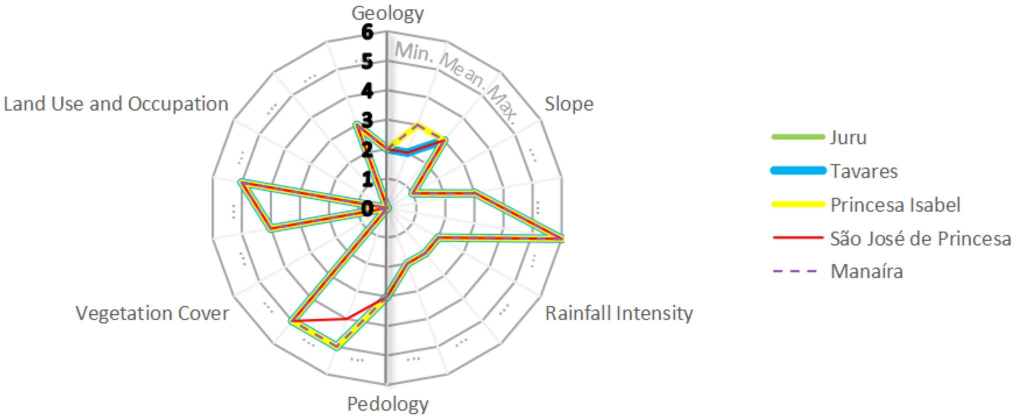
Source: The authors (2021).

In the municipal seats, the relief is almost flat and, therefore, less susceptible to environmental degradation in this aspect. It is noteworthy that, in this same range, soil type has high susceptibility to environmental degradation (value 5) and, in Tavares, the visible extensive band of land with use and occupation by anthropogenic interference is located on lithological, geomorphological, and pedological aspects of low susceptibility to degradation. Regarding rainfall intensity, the entire region has a homogeneous incidence of rain, on average between 50 and 75 mm/month.

Quantitatively the municipalities of the IGRPI had similar behavior regarding the parameters of minimum, maximum, and median values for all variables (Figure 4); however, it is worth mentioning that, regarding lithotypes and soil types, Tavares and São José de Princesa had lower susceptibility to environmental degradation than the other municipalities.

The median of the variables indicates homogeneity in the region; however, the spatial distribution of these variables reveals their spatial variability, which is important to identify the areas that need the most attention to environmental conservation. In general, the analyzed variables showed that the types of rock and soils, as well as slope, had the highest weights among the possibilities of occurring in the IGRPI.

Figure 4- Indicators of susceptibility to environmental degradation per municipality.



Source: The authors (2021).

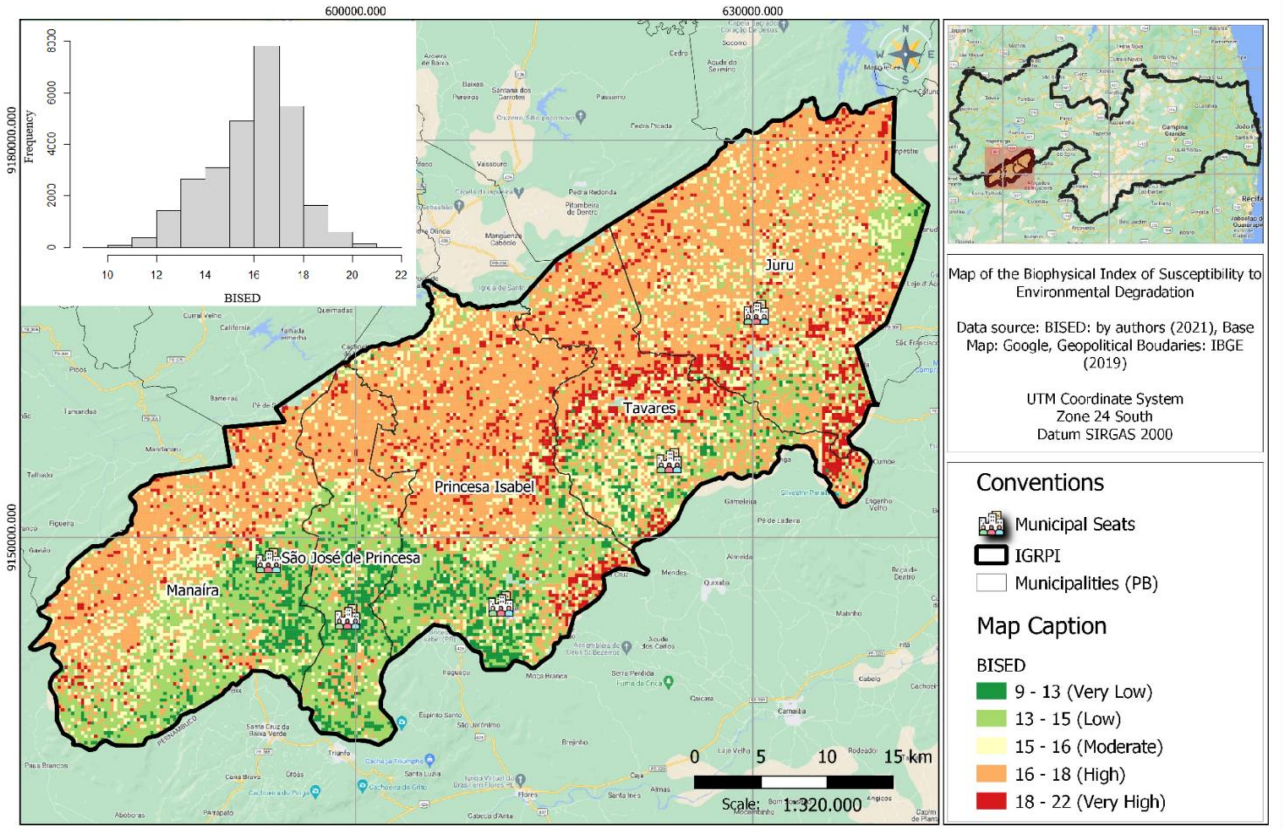
Areas with natural cover (land use and cover equal to 0), mostly overlap soil, rock, and slope occurrences with the largest weights. Therefore, in these places, there were no significant anthropogenic intervention activities in the environment, and the existence of some environmental degradation processes can be considered natural (potential environmental degradation) (MACEDO et al., 2021). In the municipality of Juru, the proportion of land cover with natural factors that provide higher susceptibility to environmental degradation is visibly higher than in the other municipalities of the IGRPI.

However, this potential degradation oscillates according to the rainfall intensity concentrated in a few months of the year, a characteristic of the semi-arid region of Brazil, and the physiological response of the caatinga vegetation to the rain. These factors mitigate the degradation in the dry season, since the lack of rain avoids the impacts of droplet incidence on fragile environments, while vegetation stores water internally to survive the period. On the other hand, rainfall intensity intensifies environmental degradation at the beginning of the rainy season, while the vegetation cover is invigorated and provides protection to the soil, followed by an ecological balance cycle.

The areas identified with anthropogenic uses mostly overlapped the areas with the lowest weights of the other variables. The spaces for urban infrastructure, agriculture, and pasture, for example, are located on rocks with high to moderate resistance to physical weathering, of flat or smooth wavy relief, and on a type of soil with low vulnerability to erosion. Among other reasons, monitoring these activities is important to prevent their expansion from affecting the natural ecological balance mentioned above.

Except for Juru, the BISED on Figure 5 corroborates the analysis that the rural areas of the municipalities of the IGRPI have a higher susceptibility to environmental degradation than the urban areas (Figure 4). However, this susceptibility ranged mostly from moderate to high in the region, indicating incipient exploitation of natural resources where there is urbanization and higher intensity of anthropogenic activities, thus presenting greater natural resistance to environmental degradation and making possible the use of environmental management instruments to prevent future impacts that may be caused during the process of temporal evolution in land use and occupation.

Figure 5 - Biophysical index of susceptibility to environmental degradation in the immediate geographical region of Princesa Isabel



Source: The authors (2021).

On the other hand, natural environmental degradation observed mainly in the rural areas of the municipalities demands more careful analysis and attention. Because they are sloping areas, with climate-sensitive vegetation and low anthropogenic activity, the conservation of their elements (biotic, such as fauna and flora, and abiotic, such as rocks) should be performed through the installation of legal units to control natural impacts, in the case of a dynamic imbalance over time, which can be detected by frequent monitoring. In this context, the present data can be used to subsidize environmental zoning in the region.

BISED values ranged from 9 to 22 in the IGRPI, reaching neither the minimum (7) nor the maximum (28). The lowest median (15) was found in São José de Princesa, which is therefore the municipality with the lowest susceptibility to environmental degradation in the region, followed by Manaíra (16), whereas Juru, Tavares, and Princesa Isabel had the highest median (17).

As shown in the histogram in Figure 4, the peak in the region was of high susceptibility to environmental degradation. However, the municipalities of Tavares and Juru had more critical susceptibility situations related to anthropogenic activities of a very high level.

CONCLUSIONS

Given the above, it is possible to conclude that the integration of environmental factors using GIS provides a valuable geospatial analysis for the identification and monitoring of susceptibility to environmental degradation, consisting of a method for assessing susceptibility to environmental degradation, as well as for obtaining essential information for environmental planning and management, especially aiming at sustainability. This allows us to state that the objective of the research was achieved.

The IGRPI has a low human and economic development, which hinders access to instruments for the intensification of natural resources exploitation, modernization of agriculture, and expansion of agriculture and livestock farming, as well as the accelerated growth of urbanized areas. This contributes significantly to stagnant environmental degradation in the region, although it does not directly mean improvement in the population's quality of life due to the incipient industrialization in the region.

However, monitoring and control of anthropogenic activities, which increase the potential of emerging environmental degradation, are fundamental, especially considering the future expansion of cities and the characteristics of the region, which suffers from drought, a phenomenon that can intensify this type of degradation by triggering and increasing socio-spatial problems.

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AUTHORS CONTRIBUTION

Eduardo Rodrigues Viana de Lima guided the methodology adopted, idealized the exploration of the theme from different points of view and collaborated in the revision of the text. Erickson Melo de Albuquerque analyzed and selected the techniques and tools adapted to the study and wrote the initial text. Maria de Fátima Barroso de Sousa operationalized the obtaining and processing of geographic data and the elaboration of maps and contributed to the writing of the text.