ENVIRONMENTAL VULNERABILITY OF ITABIRA NATURAL MONUMENT, ES, BRAZIL

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ABSTRACT – The institution of biological value areas through the creation of Natural Protected Areas is an essential tool for protecting the country's environmental resources to face advanced anthropic development in natural areas, either to increase agriculture production or for economic growth. Environmental vulnerability studies combined with geotechnological tools have been vital to identifying the most vulnerable areas and consequently help Conservation Units protection. This study aimed to analyze environmental vulnerability at the buffer zone of Itabira Natural Monument (MONAI) in Cachoeiro de Itapemirim, Brazil. The necessary methodological steps for this study were as follows: a) Photointerpretation of land use; b) Anthropic variables selection; c) Application of Euclidean distance function in variables vector images; d) Application of fuzzy membership function in variables raster images; e) Application of Analytical Hierarchical Process (AHP); and f) Spatial classification of environmental vulnerability around MONAI. Land use conflicts reveal a relevant presence of pasture areas, representing 49.80% of the buffer zone. This fact corroborates with its Euclidean distance value, which showed the lowest linear value, 836 meters. Eight anthropic variables have been incorporated, highlighting crops, urban areas, exposed soil and pasture. Jenks natural breaks defined five vulnerability classes. According to the results, 57.14% of the entire MONAI buffer zone is represented by the high and very high classes. The outdated law creation of MONAI and the need for a management plan result in a vulnerable buffer zone. The present study can support management plan formulation and assist MONAI's buffer zone delimitation.

Keywords: Natural Protected Areas; Buffer zone; Geotechnology.

VULNERABILIDADE AMBIENTAL NO ENTORNO DO MONUMENTO NATURAL DO ITABIRA, ES, BRASIL

RESUMO – A instituição de áreas de elevado valor biológico por meio da criação Unidades de Conservação (UC's) tem se tornado importante instrumento de proteção aos recursos ambientais no país, frente ao desenfreado avanço antrópico sobre ambientes naturais. Os estudos de vulnerabilidade ambiental aliados à geotecnologia têm se mostrado uma relevante ferramenta na identificação de áreas mais vulneráveis, e, consequentemente, no gerenciamento e proteção das UC's. Este trabalho objetivou analisar a vulnerabilidade ambiental no entorno do Monumento Natural do Itabira (MONAI), localizado no município de Cachoeiro de Itapemirim/ES, por meio de ferramentas geotecnológicas e inteligência artificial. As etapas metodológicas

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necessárias para este estudo foram: a) fotointerpretação do uso e ocupação da terra; b) seleção das variáveis antrópicas; c) aplicação da distância euclidiana nos vetores representativos das variáveis; d) aplicação da lógica Fuzzy nas matrizes das variáveis de distância euclidiana; e) aplicação do método Hierárquico Analítico (AHP); e f) espacialização das áreas de vulnerabilidade ambiental no entorno do MONAI. Os conflitos de uso e ocupação da terra demonstraram presença majoritária de pastagens, representando 49,80% da área de estudo, corroborando com o cálculo da distância euclidiana que atribuiu a esta variável o menor valor linear em relação à UC, 836 metros. Dentre as 5 classes de vulnerabilidade definidas pelas quebras naturais de Jenks, observou-se que 57,14% do entorno do MONAI é representado pelas classes alta e muito alta. A desatualização da lei de criação do MONAI e a inexistência de plano de manejo implicam no mapeamento de uma zona de amortecimento majoritariamente vulnerável ambientalmente. O presente estudo pode subsidiar a elaboração do plano de manejo e a demarcação da zona de amortecimento do MONAI.

Palavras-Chave: Unidade de conservação; Zona de amortecimento; Geotecnologias.

1. INTRODUCTION

Over the last century, anthropogenic pressure on natural resources has increased dramatically and uncontrolled (Tambosi, 2008). In order to ensure the protection of the main attributes existing in the vast Brazilian territory and in an attempt to reorder an already existing but sparse legislation, Law no. 9.985 of 2000 was instituted, creating the National System of Natural Protected Areas. It is considered a guideline for managing Conservation Units (CUs) and establishing criteria for their creation, implementation and management. These units are created by presidential decree or law and divided into Full Protection and Sustainable Use management categories.

As relevant as its interior, the surroundings of a CU are an area of paramount importance. Defined in the SNUC as a buffer zone (ZA), these are places where human activities are subject to specific rules and restrictions to minimize negative impacts on the unit (Brasil, 2000). At this juncture, the management plan emerges to encompass the multiplicity of attributes in the Conservation Units. Conceptualized in the SNUC as a technical document based on the general objectives of a CU, the management plan becomes the "identity" of the CUs.

The Itabira Natural Monument (MONAI), part of the Integral Protection group, is located in the southern portion of Espírito Santo is internationally recognized for its ornamental stone processing industrial park. On the other hand, it hosts important priority areas for conservation instituted in the form of CU, such as the Pacotuba National Forest, the Mata das Flores State Park and the O Frade e a Freira Natural Monument.

Initially established as a Municipal Park in 1988 and recategorized as a Natural Monument in 2008 (Municipal Law No. 6,177/2008). In 2014, Municipal Law 6.954 was enacted, which expanded, resized and repositioned the CU and established the buffer zone. However, the act was revoked by a Direct Action of Unconstitutionality (ADIN) issued by the Court of Justice of ES. MONAI currently lacks a management plan specifying its boundary and respective buffer zone.

While a legal basis is not defined, the municipality has adopted the Unit's perimeter delimited as a listed area by the State Council of Culture. Furthermore, as for the Buffer Zone, a radius of 3 km is considered, considering Item III of Art. 3 of the Resolution of the State Environment Council (CONSEMA) No. 02/2013.

Although MONAI is part of a UC category with restrictive objectives and uses, there is a substantial advance of economic activities towards it, emphasizing agricultural practices. The typically rural environment combined with economic and social aspirations means that the use of land on private properties in which MONAI is inserted is only sometimes aligned with the objectives of the CU. Hence the importance of the management body at the time of its institution, considering not only the physical and immaterial attributes but also ensuring the participation of the local community through public consultations.

An essential tool in managing territorial space, geotechnologies in mapping the main environmental attributes provides subsidies for its management, meeting conservationist principles. Based on geotechnological tools, spatial analysis can assist in identifying areas and support the preparation of technical-scientific documents by integrating different maps.

In this scenario, the objective of this work is to analyze the environmental vulnerability, with the aid of geotechnologies, of the surroundings of the Itabira Natural Monument, located in the municipality of Cachoeiro de Itapemirim, the southern region of Espírito Santo.

2. MATERIAL AND METHODS

2.1. Study area

The study area is located in the southern region of Espírito Santo (ES), in Cachoeiro de Itapemirim

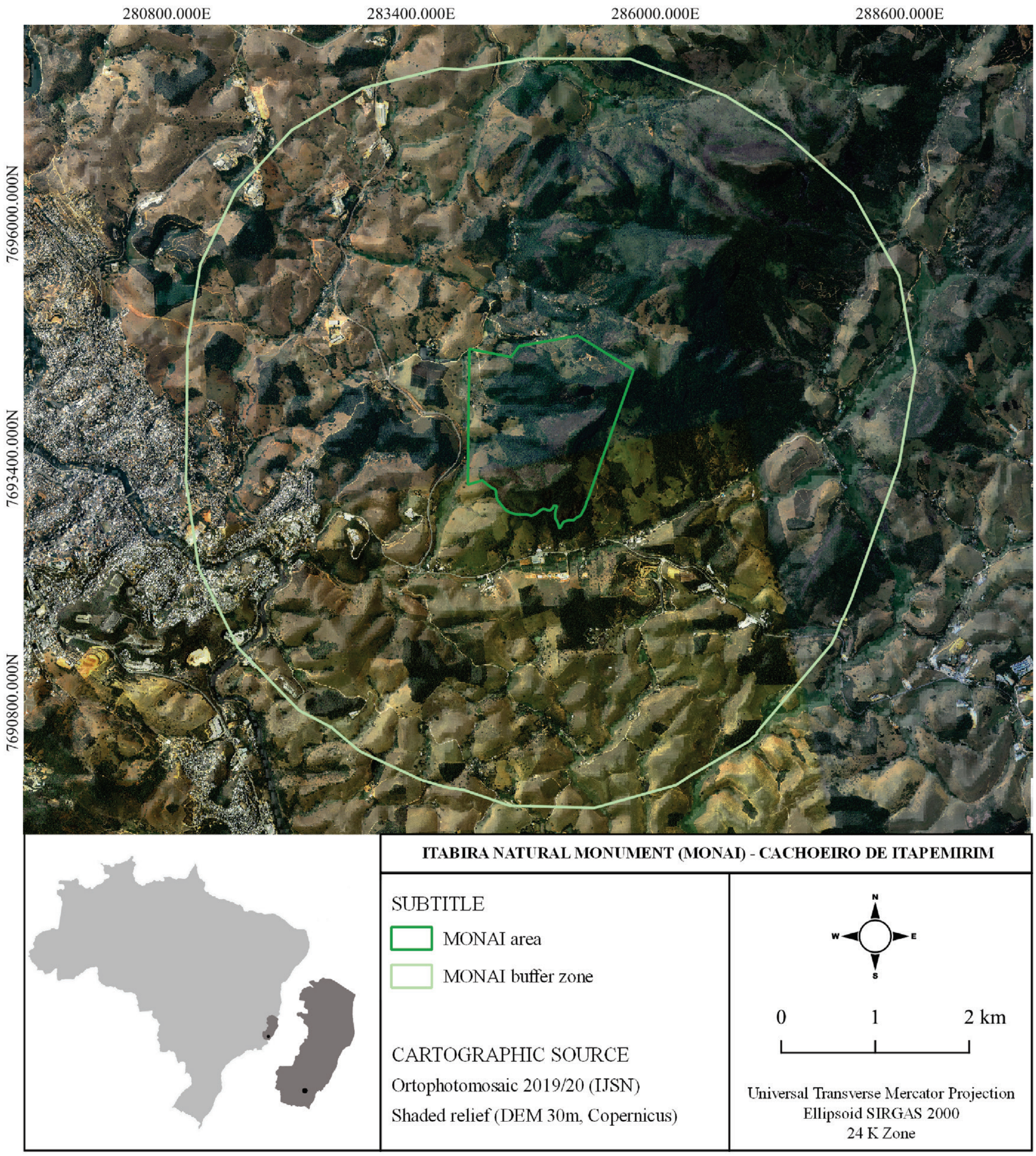


Figure 1 – Geographical location of Itabira Natural Monument (MONAI), Espírito Santo state, Brazil.
Figura 1 *– Localização geográfica do Monumento Natural do Itabira (MONAI), Espírito Santo, Brasil.*

(Figure 1). Named Itabira Natural Monument (MONAI), the UC occupies an area of approximately 2.58 km^2, demarcated by the mean geographic coordinate 285153 E / 7694213 N (UTM, ellipsoid SIRGAS 2000, zone 24 K). The buffer zone of the Monument currently comprises a radius of 3 km from the CU boundary, totalling 49.35 km^2. The management entity of the UC is the Natural Resources Management of the Secretariat for Environment of Cachoeiro de Itapemirim (SEMMA).

MONAI is characterized by a rock formation whose shape resembles an index finger pointing to the sky. According to the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural - INCAPER (1999), the region is characterized by hot, rugged and dry lands, with a minimum average temperature in the coldest month ranging from 11.8 to 18º C and maximum average in the hottest month between 30.7 to 34º C. The municipality is characterized by soils of low and medium fertility, with predominantly undulating and hilly topography, especially by Latossolos (deep soils) due to the high degree of weathering caused by the climate, which favours weathering agents (EMBRAPA, 2013).

2.2. Methodological steps

The following methodological steps were necessary for spatializing environmental anthropogenic vulnerability in the surroundings of MONAI (Figure 2). After converting the matrix images of land use, the Euclidean distances were calculated to generate the Fuzzy pertinence functions, determining the statistical weights of the Saaty model (1977) to evaluate the environmental anthropic vulnerability of the MONAI surroundings.

2.3. Definition of anthropic variables

The vector image of land use was obtained through photointerpretation on a scale of 1:2,500, the Orthophotomosaic database carried out by Instituto Jones dos Santos Neves between 2019 and 2020. To confirm the veracity of the information, field visits and aerial imaging observations were carried out using Google Earth Pro.

The anthropic variables identified in the vector image of land use were classified as urban area, crops, built area, pasture, silviculture, exposed soil, paved road and dirt road.

It is necessary to discriminate between urban and built-up areas because they are occupations with totally different characteristics. The first refers to some neighbourhoods of the city of Cachoeiro de Itapemirim, that is, the consolidated urban area defined in the municipal master plan, built by residences, businesses and industries, which has an implanted road system and other urban infrastructure equipment such as sanitary sewage, drinking water supply, electricity distribution and public lighting, stormwater drainage, urban cleaning and solid waste management. On the other hand, the second refers to the area built in a rural environment, usually isolated from other buildings, which can be described as the headquarters of rural properties, corrals, various masonry structures and companies from different sectors, without urban infrastructure devices.

The vector image of land use was converted into individualized matrix images representing each of the eight anthropogenic variables defined for the study using the QGIS computer application, version 3.22.6.

2.4. Spatialization of Euclidean distance

The Euclidean distance is the distance between two points, applied based on the Pythagorean Theorem. To calculate it, the algorithm provider System Automated Geospatial Analysis (SAGA) "Proximity Raster" was applied in QGIS to the vector layers of all eight anthropic variables defined in this study. The objective was to generate distance matrix images of the representative polygons of each anthropogenic variable. The distance is presented in meters since the geographic coordinate system adopted was the Universal Transverse Mercator Projection (UTM).

In GIS (Geographic Information System), the Euclidean distance corresponds to the distance from the pixel of occurrence to the extremities of the image, that is, to the place where vulnerability to anthropogenic action does not occur. The analysis allows us to infer that the closer to an anthropogenic variable, the greater the environmental vulnerability.

2.5. Spatialization of Euclidean distance images using fuzzy logic

Fuzzy logic is a form of multivalued logic in which the values of the variables can assume any actual number between 0 and 1 (Lanzillotti, 2014).

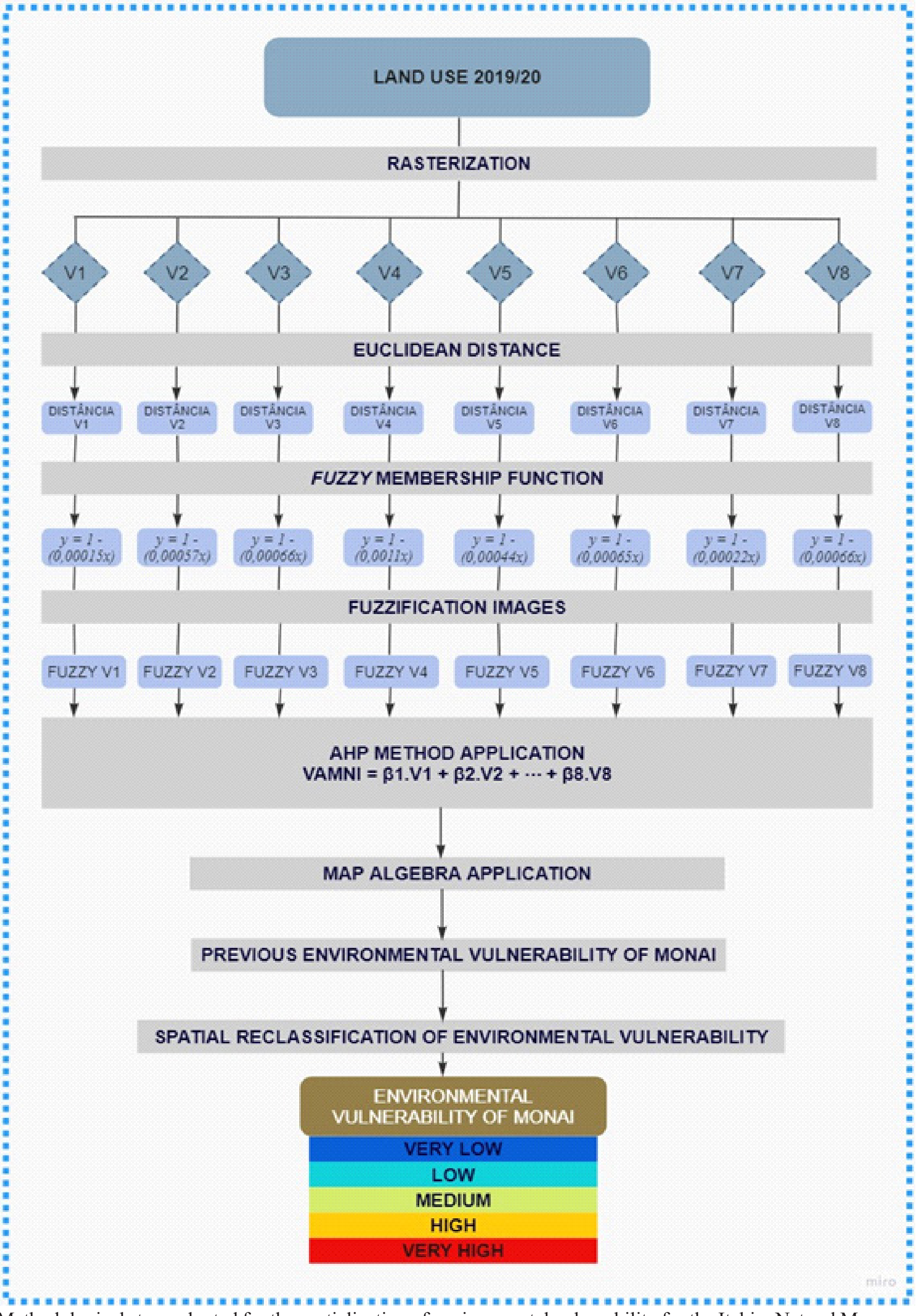


Figure 2 – Methodological steps adopted for the spatialization of environmental vulnerability for the Itabira Natural Monument (MONAI), Espírito Santo state, Brazil.

***Figura 2** – Fluxograma metodológico das etapas necessárias para espacialização da vulnerabilidade ambiental no entorno do Monumento Natural do Itabira (MONAI), Espírito Santo, Brasil.*

In order to generate a mathematical model of environmental vulnerability that globally represents all anthropogenic variables, it was necessary to standardize all Euclidean distance images. A pertinence function was defined for each anthropogenic variable studied, represented by:

$$y = 1 - (\beta n \, .x) \qquad \text{Eq. 1}$$

Where:

y: dependent variable represented by the matrix image standardized between values 0 and 1;

βn: constant representing the slope of the line;

x: independent variable represented by the Euclidean distance image of each variable.

With the pertinence functions of each variable, the "Raster Fuzzify" function with the linear association was applied in the QGIS computer application, aiming at generating matrices standardized by Fuzzy logic. The areas considered most vulnerable to the impacts of anthropic activities are indicated when the variable's actual value is close to 1, and the least vulnerable areas when the variable's actual value is close to 0.

2.6. Modeling anthropogenic environmental vulnerability

In order to develop the modelling of anthropogenic environmental vulnerability for the study area, the Analytic Hierarchy Process (AHP) proposed by Saaty (1977) was chosen. According to the author, this method allows structuring a decision in hierarchical levels, determining, through the synthesis of values of the decision-makers, a global measure for each of the alternatives, prioritizing or classifying them at the end of the method (Saaty, 1988).

The variables represented by environmental vulnerability were compared one by one with values ranging from 1 (equally important) to 9 (extremely important), using the fundamental scale of Saaty (1977).

The method of elaborating the matrix through the comparison scale allows linearly defining the hierarchy of importance between the studied variables. According to Santos (2010), the phase of choosing the weights of the variables is considered one of the most important of the entire construction process, and to arrive at these values, the researcher can: (I) use his experiences and field visits, define the scale of importance; (II) through the bibliographic survey prove his thesis that one impact has more importance than the other and (III) gather a multidisciplinary team, working together, with field visits to define the scale that comes closest to reality.

For the present study, it was decided to combine the three ideas described above to obtain a better result. Model validation is obtained by calculating the Consistency Ratio (CR), given by dividing the Consistency Index (CI) by the Random Index (RI), the latter with a value extracted for a square matrix of order n=8 (number of variables under study), according to the Oak Ridge National Laboratory, USA (apud Saaty, 1991). The model is validated if a Consistency Ratio is less than 10%.

After standardizing the data and defining the weights of the variables, the following mathematical model was proposed:

$$VAMNI= \beta 1 \,.\, V1 +\beta 2 \,.\, V2 +...+ \beta 8 \,.\, V8 \qquad \text{Eq. 2}$$

Where:

VAMNI: environmental vulnerability of the Itabira Natural Monument;

βn: statistical weights defined by the respective AHP model, with a consistency ratio of less than 10%;

Vn: anthropic environmental variables

The calculations were performed in the QGIS 3.22.6 computer application using the "Raster Calculator" tool. In order to better visualize the results, the maps were reclassified according to Jenks' natural breaks. Thus, five classes were used to find the variations of anthropogenic vulnerability: very low, low, medium, high and very high.

3. RESULTS

The photointerpretation of land use identified, in particular, 13 classes (Figure 3). It is observed that almost half of the area is occupied by pastures (49.80%), not always associated with livestock purposes.

Representative Euclidean distance maps for the eight variables studied were generated (Figure 4A). Among the anthropogenic variables found, those with the lowest distance were pasture, built area, dirt road, exposed soil and crops with linear values

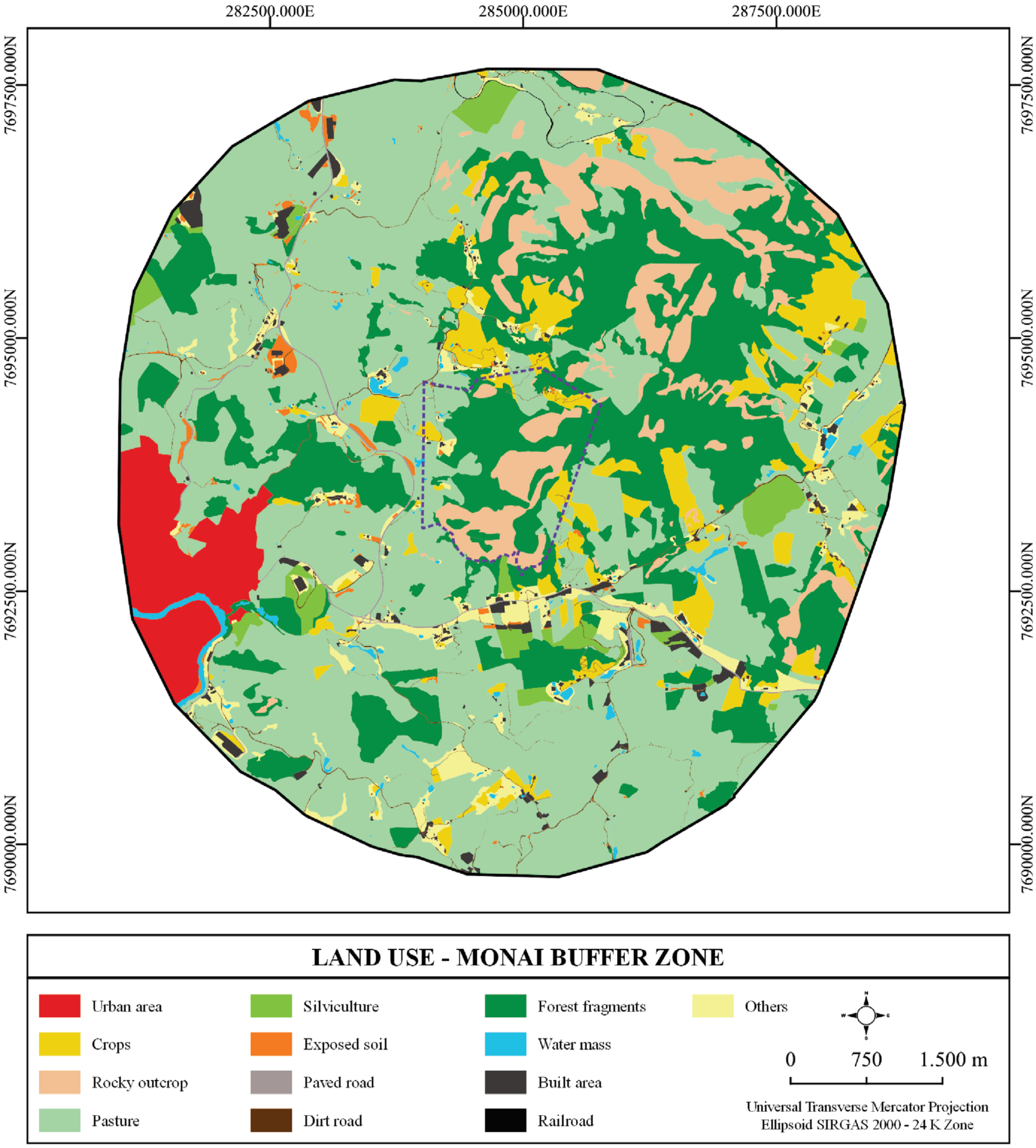


Figure 3 – Land use for the Itabira Natural Monument (MONAI), Espírito Santo state, Brazil.
Figura 3 *– Uso e ocupação da terra na zona de amortecimento do Monumento Natural do Itabira (MONAI), Espírito Santo, Brasil.*

of 836.0 m, 1,502.1 m, 1,511.6 m, 1,517.4 m and 1,725.3 m, respectively.

An association function (decreasing linear fuzzy pertinence function) was applied to each anthropogenic variable represented by its Euclidean distance. By observing these results, it is possible to conclude about the fragility in the surroundings of MONAI for each variable, and the areas considered

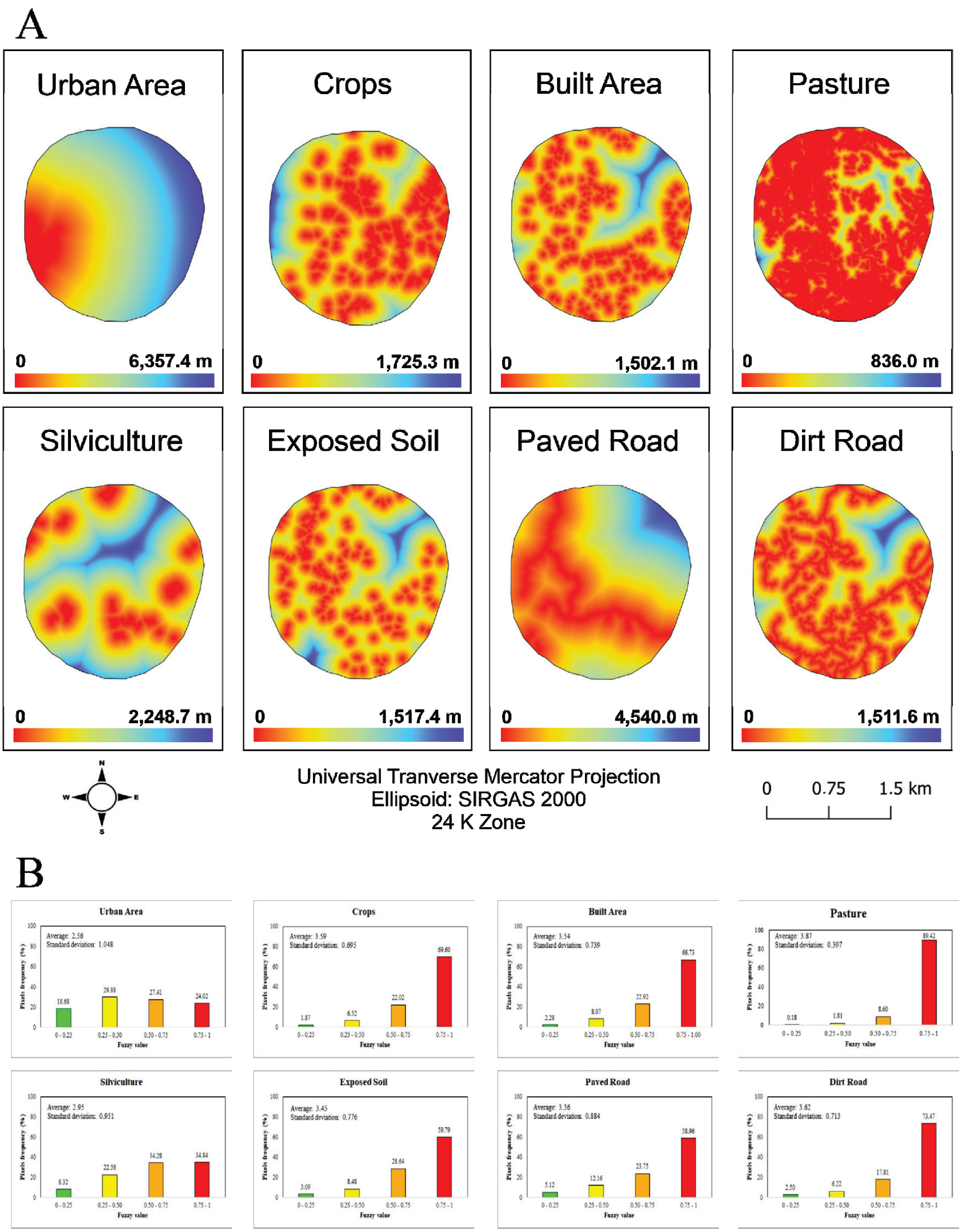
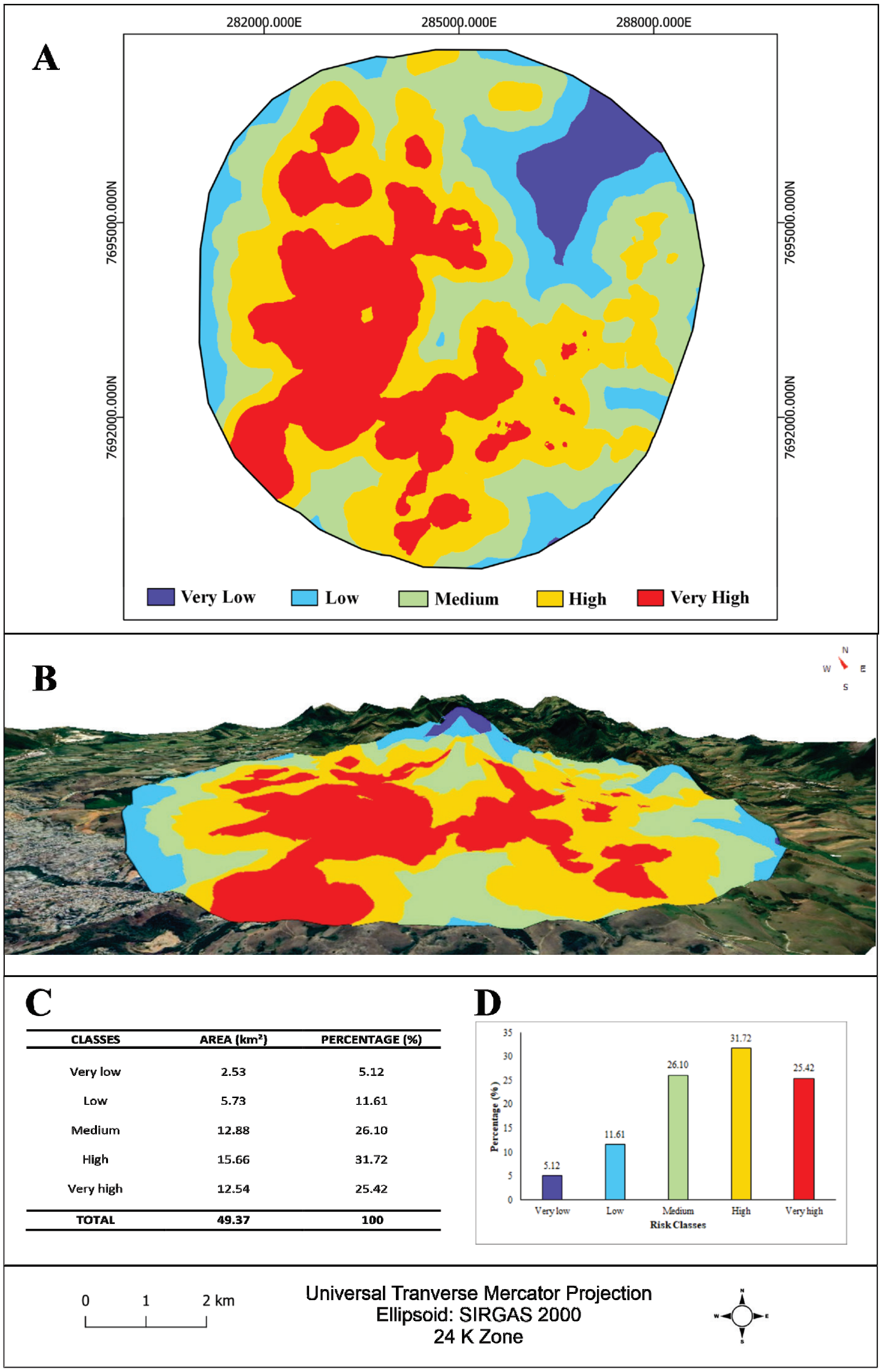


Figure 4 – (A) Euclidean distance of anthropogenic variables for the Itabira Natural Monument (MONAI); (B) Pixel frequency percentage for the decreasing linear fuzzy set interval of anthropogenic variables for the MONAI.

Figura 4 *– A) Distância euclidiana das variáveis antrópicas no Monumento Natural do Itabira (MONAI); B) Percentual de frequência dos pixels para o intervalo do conjunto Fuzzy linear decrescente das variáveis antrópicas no MONAI.*



CLASSES	AREA (km²)	PERCENTAGE (%)
Very low	2.53	5.12
Low	5.73	11.61
Medium	12.88	26.10
High	15.66	31.72
Very high	12.54	25.42
TOTAL	49.37	100

Figure 5 – Spatialization of environmental vulnerability using fuzzy logic and AHP method for the Itabira Natural Monument buffer zone, Espírito Santo state, Brazil: (A) vulnerability classes with natural Jenks breaks; (B) 3D visualization; (C) Percentage and area risk classes; (D) Pixel frequency percentage for each risk class.

***Figura 5** – Vulnerabilidade ambiental antrópica da zona de amortecimento do Monumento Natural do Itabira (MONAI): A) Mapa das classes de risco, B) Visualização 3D das classes de risco, C) Área (km²) e porcentagem (%) por classe e D) Distribuição das classes de risco (%).*

most vulnerable are those that present fundamental values of the Fuzzy set close to 1. In contrast, the least vulnerable areas have values close to 0.

Histograms representing the percentage of pixel frequency for the interval of the decreasing linear fuzzy set of anthropic variables were elaborated (Figure 4B). A uniform class interval was defined, with an amplitude of 0.25, and then the average and standard deviation of the set were calculated. The results presented are essential to visualize the behaviour of the variables in the intervals that confer greater vulnerability to the environment, that is, above 0.50, represented by the red and orange colours.

In this scenario, it is observed that six variables had higher percentage values (values above 80.00%) of the fuzzy set interval between 0.50 and 1.0, namely: pasture (98.02%), crops (91.62%), dirt road (91.28%), built area (89.65%), exposed soil (88.43%) and paved road (82.71%).

After calculating the Euclidean distance and fuzzification of the anthropic variables, a paired matrix was elaborated using the Saaty fundamental scale. For the present study, it was decided to unite the idea that the bibliographic survey, associated with field observation and consultation with professionals in the area, is sufficient for a satisfactory result. Researchers from the Federal University of Lavras (UFLA), the Federal University of Espírito Santo (UFES), the State University of Minas Gerais (UEMG), the Federal University of Viçosa (UFV) and the technical staff of the Natural Monument management body were consulted. The team's weighting of all the factors brought to light at this stage resulted in the definition of the weights of each variable.

The justification for assigning weights to the variables took into account the reality of the study area and the problems faced in MONAI. Crops was given greater weight, mainly because of the advance of plantations on the very edge of the UC. In addition, crops are associated with removing vegetation cover, reducing biodiversity, erosive processes, and reducing soil nutrients. Although somewhat distant from MONAI, the urban area was given a relevant weight due to its high polluting potential and because it considers that, in recent years, the urban expansion area, defined in the municipality's master plan, has advanced towards MONAI. After defining the weights of each variable, a Consistency Ratio (CR) of 2.9% was calculated, less than 10%, thus validating the model adopted.

The spatialization of environmental vulnerability in the MONAI buffer zone resulting from the proposed modelling was obtained with the aid of the QGIS computer application through the "Raster Calculator" function, applying the matrix map algebra of the eight variables and their respective weights. The map was categorized into five classes according to Jenks' natural breaks (very low, low, medium, high and very high). The percentages of the five pre-defined classes were also calculated, adopting colour symbology where red areas represent greater anthropogenic vulnerability and blue areas lower vulnerability (Figure 5).

The highest percentage values in the buffer zone were found in the high vulnerability class (31.72%), followed by the medium (26.10%) and very high (25.42%) classes.

Taking the MONAI boundary as a reference, it was observed that anthropic environmental vulnerability followed the trend observed in the buffer zone, where the highest percentage values were found in the high vulnerability class (38.47%), followed by the medium (31.08%) and very high (29.69%) classes. No very low vulnerability class was identified, and the low class is practically insignificant, corresponding to only 0.75% of the area.

4. DISCUSSION

The analysis of land use in the buffer zone and on the boundary of MONAI requires caution to the variables pasture and crops, present in significant quantities. Both variables were also predominant in the studies by Nery (2018) and Lopes (2019) in municipalities in the southern portion of Espírito Santo.

It is known that the closer to a given anthropogenic variable, the more significant the environmental impacts on the PA. Thus, it is understood that the variables pasture, built area, dirt road, exposed soil, and crops influence the study area's anthropogenic environmental vulnerability significantly.

In line with the land use map, one of the main problems observed in the study area is the majority presence of pastures, only sometimes associated with cattle farming. Moreover, in some points, the evolution of exposed soil was observed, with loss and total removal of soil cover. It is known that pastures originate after the destruction of the original vegetation, thus configuring a point of alert to the management of MONAI to manage these areas and avoid their possible advance to the limits of the CU.

Although MONAI belongs to the group of Full Protection PAs, the highest percentage values were found in the higher vulnerability classes; it is alarming to note that the most vulnerable areas comprise 83.24% of the entire MONAI buffer zone. A similar result was observed by Nery (2018) in a CU of the same category when she found higher percentages of vulnerability in the high and very high classes in the Pedra Azul State Park, located in the mountainous region of Espírito Santo.

The anthropic pressure on the site is associated with crops, especially bananas and coffee, near the rocky massif to which the Monument is inserted. Notably, the entire boundary of the CU is formed by private properties, which only sometimes associate land use with the objectives of this category of Conservation Unit.

The presence of economic activities surrounding PAs was also verified by Nery (2018) in Pedra Azul State Park, who pointed out the hotel chain, agrotourism and agricultural activities as the causes of the Park's high vulnerability mapping.

The most vulnerable regions of MONAI, located in the western portion in greater quantity, correlate to the presence of urban areas, crops and large pasture areas. It is essential that the current management of MONAI takes into account these areas when preparing the management plan of the CU and adopts public policies that are protective and that promote the sustainable development of the area.

5. CONCLUSIONS

The integration of geotechnologies and computational intelligence in the modelling proposed in this study is an essential tool to assess the potential fragility of the surroundings of a Conservation Unit of the Integral Protection category in the face of anthropic occupation.

The fuzzy logic associated with the multicriteria methodology allowed us to observe that more than half of the MONAI buffer zone is represented by the high and very high classes of anthropogenic environmental vulnerability. The western portion of the area concentrates on the most vulnerable areas around MONAI, with a more significant presence of economic activities such as crops and urban areas.

The absence of a management plan for the Conservation Unit influences the large percentage of high-vulnerability classes mapped. As mentioned earlier, the absence of the document and the outdated law creating MONAI contribute negatively to the delimitation of a buffer zone that needs to consider relevant environmental criteria and attributes, resulting in high vulnerability classes.

The results of spatialization are essential in understanding the relationship between society and nature to better plan and manage the geographical space. By identifying priority areas for conservation, the municipal government can act to build a risk reduction policy for the Natural Monument or establish protection measures for the most vulnerable areas.

The spatialization of environmental vulnerability to anthropic action presented in this study can support the delimitation of the MONAI buffer zone, which is currently being prepared by the management staff.

AUTHOR CONTRIBUTIONS

Conceptualization, L.M.S., L.A.C.B., A.R.d.S., and C.P; methodology, L.M.S., L.A.C.B. and A.R.d.S.; validation, L.M.S., L.A.C.B. and A.R.d.S.; formal analysis, L.M.S., L.A.C.B., M.P.L.V. and M.S.; resources, L.M.S., L.A.C.B. and A.R.d.S.; data curation, L.M.S. and A.R.d.S.; writing-original draft preparation, L.M.S., L.A.C.B., A.R.d.S., M.P.L.V., C.P., M.S. and R.M.d.S.; writing—review and editing, L.M.S., L.A.C.B. and M.P.L.V.; supervision, L.A.C.B.; funding acquisition, L.A.C.B. All authors have read and agreed to the published version of the manuscript.

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