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Environmental vulnerability mapping of the Mágoè National Park buffer zone

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Abstract: This study aimed to map anthropogenic environmental vulnerability in the Mágoè National Park (PNM) buffer zone, Tete Province, Mozambique, using geospatial techniques and fuzzy logic. Anthropogenic variables, including built-up areas, agricultural land, pastures, and exposed soils, were identified and analyzed. Euclidean distance maps for each variable were generated using GRASS GIS, followed by a fuzzification process to assign membership degrees ranging from 0 to 1. A gamma fuzzy operator ($\gamma = 0.6$) was applied to model the integrated vulnerability. The results reveal a predominance of high anthropogenic vulnerability, affecting approximately 37.40% of the study area, while medium vulnerability accounts for 32.84%, and very low vulnerability covers only 0.8%. The findings align with previous research indicating intense anthropogenic pressures on conservation areas. The study underscores the urgency of implementing strategic measures for sustainable management and conservation of the PNM buffer zone, balancing ecological preservation with the needs of local communities.

Key-words: Anthropogenic Vulnerability, Geospatial Mapping, Buffer Zone.

Mapeamento da Vulnerabilidade Ambiental da Zona de Amortecimento do Parque Nacional de Mágoè

Resumo: Este estudo teve como objetivo mapear a vulnerabilidade ambiental antropogênica na zona de amortecimento do Parque Nacional de Mágoè (PNM), Província de Tete, Moçambique, utilizando técnicas geoespaciais e lógica fuzzy. Variáveis antropogênicas, incluindo áreas construídas, terras agrícolas, pastagens e solos expostos, foram identificadas e analisadas. Mapas de distância euclidiana para cada variável foram gerados usando o GRASS GIS, seguidos por um processo de fuzzificação para atribuir graus de pertinência variando de 0 a 1. Um operador fuzzy gama ($\gamma = 0{,}6$) foi aplicado para modelar a vulnerabilidade integrada. Os resultados revelam uma predominância de alta vulnerabilidade antropogênica, afetando aproximadamente 37,40% da área de estudo, enquanto a vulnerabilidade média representa 32,84%, e a vulnerabilidade muito baixa cobre apenas 0,8%. Os resultados estão alinhados com pesquisas anteriores que indicam intensas pressões antropogênicas sobre áreas de conservação. O estudo destaca a urgência de implementar medidas estratégicas para a gestão sustentável e conservação da zona de amortecimento do PNM, equilibrando a preservação ecológica com as necessidades das comunidades locais.

Palavras-chave: Vulnerabilidade Antropogênica, Mapeamento Geoespacial, Zona de Amortecimento.

1. INTRODUCTION

According to the National Administration of Conservation Areas (ANAC), Conservation Areas (CAs) occupy approximately 18.57 million hectares in Mozambique, representing about 25% of the national territory. These areas include seven National Parks, nine National Reserves, 20 Official Hunting Areas, three Community Conservation Areas, and 50 Wildlife Farms. Recognizing the importance of CAs not only for biodiversity conservation but also for the country's socioeconomic development and the well-being of local communities, the Government created the National Administration of Conservation Areas (ANAC) through Decree No. 11/2011, later updated by Decree No. 9/2013. This institution was designed to meet the modern dynamics of conservation and to contribute to generating revenue that ensures the sustainability of these efforts.

The Mágoè National Park (PNM), located in Tete Province, stands out as one of the most important protected areas in the country. Established in 2013, the park covers an area of approximately 3,559 km², comprising terrestrial and aquatic ecosystems associated with the Zambezi River and Cahora Bassa Lake (MITADER & ANAC, 2016). These diverse environments provide habitats for rich biodiversity, including emblematic species such as elephants, buffaloes, hippos, crocodiles, antelopes, lions, leopards, and various aquatic and terrestrial birds, which play fundamental roles in the ecosystems, such as seed dispersal and the control of smaller herbivore populations.

The miombo forests, predominant in PNM, provide essential resources such as timber, honey, and medicinal plants, in addition to contributing to climate change mitigation through carbon sequestration. The park also plays a critical role in regulating the regional hydrological cycle, being vital for the sustainability of communities that depend on fishing in the Zambezi River and Cahora Bassa Lake. Additionally, PNM integrates a larger network of protected areas in southeastern Africa, serving as an ecological corridor for migratory species, which is crucial in the face of the challenges of climate change and habitat fragmentation.

Despite its relevance, the park faces significant anthropogenic pressures, including deforestation, illegal hunting, predatory fishing, agricultural expansion, natural resource exploitation, and mining (MITADER & ANAC, 2016). These activities threaten its biodiversity, and the ecosystem services provided, such as climate regulation, water purification, provision of natural resources, and maintenance of cultural values. For example, deforestation, caused by timber extraction and agricultural expansion, fragments habitats, reduces vegetation cover, and intensifies soil erosion, while illegal hunting compromises populations of key species, affecting the ecological balance and the ecotourism potential of the region.

In this context, advanced methodologies, such as fuzzy logic, emerge as effective tools to assess environmental vulnerability, considering the uncertainty and complexity of environmental systems. Developed by Zadeh (1965), fuzzy logic allows modeling continuous and diffuse variables, adapting to the analysis of ecosystems. Previous studies, such as those by Rodrigues & Silva (2019) in Brazil and Adiat et al. (2012) in Nigeria, have demonstrated the applicability of this approach in urban and natural contexts. In the case of protected areas, Ahmed and De Oliveira (2020) assessed vulnerabilities in the Amazon, while Resende et al. (2018) mapped buffer zones of parks in Brazil, correlating human pressures with environmental degradation.

Thus, the main objective of this study is to map the environmental vulnerability of the Mágoè National Park, applying fuzzy logic integrated with geographic information systems (GIS). This method will allow the identification of critical areas, support the sustainable management of the park's natural resources and contribute to its long-term conservation.

2. MATERIAL AND METHODS

2.1 Study Area Location

Located in the districts of Mágoè and Cahora-Bassa along the Cahora Bassa Reservoir, the Mágoè National Park has a total area of 355,852.044 hectares, i.e., 3,558.520 km². The area is situated in a plateau zone, with altitudes ranging from 400-800 meters. There are several granite hills, especially in the northeast and southwest, notably the Tsacale hill aggregates (732 m). However, this mountainous aggregate extends along the Luia River, the southern boundary of PNM.

The Mágoè National Park presents a diversity of soils, predominantly clay-loam and sandy, with variations in depth and drainage. The hydrographic network is dense, with the Zambezi River being the main watercourse, making some areas inaccessible during the rainy season. The vegetation consists of Mopane forests, in addition to riparian and mountain forests. The fauna is rich in biodiversity, with a highlight on large mammals such as elephants, buffaloes, and hippos. The presence of diverse bird species makes the region an attraction for ecotourism. In the past, the park harbored species such as wild dogs, leopards, and lions (MITADER & ANAC, 2016).

The climate is hot and dry, with precipitations concentrated between December and March. Temperatures and evapotranspiration are higher in areas with less forest cover. The Mágoè National Park faces several threats, such as the presence of human settlements, livestock farming, uncontrolled fires, poaching, and illegal fishing in the Cahora Bassa Reservoir. These activities compromise biodiversity conservation and ecosystem integrity (MITADER & ANAC, 2016).

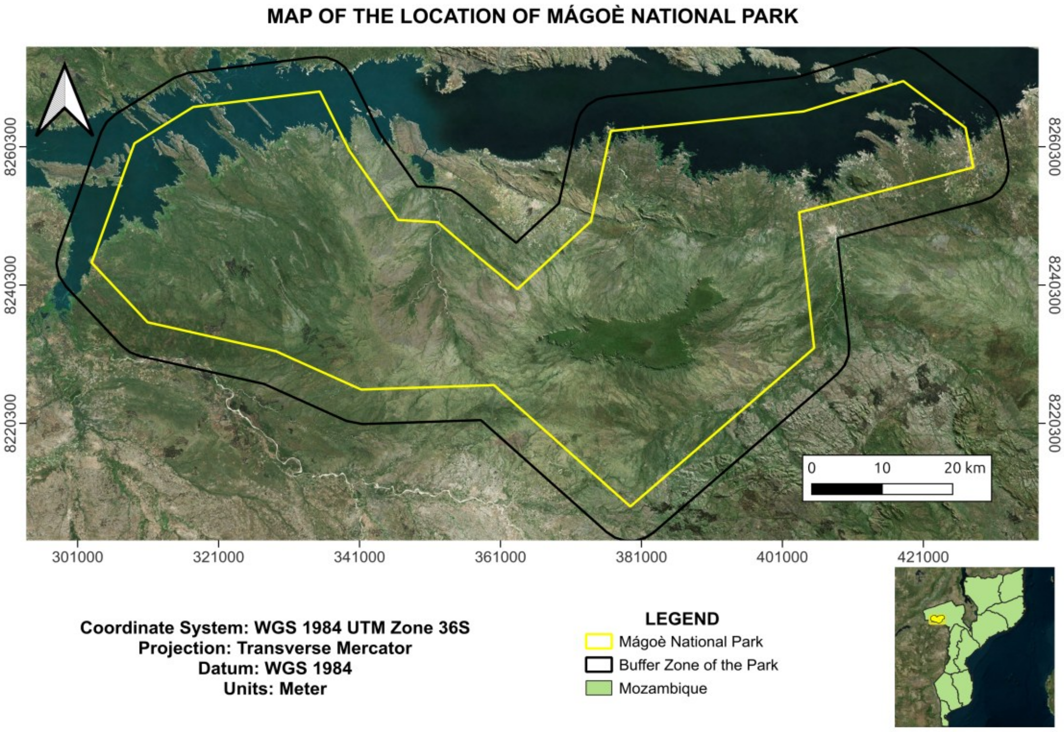

Figure 1. Location of the National Park

2.2 Methodological Steps

2.2.1 Land Use and Land Cover (LULC)

In this study, the land use and land cover classification map of the Mágoè National Park (PNM) was used, generated from ESA Sentinel-2 images with a spatial resolution of 10 meters (Figure 2). This map is produced annually using the Impact Observatory's artificial intelligence (AI) deep learning classification model, trained with billions of human-labeled pixels from the National Geographic Society (KARRA et al., 2021).

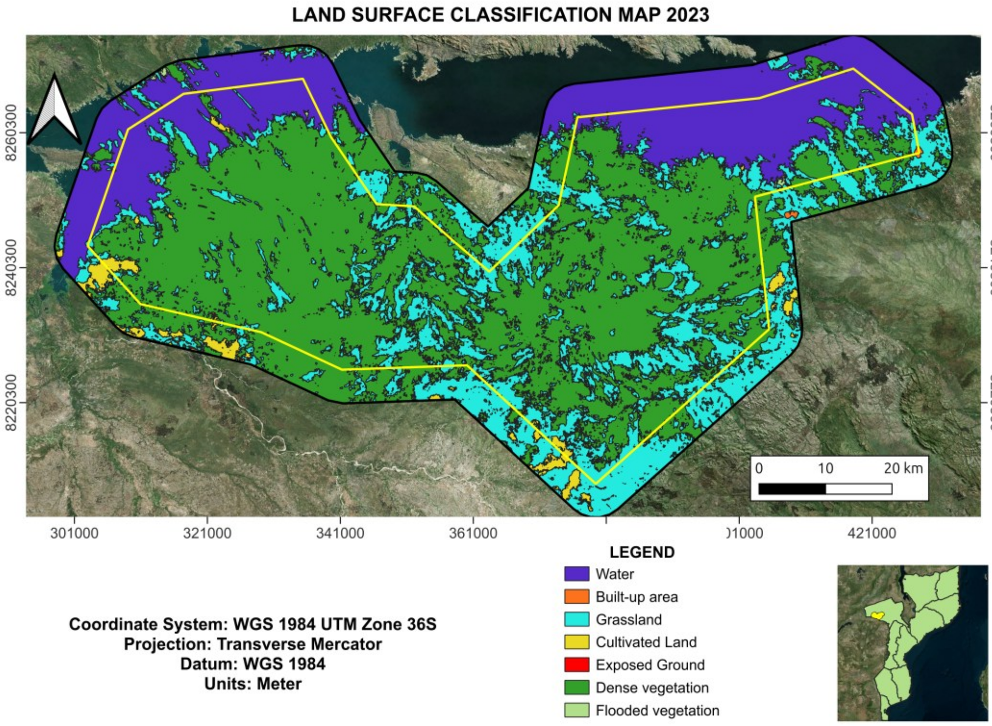

Figure 2. Land Use and Land Cover (LULC) Map for the study area.
Source: Karra et al., 2021

2.2.2 Definition of Anthropogenic Variables

After obtaining the LULC images from the ESA Living Atlas portal (https://livingatlas.arcgis.com/), the following relevant anthropogenic variables were identified: built-up areas, pastures, cultivated and/or agricultural areas, and exposed soils. These variables were selected based on their relevance as environmental impact factors in PNM.

2.2.3. Euclidean Distance Calculation

With the anthropogenic variables defined, the Euclidean distance for each was calculated using the r.grow.distance module of the GRASS GIS software. This procedure calculates the distance from each image pixel to the nearest element of the analyzed variable. For example, in the case of "built-up areas," the calculation determines the distance from each pixel to the nearest built-up area. This process was repeated for all variables, generating a series of Euclidean distance maps representing the proximity or distance to anthropogenic pressure sources.

2.2.4. Spatialization of Euclidean Distance Images Using Fuzzy Logic

With the generated Euclidean distance maps, fuzzy logic was applied to transform the absolute distances into membership degrees, ranging between 0 and 1. This process allows for a continuous and more flexible analysis (SANTOS et al., 2024). Fuzzification was performed using the Geo Value Functions plugin in QGIS, adopting the decreasing linear function (Table 1). According to Santos et al. (2024), as the distance to an anthropogenic variable decrease, the environmental impact increases, and the opposite occurs as the distance increases.

Table 1. Decreasing linear function of each variable used.

Anthropogenic Variable	Decreasing Linear Function
V1 – Agricultural Area	$-5.22^{-05}x + 1$
V2 – Built-up Area	$-3.64^{-05}x + 1$
V3 – Exposed Soil	$-2.272^{-05}x + 1$
V4 – Pasture	$-9.26^{-05}x + 1$

*Vx – Anthropogenic variable

The fuzzified images were reclassified in QGIS using the Reclassify by Table module, according to the criteria set in Table 2. This step allowed for the creation of frequency histograms for subsequent analysis.

Table 2. Reclassification Criteria

Minimum	Maximum	Value
-1	0.25	1
0.25	0.50	2
0.50	0.75	3
0.75	1	4

Source: Author (2024)

2.2.4. Anthropogenic Environmental Vulnerability Modeling

After fuzzification, environmental vulnerability modeling was performed by combining the fuzzy maps of anthropogenic variables into an integrated model (Santos et al., 2024). For this study, the fuzzy Gamma operator = 0.6 was used, which combines the algebraic sum and product operations (Equation 1). The choice of the γ value allows for flexibility between the maximization tendency of the fuzzy sum and the minimization of the fuzzy product (Santos et al., 2024; Pautz et al., 2023; Ramalho et al., 2022).

The combination of variables was processed in the QGIS Raster Calculator. The final product was an environmental vulnerability map, which highlights the area's most susceptible to anthropogenic pressures in PNM. Subsequently, the map was reclassified again using the Reclassify by Table module in QGIS, based on the intervals defined in Table 3. This result is essential for prioritizing management and conservation actions in the park.

$$\mu = (1 - (\prod_{i=1}^{n} 1 - \mu_1))^{\gamma} * (\prod_{i=1}^{n} 1 - \mu_i)^{1-\gamma} \quad \text{Equation 1}$$

Table 3. Color specifications for environmental vulnerability classes.

Minimum	Maximum	Value	Class
-1	0.2	1	Very Low
0.2	0.4	2	Low
0.4	0.6	3	Medium
0.6	0.8	4	High
0.8	1	5	Very High

Source: SANTOS et al., 2024

3. RESULTS AND DISCUSSION

3.1 Euclidean Distance

As previously described, the Euclidean distance provides, in meters, the maximum distance between anthropogenic variables, allowing an understanding of the spatial distribution of classes in the study area. This indicator aids in assessing the density or dispersion of classes in the landscape.

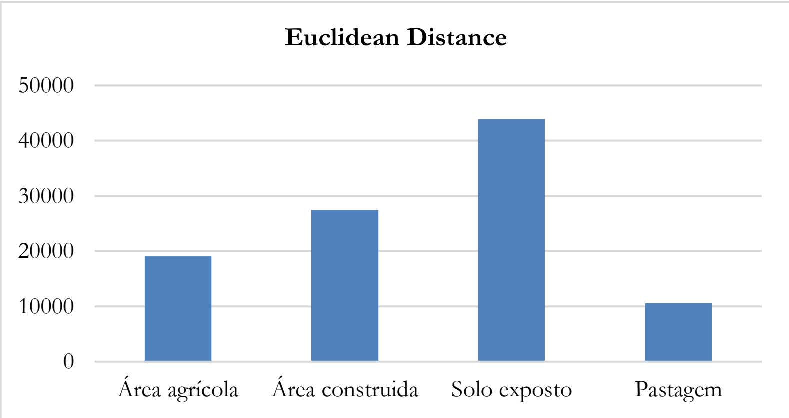

Figure 3. Euclidean distance of anthropogenic variables.

Source: Author (2024), research result

In the Mágoè National Park (PNM), the exposed soil variable showed the greatest maximum distance, while pasture showed the least (Figure 3). This reflects a lower occurrence of areas with exposed soil and a predominance of pasture areas. This pattern is beneficial in terms of conservation, as the lower occurrence of exposed soil is associated with a reduction in the risk of erosive processes.

However, even with the low occurrence of exposed soil, approximately 95% of the pixels in this class have fuzzy values close to 1 (Figure 4). This is a cause for concern, as high fuzzy values indicate proximity of these areas to environmental impact sources, increasing risks to the ecosystem.

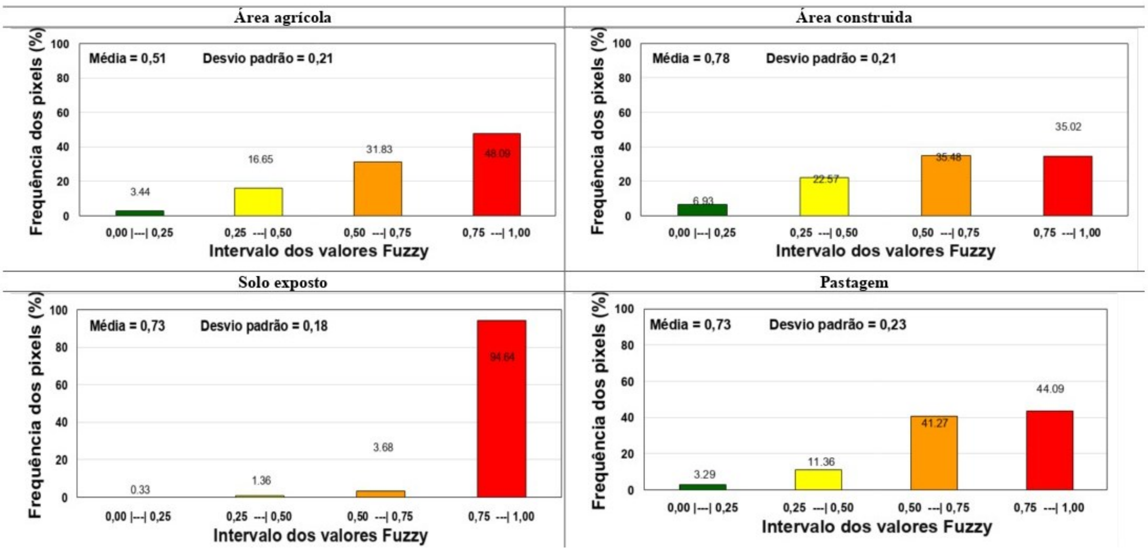

Figure 4. Frequency histogram of pixels of anthropogenic variables.

Source: Author, 2024

Similar scenarios were observed in the agricultural area, built-up areas, and pasture variables, with varying impacts depending on the proximity of pixels to these pressure sources.

3.2 Anthropogenic Environmental Vulnerability

The results of the environmental vulnerability modeling reveal that PNM presents a predominance of the high environmental vulnerability class, which covers approximately 37.40% of the study area. This is followed by the medium vulnerability class, covering about 32.84% of the area. The least occurring class is the very low vulnerability, which represents only 0.8% of the total area (Figure 5).

These data indicate that a considerable portion of the park is subject to significant anthropogenic pressures, with important implications for management and conservation. High vulnerability areas demand priority attention, while very low vulnerability areas can be considered zones of lower immediate risk but still require monitoring to prevent future pressures.

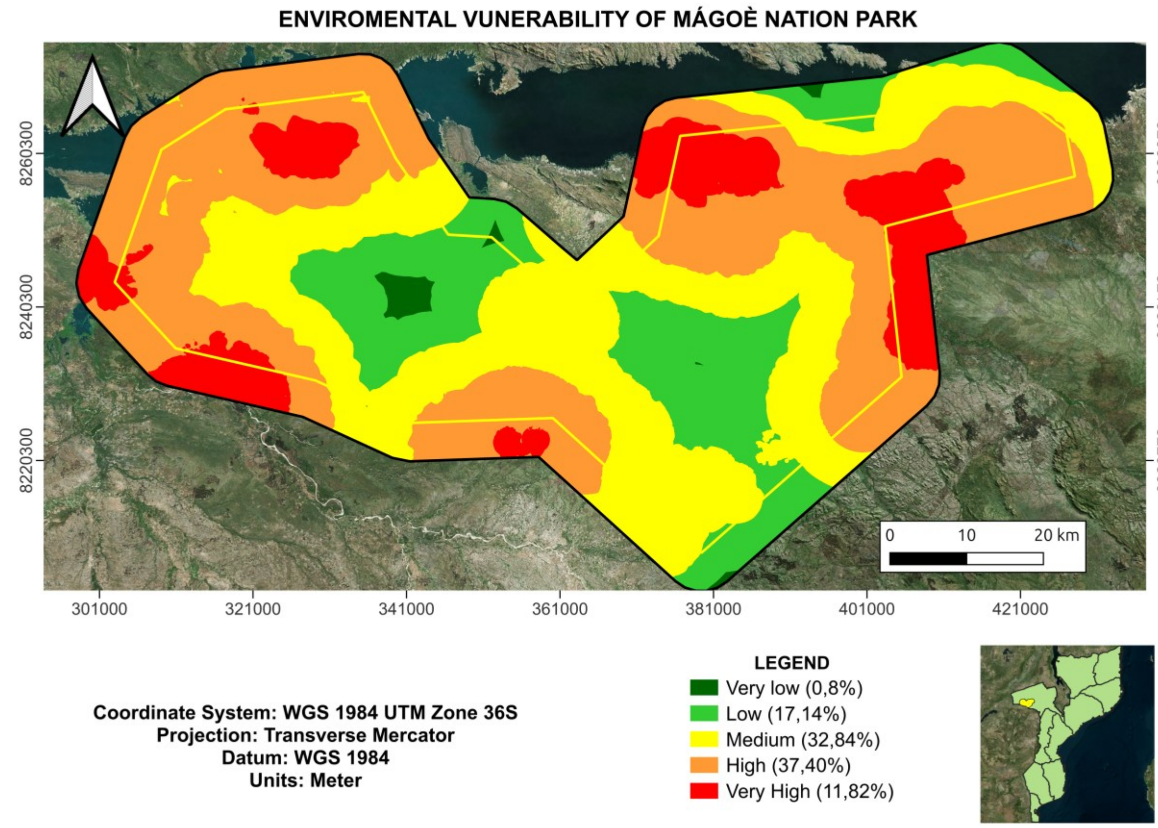

Figure 5. Anthropogenic Environmental Vulnerability.

Source: Author (2024), research result

3.4 Discussion

The analysis of land use and land cover in the buffer zones and within the Mágoè National Park (PNM) reveals significant concerns, particularly regarding the pasture and agricultural area variables, which appear in significant proportions. These findings align with previous studies, such as those by Scaramussa et al. (2023), Nery (2018), and Lopes (2019), which observed the predominance of such variables in protected areas and adjacent regions, especially in the southern portion of Espírito Santo, Brazil.

In the case of PNM, the predominance of pastures, largely resulting from the destruction of native vegetation, highlights considerable pressure on the ecosystem. In some places, the evolution of areas with exposed soil was identified, indicating the total loss of vegetation cover. This process can accelerate environmental degradation, increase the risk of erosion and reduce the soil's capacity to support natural regeneration. The expansion of agricultural areas and the use of pastures for livestock also suggest a continuous modification of the landscape, jeopardizing the ecological integrity of the park.

These observations corroborate the Strategic Plan of the National Administration of Conservation Areas (ANAC) 2015–2024, which warns of the intense anthropogenic pressures on conservation areas, both within their interiors and in adjacent zones (ANAC, 2013). According to the document, the main causes include:

- Deforestation for agricultural and livestock activities;
- Illegal hunting of animals, especially emblematic species;
- Extraction of timber for fuel and construction;
- Illegal mining and other extractive practices.

These activities, often justified by local communities as subsistence needs, have caused the degradation and fragmentation of habitats, as well as a drastic reduction in wildlife. Large mammals, the main attractions for ecotourism, are particularly threatened. The approaches adopted so far, as recognized by ANAC, have been insufficient to achieve conservation objectives or meet the expectations of local communities.

In parallel, the findings of this work resemble those of Leopoldo et al. (2020), who analyzed the environmental vulnerability of the *Nascentes do Rio Parnaíba* National Park (PNNRP). The authors identified extensive vulnerable areas, largely associated with the progressive removal of native *Cerrado* vegetation for agricultural projects. Such practices have compromised the ecological balance and resilience of conservation units.

Similarly, Castro (2021) highlights that, in many protected areas, deforestation for agriculture and livestock is carried out in violation of legal regulations, intensifying environmental vulnerability. This pattern of incompatibility between land use in surrounding regions and conservation objectives is also observed in PNM, reinforcing the need for more effective management strategies and public policies that promote sustainability.

Furthermore, the predominance of high environmental vulnerability classes (37.40%) and medium vulnerability (32.84%) in PNM, according to the results obtained, demands a proactive management response. Areas with high vulnerability should be prioritized for interventions that seek to mitigate impacts and restore native vegetation. Meanwhile, low vulnerability areas (0.8%) can be managed to prevent future pressures, ensuring their long-term preservation.

4. CONCLUSIONS

The mapping of anthropogenic environmental vulnerability in the buffer zone of Mágoè National Park revealed a predominance of high (37.40%) and medium vulnerability (32.84%) classes, confirming the intensity of human pressures on the area. These results reinforce the need for management strategies that prioritize interventions in critical areas, including forest restoration, sustainable soil management, and continuous monitoring. The integration of local communities into productive alternatives, such as agroforestry and ecotourism, combined with institutional strengthening and the implementation of effective public policies, is essential to reduce pressures and promote conservation. Thus, the study provides practical inputs for decision-making and contributes to aligning biodiversity protection with local sustainable development.

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