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Scientific Article

SPATIO-TEMPORAL ANALYSIS OF FOREST FRAGMENTATION AND LANDSCAPE MANAGEMENT SCENARIOS IN THE PERUÍPE RIVER BASIN, STATE OF BAHIA, BRAZIL

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ABSTRACT

This study aimed to evaluate the spatiotemporal changes in vegetation fragments and the degree of forest fragmentation in the Peruípe River Basin, state of Bahia, between 1985 and 2021. Forest fragments were analyzed using landscape metrics related to size, edge, shape, and isolation using the Patch Analyst 5.2 extension in ArcGIS 10.8. Over the 36-year period, only minor changes were observed, with a 0.36% variation in the vegetation classes. The degree of fragmentation in the landscape decreased during the evaluation. However, it can still be concluded that the basin exhibits a high degree of fragmentation because the vegetation remains discontinuous, forming forest mosaics within a matrix that is predominantly pasture and forestry areas. Furthermore, most forest fragments in the Peruípe River Basin are smaller than five hectares (ha). Landscape management scenarios showed the importance of small fragments in the area, as they reduced the average isolation between fragments. In the scenario in which PPAs were restored, the forest area increased, whereas the number of fragments decreased. These results indicate that restoring PPAs can minimize the impact of forest fragmentation. These results are expected to contribute to the development of management and conservation strategies for the Peruípe River Basin.

Keywords: Landscape ecology; Landscape metrics; Geoprocessing

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ANÁLISE ESPAÇO-TEMPORAL DA FRAGMENTAÇÃO FLORESTAL E CENÁRIOS DE MANEJO DA PAISAGEM NA BACIA HIDROGRÁFICA DO RIO PERUÍPE – BA

RESUMO Este estudo teve como objetivo avaliar as mudanças espaço-temporais dos fragmentos de vegetação, bem como, o grau de fragmentação florestal da Bacia Hidrográfica do Rio Peruípe, Bahia, entre os anos de 1985 e 2021. Os fragmentos florestais foram avaliados por meio de métricas de paisagem quanto ao tamanho, borda, forma e isolamento usando a extensão Patch Analyst 5.2 do ArcGIS 10.8. Foi possível observar que as mudanças ocorridas ao longo de 36 anos foram pequenas, com uma alteração de 0,36% da classe de vegetação. Observa-se que a paisagem diminuiu o grau de fragmentação ao longo dos anos avaliados. No entanto, ainda é possível afirmar que a bacia possui um alto grau de fragmentação, uma vez que a vegetação ainda se encontra descontínua formando mosaicos de florestas em uma matriz composta majoritariamente por pastagem e silvicultura. Ademais, pode-se afirmar que a maioria dos fragmentos florestais que compõem a Bacia Hidrográfica do Rio Peruípe são menores que 5 hectares (ha). Os cenários de manejo da paisagem evidenciaram a importância dos pequenos fragmentos para área, uma vez que, os mesmos são responsáveis por diminuir o isolamento médio entre os fragmentos. No cenário que as APPs foram restauradas, a área de floresta aumentou e o e o número de fragmentos reduziu. Esses resultados mostraram que a restauração das APPs pode minimizar o impacto da fragmentação. Espera-se que os resultados possam contribuir para o desenvolvimento de estratégias de manejo e conservação na Bacia Hidrográfica do Rio Peruípe.

Palavras-Chave: Ecologia de paisagem; Métricas de paisagem; Geoprocessamento

1. INTRODUCTION

In recent decades, human activities have intensely modified forest landscapes. These changes have led to habitat loss and landscape fragmentation, reducing biodiversity and altering the functional diversity of forests (Zambrano et al., 2020; Martins et al., 2018).

The Atlantic Forest biome in Brazil has particularly suffered a reduction in forest areas over the years (Ribeiro et al., 2009) and is considered one of the most threatened ecosystems on the planet (Juvanhol et al., 2011). It is classified as a hotspot, meaning it is a priority area for conservation due to its high biodiversity and high degree of threat of extinction (Bezzera et al., 2011). According to the National Institute for Space Research (INPE, 2019), in collaboration with SOS Mata Atlântica, the biome retains only 12.4% of its original coverage, which once occupied a large part of the Brazilian territory. Due to various changes over time, it has become one of the most fragmented ecosystems (Cunha et al., 2021; Fernandes & Fernandes, 2017). It currently consists of small, isolated patches with low habitat diversity and a high degree of fragmentation (Ribeiro et al., 2009). Thus, these areas are considered priorities for conservation due to their high biodiversity (Bezzera et al., 2011).

Forest fragmentation is defined as a process in which a continuous area is divided into fragments separated by a matrix different from the previous one, resulting in varying degrees of isolation (Bispo et al., 2022; Cunha et al., 2021). The expansion of these fragmented areas alters forest functional diversity, resulting in prolonged modifications that interfere with biodiversity and lead to species loss and the isolation of remnants. This creates different forms of matrices that are clearly visible in the landscape and cause changes in forest community structure and function (Zambrano, 2020; Fernandes & Fernandes, 2017).

Forest fragmentation patterns can be analyzed using landscape ecology principles (Fernandes & Fernandes, 2017). This approach uses landscape metrics to qualitatively and quantitatively describe the landscape by taking into account the size, shape, and degree of isolation of the fragments (Martins et al., 2018; Santos et al., 2017; Fernandes et al., 2017). Geographic Information System (GIS) and Remote Sensing (RS) tools are indispensable for conducting analyses in landscape ecology because they enable the creation of maps and the calculation of metrics that demonstrate changes in the landscape over time. These tools allow for the assessment of forest fragmentation and support decision-making processes related to the restoration of fragmented areas (Zambrano et al., 2020; Martins et al., 2018; Fernandes et al., 2017; Pirovani et al., 2014; Souza et al., 2014).

The Peruípe River Basin is one of the main basins in the southern Bahia (Sarmento-Soares et al., 2007). It plays an important role in the development of irrigation, agriculture, and human consumption in the region (Farias et al., 2020). Located in the Atlantic Forest biome, the basin consists of large-scale agricultural systems, particularly eucalyptus plantations (Farias et al., 2020). Changes in land use, especially for extractive purposes without adequate management, can harm the natural resources of the region, including its fauna, flora, and water resources (Almeida et al., 2008). Given the economic importance of the region for pulp production, it is crucial to understand how these practices affect the forest dynamics of the Peruípe River Basin. Thus, analyzing forest fragmentation is an important step in diagnosing current landscape issues.

Assessing habitat fragmentation is essential for understanding ecological relationships within a landscape. This, in turn, enables more effective management of natural heritage. However, studies on the degree of forest fragmentation in this basin are scarce, making this study highly important. This study provides valuable insights for investigating and mitigating environmental impacts in the region and supports the development of management plans. Additionally, this study characterizes the structure of the remaining natural vegetation surrounding two conservation units: the Cassurubá Extractive Reserve and the Ponta da Baleia/Abrolhos Environmental Protection Area (ICMBio, 2018).

The main objective of this study was to quantify the spatio-temporal changes in natural vegetation and analyze the degree of forest fragmentation in the landscape over 36 years (1985–2021). The secondary objectives were: (1) to assess fragmentation according to fragment size classes, (2) to evaluate the importance of small fragments for landscape connectivity, and (3) to analyze management scenarios with the aim of guiding landscape conservation.

2. MATERIAL AND METHODS

To characterize forest fragmentation in the Peruípe River Basin, modeling techniques were used to integrate land use and land cover information with landscape ecology metrics. This approach enabled us to understand the spatio-temporal dynamics of vegetation, assess the degree of landscape fragmentation, and model landscape scenarios. Data manipulation was performed in a Geographic Information System (GIS) using ArcGIS Desktop 10.8 software and the Patch Analyst 5.2 extension to generate landscape metrics, developed by Rempel, Kaukinen, and Carr (2012).

2.1 Study area

This study was conducted in the Peruípe River Basin, located in the southernmost region of the state of Bahia (Figure 1). The basin has a total area of 4,667.27 km² (Farias et al., 2020) and covers eight municipalities: Alcobaça, Caravelas, Ibirapuã, Lajedão, Medeiros Neto, Mucuri, Nova Viçosa, and Teixeira de Freitas. It is situated between the parallels 17º 22’ 15.507” and 17º 55’ 59.12” S and the meridians 39º 10’ 38.385” and 40º 31’ 6.145” W (Farias et al., 2020). The climate is sub-humid, hot tropical. Rainfall is well distributed throughout the year, with November and January being the rainiest months. The vegetation cover is a dense ombrophilous forest belonging to the Atlantic

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Forest biome. The temperature ranges from 23 °C to 27 °C (Farias et al., 2020; Almeida et al., 2008), and the average annual rainfall on the coast of Bahia ranges from 1,400 to 2,600 mm (Sarmento-Soares et al., 2007).

2.2 Mapping of land use and cover

For the mapping of land use and land cover, data provided by the Annual Mapping Project of Land Use and Land Cover in Brazil (MAPBIOMAS, 2021) were used. The

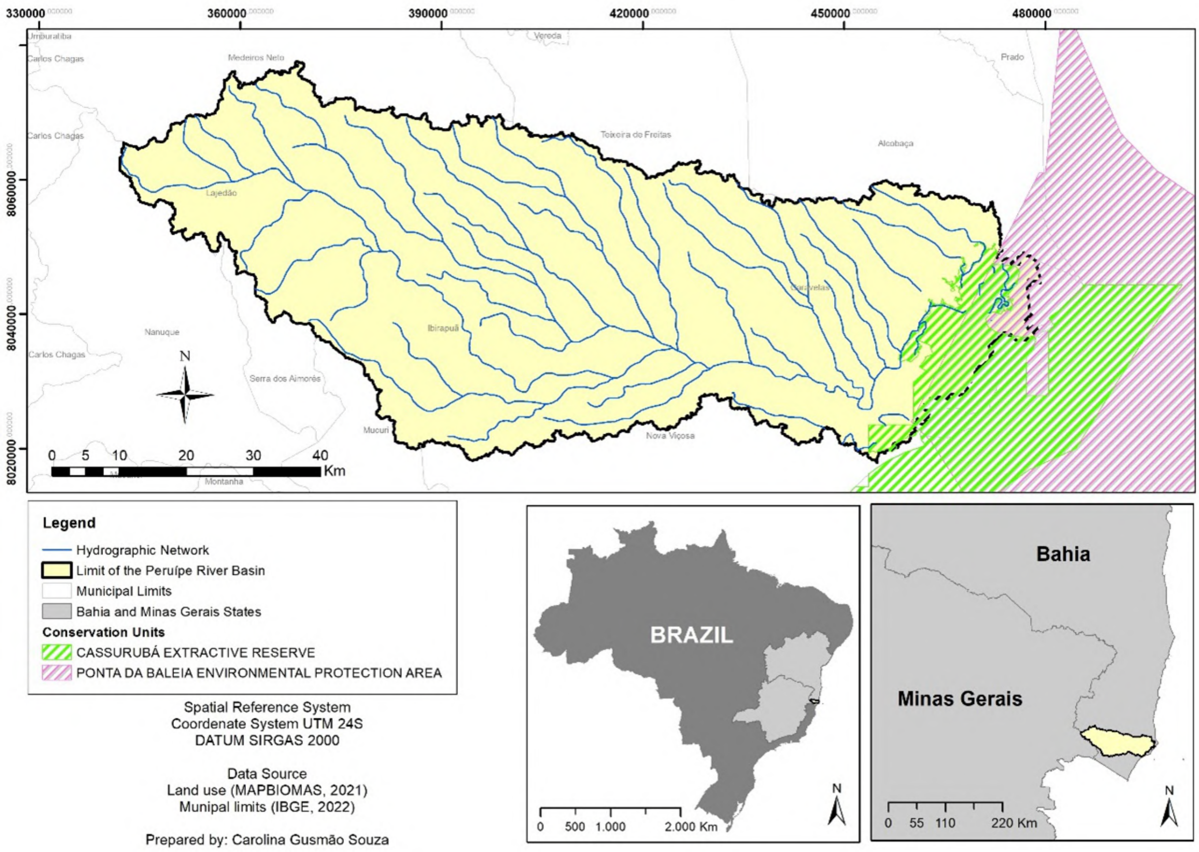


Figure 1. Location map of the Peruípe River Basin, state of Bahia, between the states of Bahia and Minas Gerais, Brazil

Figura 1. Mapa de localização da Bacia Hidrográfica do Rio Peruípe - BA. Situada entre os estados da Bahia e Minas Gerais, Brasil

MapBiomas project uses images from the historical series of the Landsat satellite, which have a spatial resolution of 30 m, in which the images available for the year are compiled into a mosaic, with reflectance bands, as well as spectral, temporal, and texture indices (MAPBIOMAS, 2021). All processing is performed in the cloud using classifications supervised by the Random Forest algorithm, on the Google Earth Engine platform. For this study, data from the years 1985, 2005, and 2021, from Collection 7 of MapBiomas (MAPBIOMAS, 2021), were used. The data were reprojected to UTM 24S Coordinate Reference System, SIRGAS 2000 Datum. All analyses were performed using ArcGIS 10.8 software.

2.3 Permanent Preservation Areas (PPAs)

Data on Permanent Preservation Areas (PPAs) were obtained from the Rural Environmental Registry System (SICAR), a public platform maintained by the federal government that collects environmental information on rural properties throughout the country. For this stage, we extracted the vector data made available by SICAR, which contains the spatial delimitation of PPAs declared by rural landowners. Using this database, we quantified the total extent of the declared PPA areas and classified their land cover, differentiating between natural vegetation and other uses.

2.4 Fragmentation Analysis

To assess forest fragmentation, land use maps were reclassified into two classes: (1) forest, which represents areas of forest formation, mangroves, and wooded restinga; and (2) non-forest, representing areas such as agriculture, forestry, water bodies, urban areas, among others.

To analyze the degree of fragmentation of the forest class over the years, landscape metrics were calculated for each year under study. Patch-level metrics were used, namely: area (CA, PLAND), size and density (NUMP, MPS, PSSD, and PSCoV), edge (TE, ED), shape (MSI, AWMSI, MPFD, MPAR), and proximity (MNN), as described in Table 1. Processing was performed using ArcGIS 10.8 software and the Patch Analyst 5.2 extension.

Table 1. Summary of landscape metrics considered in this study, with their respective abbreviations and descriptions, analyzed using Patch Analyst 5.2
Tabela 1. Resumo das métricas da paisagem consideradas nesse estudo, com suas respectivas siglas e descrição, analisadas com o Patch Analyst 5.2

Index	Abbreviation	Unit	Name	Description
Area	CA	Hectare (ha)	Class area	Sum of patches of the class present in the area.
	PLAND	%	Class percentage	Percentage of the area occupied by each class in the landscape.
Size and Density	PSCoV	%	Coefficient of variation of patch size	Standard deviation in percentage, that is, of the variation for each class.
	NUMP	Dimensionless	Patch number	Total number of patches in the landscape.
	MPS	Hectare (ha)	Mean patch size	Mean patch size by class.
	PSSD	Hectare (ha)	Standard deviation of patch size	Variation in patch size around the mean value.
Edge	TE	Meter (m)	Total edge	Total edges.
	ED	(ha)	Edge density	Edge density, TE divided by total area in hectares.
	MPE	Meter (m)	Perimeter mean (edge)	Mean edge length.
Shape	MSI	Dimensionless	Mean shape index	It approaches 1 when all of the patches are circular, and increases with increasing irregularity of patch shape.
	AWMSI	Dimensionless	Area-weighted mean shape index	It indicates how close a patch is to being a circle.
	MPFD	Dimensionless	Mean patch fractal dimension	It expresses the complexity of the shape of the patch.
	MPAR	Dimensionless	Mean perimeter-to-area ratio	It is similar to edge density (ED). It is calculated as the ratio of each class's perimeter (TE) to its total class area (CA), divided by the number of patches (NUMP).
Proximity	MNN	Meter (m)	Mean nearest-neighbor distance	Mean nearest-neighbor distance. A lower value favors the agglutination of fragments.

Source: Adapted from Orlandi & Santos (2022).
Fonte: Adaptado de Orlandi & Santos (2022)

2.5 Fragmentation analysis by fragment size class

Five size classes were established to assess the degree of fragmentation by size of the remnants, according to the methodology described by Fernandes and Fernandes (2017) and Santos et al. (2015). These size classes are very small (fragments smaller than 5 ha), small (between 5 and 10 ha), medium (between 10 and 100 ha), large (between 100 and 250 ha), and very large (larger than 250 ha). The following metrics were evaluated at this stage: area (CA), size and density (NUMP), edge (ED), shape (MSI, MPAR, and MPFD), and proximity (MNN). Assessments were carried out only for the data from 2021, as it represents the most recent landscape configuration in the area.

2.6 Landscape management scenarios

2.6.1 Simulation of the removal of small fragments

To assess the importance of small fragments for landscape connectivity, we developed different management scenarios that simulated the removal of these fragments from the landscape. Seven distinct scenarios were categorized according to the methodology proposed by Souza et al. (2014): Category 1: all forest fragments; Category 2: fragments ≤ 1 ha were removed; Category 3: fragments ≤ 5 ha were removed; Category 4: fragments ≤ 10 ha were removed; Category 5: fragments ≤ 50 ha were removed; Category 6: fragments ≤ 100 ha were removed; and Category 7: fragments ≤ 250 ha were removed. The mean nearest-neighbor distance (MNN) was calculated for each scenario to analyze isolation after removing the fragments.

2.6.2 Simulation of the recomposition of PPA areas

To compare the degree of landscape fragmentation and connectivity between fragments, we simulated the recomposition of the PPA areas declared in SICAR (see item 2.3) and compared it with the forest area of the basin in 2021 (FO2021). Thus, cross-referencing was performed between the PPAs and natural vegetation (forest) of 2021 (FOPPA), simulating the recomposition of the non-preserved PPAs. Landscape ecology metrics were calculated using simulated data and the same parameters as in previous analyses.

3. RESULTS

3.1 Forest Dynamics

The degree of forest fragmentation in the Peruípe River Basin was quantified by assessing the temporal dynamics of changes in natural vegetation and analyzing landscape indices. Over the analyzed years, the forest class underwent a few changes compared to the non-forest class. Table 2 shows the quantification of forest and non-forest classes in 1985, 2005, and 2021.

Over 36 years (1985–2021), the percentage of change was small at 0.36%. This represents an increase of 1,650.51 ha in forest areas and a corresponding decrease in non-forest areas. Figure 2 shows the spatial distribution of forest and non-forest areas within the basin during the study period.

3.1.1 *Natural Vegetation in PPAs*

The total area of Permanent Preservation declared in the Rural Environmental Registry is 290.70 km². Of this total, 108.12 km² (37.2%) is occupied by natural vegetation, while 182.56 km² (62.8%) has other types of

Table 2. Area occupied by the forest and non-forest classes of land use in the Peruípe River Basin in 1985, 2005, and 2021

Tabela 2. Área ocupada pelas classes Floresta e Não floresta do uso do solo na Bacia Hidrográfica do Rio Peruípe nos anos de 1985 e 2005, 2021

Classes	1985		2005		2021		Change (1985-2021)	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Forest	56,033.37	11.96	50,505.21	10.78	57,683.88	12.31	1,650.51	0.36
Non-forest	412,310.07	88.04	417,838.23	89.21	410,659.56	87.68	-1,650.51	-0.36

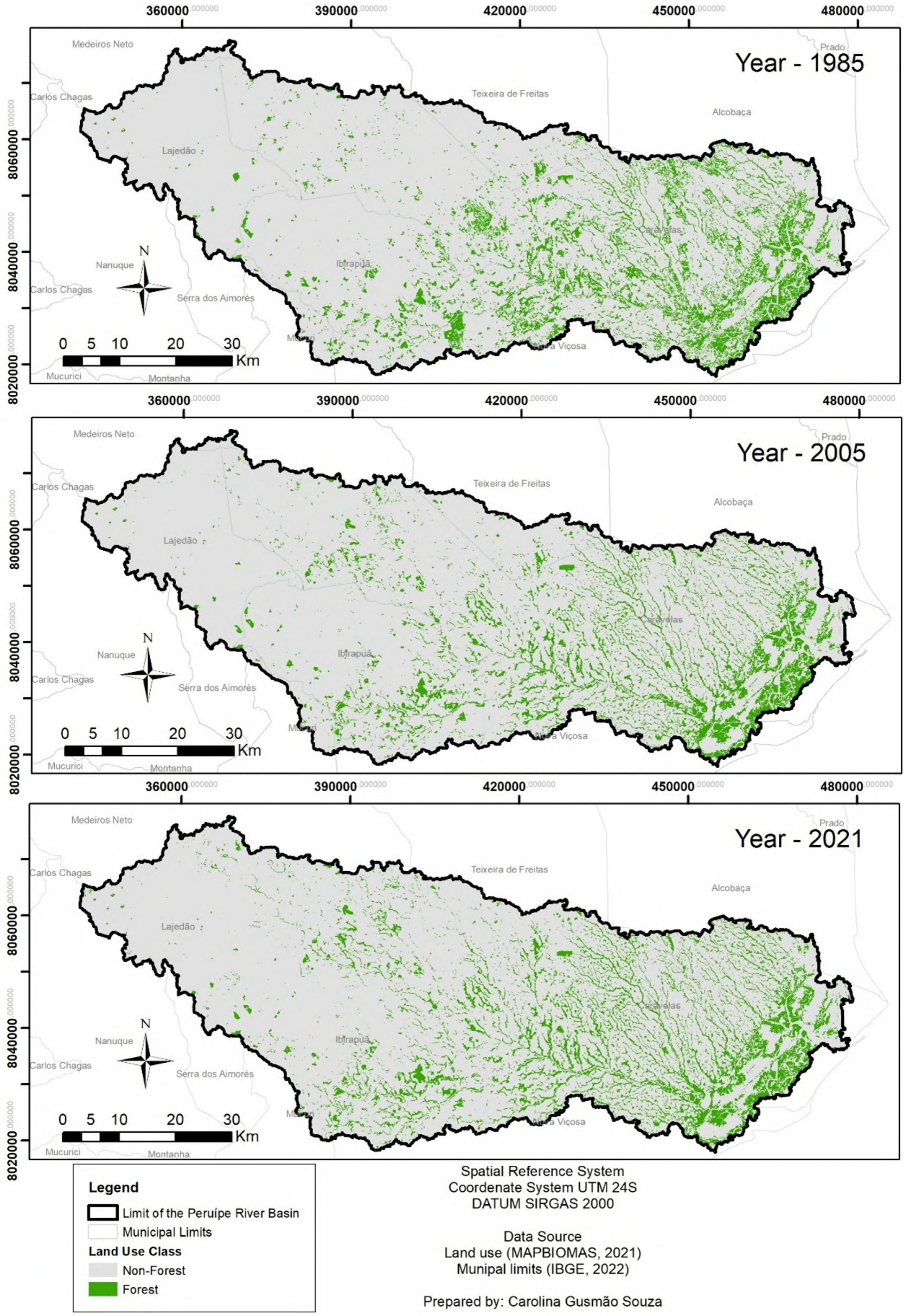


Figure 2. Map showing the spatial distribution of forest fragments in the Peruípe River Basin in 1985, 2005, and 2021

Figura 2. Mapa com a espacialização dos fragmentos florestais na Bacia Hidrográfica do Rio Peruípe nos anos de 1985, 2005 e 2021 land use and cover. Figure 3 illustrates the spatial distribution of the PPAs and the vegetation cover within their limits.

3.2 Analysis of Forest Fragmentation

The Peruípe River Basin has a total area of 468,356.41 ha. In 1985, the region consisted of an area (CA) of 57,683.00 ha, represented by the forest class, corresponding to 11.96% (PLAND) (Table 3), distributed among 14,509 vegetation fragments (NUMP). By 2005, CA and PLAND had decreased to 50,505.21 ha and 10.78%, respectively, corresponding to 10,475 fragments. In 2021, the forest area increased, reaching an area (CA) of 57,683.88 ha, corresponding to 12.31% (PLAND), and was distributed among 12,921 vegetation fragments. Although 2021 presented a higher percentage of natural vegetation (PLAND), the number of fragments (NUMP) decreased compared with previous years. It is reasonable to infer that this decrease is related to the increase in the average fragment size (MPS), which grew from 3.86 ha in 1985 to 4.46 ha in 2021 (Table 3). This increase may be due to the agglutination of forest fragments in the landscape.

The mean patch size (MPS) was 3.86 ha in 1985, 4.82 ha in 2005, and 4.46 ha in 2021. The patch size standard deviation (PSSD) was 33.42 in 1985, 33.40 in 2005, and 37.54 in 2021.

The mean shape index (MSI), which compares the size of a fragment to that of a circle with the same area, was 1.51, 1.56, and 1.55 in 1985, 2005, and 2021, respectively. These values indicate that the fragments are irregularly shaped because they are far from 1. The area-weighted mean shape index (AWMSI) had higher values than the MSI,

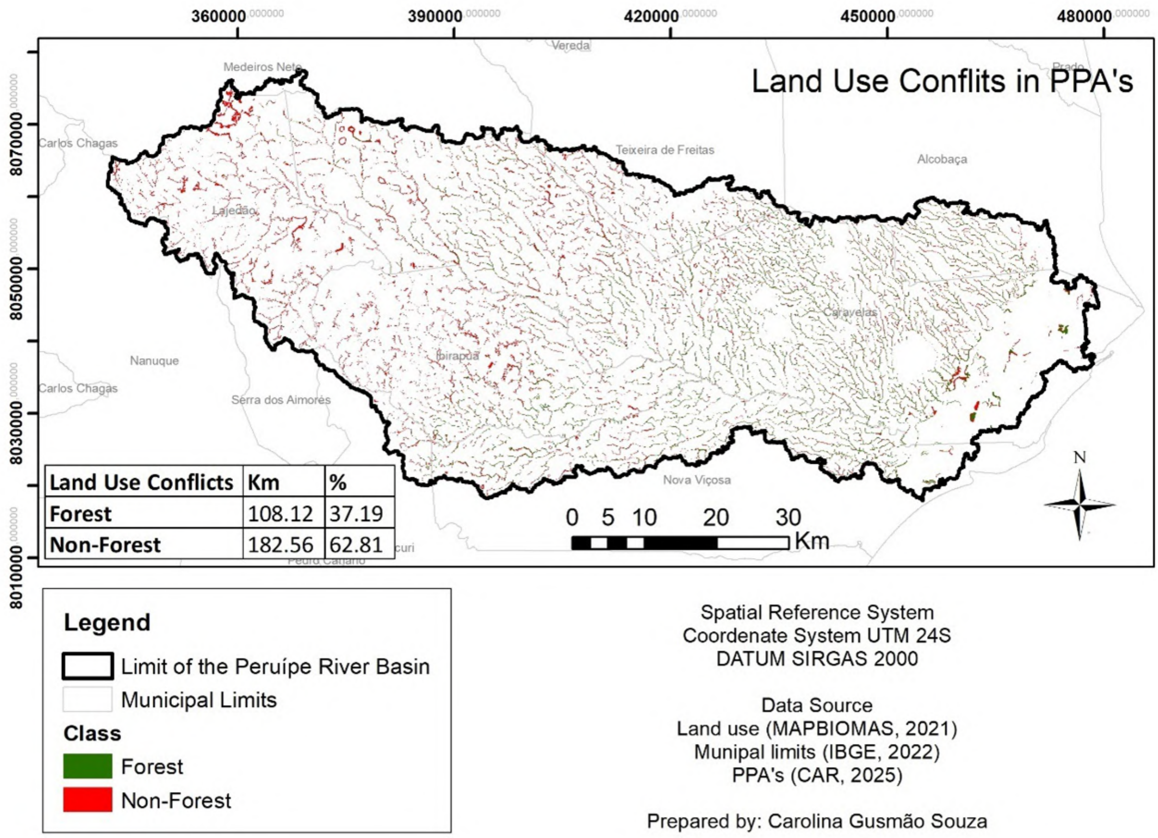


Figure 3. Conflict of land use (Forest) in Preservation Permanent Areas (PPA) in the Peruípe River Basin

Figura 3. Conflito de uso da terra nas Áreas de Preservação Permanente (APP) na Bacia Hidrográfica do Rio Peruípe

Table 3. Results of the landscape metrics for the Peruípe River Basin for the years 1985, 2005, and 2021
Tabela 3. Resultado das Métricas da paisagem da Bacia Hidrográfica do Rio Peruípe nos anos de 1985, 2005 e 2021

Metrics (Groups)	Abbreviation	Years		
		1985	2005	2021
Area	CA (ha)	56,033.37	50,505.21	57,683.88
	PLAND (%)	11.96	10.78	12.31
Size and density	NUMP	14,509	10,475	12,921
	MPS (ha)	3.86	4.82	4.46
	PSSD (ha)	33.42	33.40	37.54
	PSCoV (%)	865.60	692.82	840.93
Edge	MPE (m)	977.72	1,064.51	1,051.52
	TE(m)	14,185,740.00	11,150,820.00	13,586,760.00
	ED (m/ha)	253.16	220.78	235.53
Shape	MSI	1.51	1.56	1.55
	AWMSI	6.37	4.68	5.85
	MPFD	1.38	1.38	1.38
	MPAR	892.78	838.41	858.96
Proximity	MNN (m)	170.57	210.61	191.66

with values of 6.37, 4.68, and 5.85, respectively. This corroborates the presence of irregularly shaped fragments.

The edge total (TE) quantify the perimeters of all the fragments. In 1985, the TE was 14,185,740 m. The lowest TE value was recorded in 2005 at 11,150,820 m. In 2021, this increased to 13,586,760 m. The fragments presented similar edge density (ED) values of 253.16, 220.78, and 236.53 m in 1985, 2005, and 2021, respectively.

When analyzing the degree of isolation of the fragments, as expressed by the mean nearest-neighbor distance (MNN), it is evident that isolation increased from 170.57 in 1985, subsequently decreasing to 210.6 in 2005, and then decreasing further to 191.66.

3.3 Analysis of fragments by size class

The analysis of fragments by size class was conducted for the year 2021 (Figure 4). In terms of total area, very small fragments (≤5 ha) represented 14% of the total area of the class natural vegetation in river basin, while small fragments (5–10 ha) corresponded to 7%, being considered small and representing the smallest class of the landscape (Figure 4A). The intermediate fragment class (area of 10 – 100 ha) is equivalent to 32%, followed by the very large class which also presents the same percentage value (32%), the intermediate class has a slightly larger area of 18,645.00 ha, compared to the very large class, with an area of 18,246.00 ha. Finally, is the large class (100–250 ha) which constitutes 15% of the total area of the class natural vegetation in basin (Figure 4A). The smallest class of the year 2021 had fragments up to 5 ha and comprised 9,114 patches out of a total of 12,921.

Despite representing only 14% of the total area of the class natural vegetation in basin, the ≤ 5 ha fragment class had the largest number of fragments, with a NUMP of 11,593 (Figure 4B). This indicates that the landscape is mostly represented by very small forest patches, which correspond to 89.72% of the total fragments in the basin and suggest high fragmentation and a low degree of conservation.

Regarding the shape of the remnants, the patch fractal dimension (MPFD) indicates that the fragments are irregularly shaped (Figure 4C) because these values are far from 1. However, there was little variation in the MPFD between the size classes.

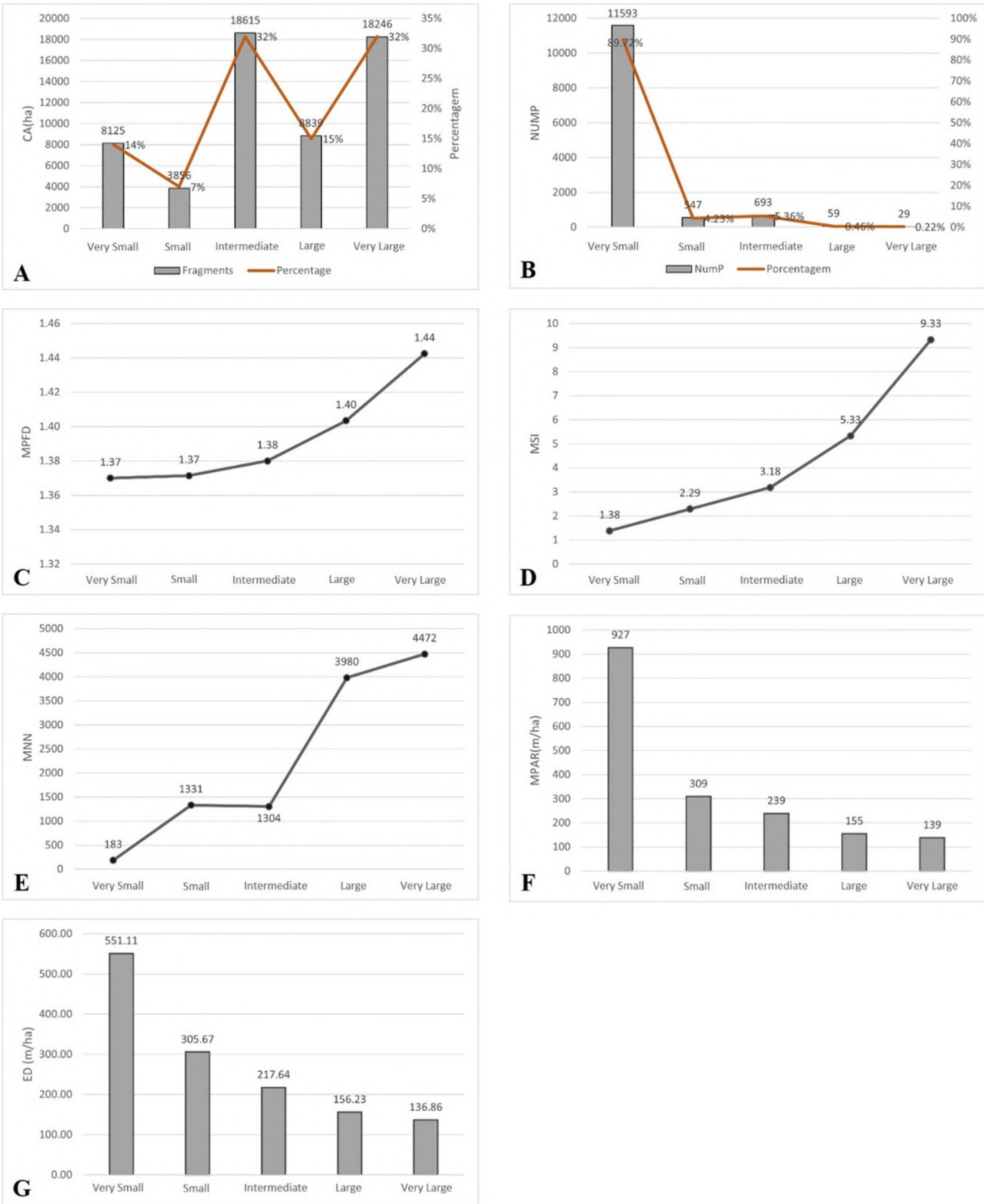


Figure 4. Metrics for forest fragment size classes for the year 2021. A. Class Area (CA) B. Number of Fragments (NUMP). C. Mean Patch Fractal Dimension (MPFD). D. Mean Shape Index (MSI). E. Mean Nearest-Neighbor Distance (MNN). F. Mean Perimeter-to-Area Ratio (MPAR). G. Edge Density (ED)

Figura 4. Métricas para classes de tamanho de fragmentos florestais para o ano de 2021. A. Área da Classe (CA) B. Número de fragmentos (NUMP). C. Dimensão Fractal média da mancha (MPFD). D. Indicador médio de forma. E. Distância média do Vizinho mais próximo (MNN). F. Média da relação perímetro/área (MPAR). G. Densidade de borda (ED)

3.4 Landscape management scenarios

3.4.1 Importance of small fragments

In order to assess the importance of small fragments, we created scenarios to show how these fragments reduced the average isolation of the landscape at each stage (Figure 5).

After removing the fragments, the average isolation between the fragments in the full landscape was 191 m (Figure 5). As progressively larger fragments were removed, the isolation increased substantially. Removing fragments smaller than 1 ha increased the average isolation to 512 m. Removing fragments up to 5 ha increased it further to 996 m, and isolation continued to increase with the removal of larger fragment categories. Notably, removing category 4 fragments caused a sharp increase in isolation, raising it from 1,275 to 2,771 m and placing the landscape in a high-isolation category.

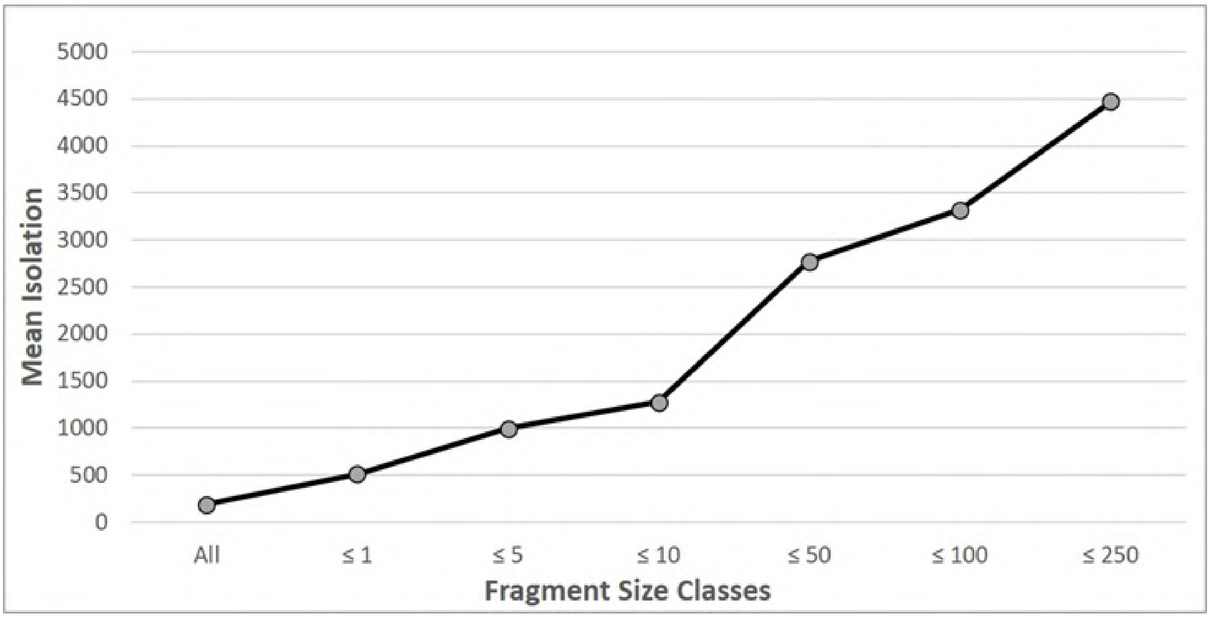


Figure 5. Isolation index from the removal of small fragments for the year 2021. With all fragments (category 1), fragments ≤ 1 ha were removed from the analysis (category 2), ≤ 5 ha (category 3), ≤10 ha (category 4), ≤50 ha (category), ≤ 100 ha (category 6), and ≤ 250 ha (category 7)

Figura 5. Índice de isolamento a partir da retirada dos pequenos fragmentos para o ano de 2021. Com todos os fragmentos (categoria 1); fragmentos ≤ 1 ha foram removidos da análise (categoria 2); ≤ 5 ha (categoria 3); ≤10 ha (categoria 4); ≤50 ha (categoria); ≤ 100 ha (categoria 6); ≤ 250 ha (categoria 7)

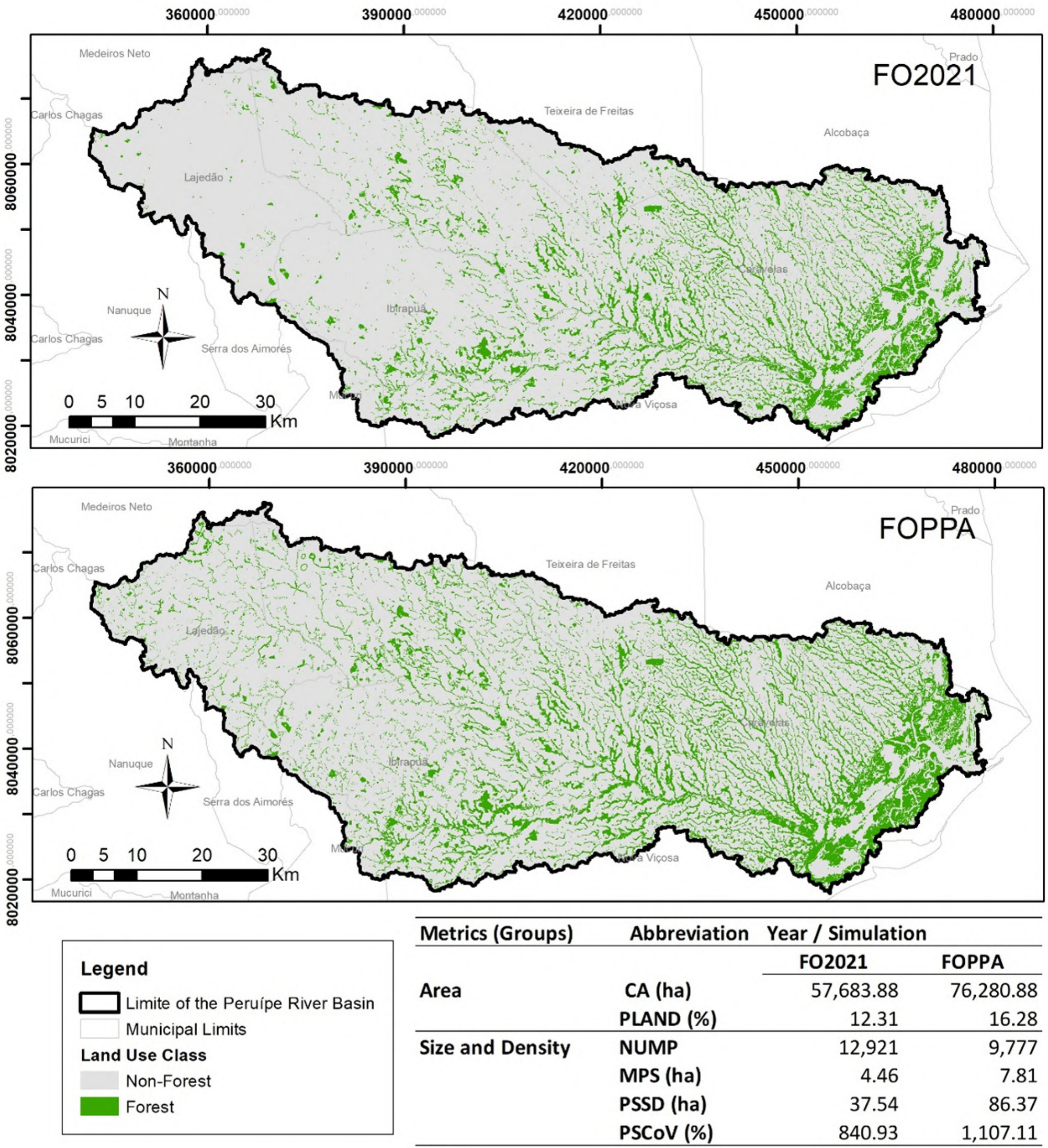
3.4.2 Importance of restoring PPAs

Simulating the restoration of PPA areas revealed notable changes in the forest landscape of the basin. Figure 6 presents a comparative analysis of the landscape. The area of natural vegetation increased from a class area (CA) of 57,683.88 ha in the FO2021 class (forest cover in 2021) to 76,280.88 ha in the FOPPA class (forest cover in 2021, including restored PPAs). This corresponds to a 4% increase in the percentage of landscape (PLAND) covered by forests.

The metrics of fragment size and density increased when the two scenarios were compared. The FOPPA class exhibited a significantly higher mean patch size (MPS) and patch size standard deviation (PSSD) than the FO2021 class. This trend was also evident when compared with the previous years (Table 3).

The total edge (TE) was also higher in the FOPPA scenario. However, the difference in edge density (ED) between FOPPA and FO2021 was not very large when comparing the edge values relative to the fragment areas, increasing from 235.53 (FO2021) to 258.08 (FOPPA). Additionally, the mean shape index (MSI) increased for the FOPPA class, rising from 1.55 (FO2021) to 1.81 (Figure 6).

Evaluating the mean nearest-neighbor distance (MNN), we observed a decrease for the FOPPA class, which exhibited an average distance of 115.00 m, compared to 191.66 m for the FO2021 class.



Metrics (Groups)	Abbreviation	Year / Simulation FO2021	FOPPA
Area	CA (ha)	57,683.88	76,280.88
	PLAND (%)	12.31	16.28
Size and Density	NUMP	12,921	9,777
	MPS (ha)	4.46	7.81
	PSSD (ha)	37.54	86.37
	PSCoV (%)	840.93	1,107.11
Edge	MPE (m)	1,051.52	2,013.38
	TE(m)	13,586,760.00	19,684,852.00
	ED (m/ha)	235.53	258.05
Shape	MSI	1.55	1.81
	AWMSI	5.85	12.63
	MPFD	1.38	1.42
Proximity	MPAR	858.96	2,017.41
	MNN (m)	191.66	115.75

Figure 6. Comparison map of landscape metrics for Forest Formation in 2021 (FO2021) and the simulation scenario with the recomposition of APPs (FOPPA)

Figura 6. Mapa de comparação das métricas de paisagem para a Formação Florestal em 2021 (FO2021) e o cenário de simulação com a recomposição das APPs (FOPPA)

4. DISCUSSION

The results indicated that the study area exhibited a low percentage of forest cover throughout the years evaluated. According to Bircol et al. (2018), in order to prevent alterations to the structure of forests and declines in biodiversity, native vegetation must cover between 30% and 50% of the area. This condition is not met in the Peruípe River Basin, where forest cover never exceeds 15%.

Based on the legal framework of Permanent Preservation Areas (PPAs), it is clear that many PPAs registered in the Rural Environmental Registry (CAR) do not fulfill their intended legal purpose because they are occupied by land uses that are incompatible with forest cover. This reflects a high degree of degradation or misuse of PPAs, which undermines their legal role in protecting water resources, soil, and biodiversity (Fernandes et al., 2024). Since only 37.2% of PPAs maintain their ecological function, the provision of essential environmental services, such as riparian forest protection, water regulation, and erosion control, is likely to be compromised in the Peruípe River Basin. Consequently, environmental recovery in these irregular areas has become a pressing necessity, as stipulated in the Forest Code (Brasil, 2012). One viable approach to addressing this issue is Environmental Regularization Programs (PRAs), which property owners with irregularities can undertake. These findings highlight that although CAR and PPA delineations are valuable tools for monitoring and planning, effectively enforcing environmental legislation on rural properties remains a significant challenge (Fernandes et al., 2024).

The results (Table 3) revealed high heterogeneity in fragment sizes within the region's landscape, which predominantly consisted of very small fragments. Despite their small size, these fragments are ecologically significant because they play fundamental roles in maintaining landscape functionality (Orlandi & Santos, 2022; Martins et al., 2018). Similar findings were reported by Bispo et al. (2022) for a river basin dominated by fragments smaller than five hectares.

Average fragment size is a key metric for assessing environmental risks in a region (Santos et al., 2017). Studies by Orlandi & Santos (2022), Martins et al. (2018), and Santos et al. (2017) indicated that areas dominated by fragments smaller than five hectares are considered at risk because of their increased susceptibility to edge effects. Consequently, these fragments are more susceptible to degradation, especially along their margins, where they border anthropogenic landscapes such as pastures and agricultural lands (Santos et al., 2017).

Although the landscape has shown a reduction in the degree of fragmentation over the years evaluated, the Peruípe River Basin remains highly fragmented. Natural vegetation persists as discontinuous patches, forming forest mosaics within a matrix dominated by pastures and forestry. Similar studies conducted in other river basins in the state of Bahia reported a high degree of fragmentation in areas with Atlantic Forest vegetation, where forest cover is only 6.05%, distributed among small vegetation fragments (Bispo et al., 2022).

The differences between the MSI and AWMSI values arise because the AWMSI calculation incorporates the fragment size. Smaller fragments are more vulnerable to edge effects than larger ones (Martins et al., 2018; Pirovani et al., 2014). Nearly circular fragments have a lower edge-to-area ratio, which means that the center of the fragment is equidistant from the edge (Pirovani et al., 2014). This effectively "protects" the core area from external influences. Conversely, elongated or narrow fragments have a higher proportion of edges relative to the area. Therefore, larger fragments with fewer indentations or cutouts are preferable because they minimize the edge-to-area ratio and reduce exposure to edge effects (Orlandi & Santos, 2022; Azevedo et al., 2016; Almeida, 2008).

The results related to edge effects indicated that 2005 exhibited the highest degree of conservation. Edge effects impact the development of species along fragment margins and tend to promote the proliferation of predators, parasites, and generalist species, which can outcompete or prey upon interior species, leading to their exclusion (Cunha et al., 2021; Fernandes et al., 2017). Colavite et al. (2019) showed that edge effects can increase tree mortality rates and favor pioneer species at the expense of species that are typical of undisturbed areas.

The quantitative differences observed in edge density (ED) were influenced by the occupied area and fragment size, with ED being inversely proportional to the occupied area. These results suggest that higher edge densities correspond to greater edge effects, where the transition between the fragments and the surrounding matrix becomes more abrupt. These edges are more exposed to external environmental conditions and are therefore more susceptible to edge effects (Azevedo et al., 2016; Pirovani et al., 2014).

In general, the fragments in the Peruípe River Basin exhibited a high degree of average isolation (Figure 2). According to Santos et al. (2017), isolation values between 120 and 200 meters are considered high, and values equal to or greater than 200 meters are classified as very high. The landscape matrix is predominantly composed of pastures and agricultural areas, which have low permeability between land uses and forest fragments. Reduced connectivity hinders various ecological interactions among flora and fauna (Fernandes & Fernandes, 2017; Azevedo et al., 2016).

Human activities that disrupt landscape continuity largely drive the fragmentation of natural habitats, resulting in changes in the structure, composition, and diversity of local communities (Zambrano et al., 2020). Fragmentation also leads to the isolation of habitat patches, reducing the frequency of crossings between them and consequently decreasing genetic variation. This isolation can cause local extinction and ultimately contribute to biodiversity loss (Zambrano et al., 2020; Metzger, 1999).

An inverse relationship was observed between the number of patches and their total areas. Specifically, the smallest patches (less than 5 ha) represented the smallest total area (Figure 4A), yet they were the most numerous. In contrast, patches larger than 100 ha accounted for only 0.68% of the total number of fragments in the basin (Figure 4B), despite covering the largest area. Pirovani et al. (2014) argue that larger, irregularly shaped fragments are preferable to smaller, circular ones because the latter are more susceptible to edge effects. Additionally, Zambrano et al. (2020) highlighted that very small fragments may reduce species richness by becoming unsuitable for certain animal species to survive.

The size and number of fragments within a watershed are critical factors to consider when assessing environmental risks (Moreira & Peluzio, 2022). Bispo et al. (2022) indicate that areas smaller than 5 ha exhibit high relative ecological vulnerability because most fragments of this size fail to provide adequate shelter for species. These small fragments are particularly susceptible to edge effects, which can degrade the outer portions in contact with an anthropogenic matrix and directly impact the internal ecological dynamics of the fragment (Moreira & Peluzio, 2022).

Analysis of the mean shape index (MSI) revealed that this metric exhibited different values compared to the MPDF, reaching a value of 9.33 for the very large fragment class (Figure 4D). MSI values increased with fragment size, with the lowest value (closer to 1) associated with the very small fragment class. Similar patterns were reported by Orlandi & Santos (2022) in their landscape analysis. The greater differences between class values compared to the MPDF are explained by the higher sensitivity of MSI and its lack of an upper value limit (McGarigal & Marks, 1995).

The size classes of forest remnants increased proportionally with the mean nearest-neighbor distance (MNN) (Figure 4E). The distance between the fragments in all classes increased as the mean shape index

(MSI) increased. This trend indicates that as isolation among classes increased, the shape of the fragments became more irregular. This relationship is linked to the number of fragments in each class. Very small fragments, which were more numerous (9,114), tended to be closer to each other. In contrast, very large fragments, of which there are only 29, show a higher degree of isolation. The very small fragment class exhibited both the lowest MNN value and shapes closest to circular. These findings align with those of Azevedo et al. (2016), who observed a similar pattern: as the number of fragments decreased, their isolation increased.

The large and very large fragments have the advantage of a larger area, but they have the disadvantage of irregular shapes, with MSI values of 5.33 and 9.33, respectively. However, despite their irregular shapes, larger fragments experience fewer edge effects because of their lower perimeter-to-area ratio. This implies that they have a greater proportion of core areas relative to their edges. Most of these fragments are situated in the eastern part of the basin, where the two Conservation Units (UCs) are located (ICMBio, 2018). According to the management plan of RESEX Cassurubá, this region harbors diverse and threatened ecosystems, such as mangroves, restingas, and marshes. This makes the region critically important for preserving the remaining vegetation and local fauna (ICMBio, 2018).

Similar patterns of the mean perimeter-area ratio (MPAR) were reported in studies by Santos et al. (2017) and Pirovani et al. (2014), with class size values that were inversely proportional to the perimeter-to-area ratio (Figure 4F). The edge density (ED) decreased as the fragment size class increased. The very small fragment class exhibited a high ED of 551.11 m/ha, compared with 136.86 m/ha for the very large class. The difference in ED was determined by the total area occupied by each fragment size class; edge density was inversely proportional to the area occupied by the class. These results suggest that larger fragments have smaller edge effects, indicating better-preserved patches (Fernandes & Fernandes, 2017; Azevedo et al., 2016; Pirovani et al., 2014). Furthermore, fragment shape influences the propensity for edge effects, as more irregularly shaped fragments have larger edges relative to their area, which is directly linked to the perimeter-to-area relationship (Orlandi & Santos, 2022; Martins et al., 2018).

The results of the management scenario emphasize the significance of small remnants that serve as "ecological stepping stones" connecting the landscape (Orlandi & Santos, 2022; Souza et al., 2014). These fragments facilitate the dispersal of animals and plants and help to maintain connectivity. Azevedo et al. (2016) found that smaller fragments reduce isolation between patches and noted that some understory birds tend to avoid crossing open areas wider than 40 meters.

Analysis of the other categories revealed that isolation increased as smaller fragments were removed (Figure 5). These findings suggest that fragments up to 10 hectares are essential for conserving the landscape of the Peruípe River Basin because they enhance connectivity among the remaining forest patches (Souza et al., 2014). Souza et al. (2014), Zanella et al. (2012), and Ribeiro et al. (2009) corroborate these findings, highlighting the important role of small fragments in facilitating animal movement, promoting landscape connectivity, enabling species persistence in human-modified areas, and serving as stable sources of seeds and individuals (Ribeiro et al., 2009). As the fragments were progressively removed, the average isolation increased significantly. Overall, small fragments are crucial for reducing isolation throughout all stages of analysis. Scenarios designed to evaluate the influence of small fragments confirmed their importance in decreasing average isolation across the landscape.

The increase in forest area predicted for the FOPPA scenario was greater when compared to FO2021 (Figure 6), which likely contributed to a decrease in the number of patches (NP) owing to the incorporation of

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new areas and the merging of smaller patches into larger ones. This trend is supported by the increase in the mean patch size (MPS) and patch size standard deviation (PSSD) metrics; the MPS nearly doubled in the FOPPA scenario. These findings suggest that the effects of landscape fragmentation can be reduced under the FOPPA scenario. Similar patterns have been reported by Seganfredo et al. (2019) and Zanella et al. (2012).

The shape indices (MSI and AWMSI) were higher in the FOPPA scenario, likely due to the elongated shapes characteristic of PPAs (Permanent Preservation Areas), which tend to produce less circular fragments. However, these values were not markedly different from those in the FO2021 scenario. This similarity is explained by the recovery of PPAs in the FOPPA scenario, which promotes connectivity between fragments and reduces their overall number without substantially altering their shapes within the landscape.

The average isolation of fragments decreased in the APP restoration scenario. The landscape, previously classified as having medium-high isolation (FO2021) (Santos et al., 2017), now has closer fragments. A decrease in the distance between fragments can enhance species mobility by facilitating the movement of those that previously had difficulty crossing the matrix (Zanella et al., 2012).

Despite the restoration of the PPAs, forest cover in the basin remains low. To prevent species loss and alterations in tropical forest structure, it is crucial to maintain a vegetation cover of at least 30% of the landscape (Bircol et al., 2018). Small forest fragments usually contain plant populations—especially trees—with few individuals per species, which promotes inbreeding and increases the risk of local extinction (Zanella et al., 2012). Nevertheless, these fragments play a crucial role in increasing matrix heterogeneity and serving as refuges for species dependent on specific habitats found only in such areas (Almeida, 2008). Thus, small fragments, particularly those near biodiversity hotspots, can fulfill significant ecological functions. According to Zambrano et al. (2020), implementing management and restoration strategies aimed at the long-term persistence of the remaining forests is vital.

Therefore, Orlandi and Santos (2022) emphasized the importance of developing strategies that enhance connectivity in fragmented landscapes. Restoring connectivity can prevent species extinction, especially for species with limited dispersal abilities or those struggling to survive amid the impacts of fragmentation.

5. CONCLUSION

Although the natural forest areas in the Peruípe River Basin showed a slight increase in the last year of the study, this change was not substantial. The landscape is historically fragmented, with a high degree of isolation among the remnants of natural vegetation.

While most forest fragments in the landscape are small (< 5 ha), management scenarios emphasize their crucial role in reducing average isolation, maintaining essential ecological functions, and facilitating wildlife movement.

Even though the total forest area in the basin has not increased significantly, restoring natural vegetation in Permanent Preservation Areas (PPAs) improves the quality of the landscape. This improvement is reflected in landscape metrics, showing reduced fragmentation, fewer fragments, increased average fragment size, and decreased average distance between fragments, thereby enhancing connectivity. Furthermore, restoring PPAs is essential to ensure compliance with the environmental functions mandated by current legislation.

Effective public management actions and conservation policies are urgently needed to protect the remnants of natural vegetation, given their strategic importance in maintaining ecosystem services and local biodiversity. This is particularly important because they are located within a priority conservation region.

Therefore, future research should focus on assessing the effectiveness of PPA restoration and forest fragment area expansion and examining the role of small fragments in promoting ecological connectivity and enhancing ecosystem resilience in the face of anthropogenic pressures.

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AUTHOR CONTRIBUTIONS

Martins, I. S.: Conceptualization, Data curation, Data analysis, Writing - original draft, Writing - editing; Souza, C. G.: Project administration, Supervision, Methodology, Data and experiment validation, Data analysis, Writing - review and editing; Santos, R. B. S.: Conceptualization, Methodology, Data and experiment validation, Writing – review and editing; Silva, D. P.: Conceptualization, Data analysis, Writing - review and editing.

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