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Forest cover analysis of a highly fragmented basin in northern Espírito Santo State, Brazil

Análise da cobertura florestal de uma bacia altamente fragmentada no norte do estado do Espírito Santo, Brasil

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Abstract

This study aimed to determine and analyze landscape ecology metrics to characterize the spatial pattern of fragments of native forest in São Mateus River basin, Espírito Santo State, Southeastern Brazil. Fragments were divided into four size classes called C1 (<5 ha), C2 (5-25 ha), C3 (25.10-50 ha) and C4 (>50 ha). Metrics were grouped according to their nature in (i) area and density, (ii) edge, (iii) shape, (iv) central area and (v) proximity. In total, 4,286 native forest fragments were identified, which represented 7.80% of total area of the basin. There is a predominance of fragments with more regular shapes, small (<25.10 ha) and, consequently, with greater edge effect. Results showed that the drainage basin studied is highly fragmented, which reinforces the need for strategies aimed at forest conservation and restoration of degraded forests in this region.

Keywords: Landscape ecology; Atlantic Forest; Geoprocessing; Native forest.

Resumo

Este estudo teve como objetivo determinar e analisar métricas de ecologia da paisagem para caracterização do padrão espacial de fragmentos de floresta nativa na bacia hidrográfica do Rio São Mateus, no estado do Espírito Santo, Brasil. Os fragmentos foram divididos em quatro classes de tamanho denominadas como C1 (< 5 ha), C2 (5-25 ha), C3 (25,10-50 ha) e C4 (>50 ha). As métricas foram agrupadas de acordo com sua natureza em (i) área e densidade, (ii) borda, (iii) forma, (iv) área central e (v) proximidade. Foram identificados 4.286 fragmentos de floresta nativa, que representaram 7,80% da área total da bacia. Há predominância de fragmentos com formas mais regulares, pequenos (<25,10 ha) e, consequentemente, com maior efeito de borda. Os resultados demonstraram que a bacia hidrográfica avaliada é altamente fragmentada, o que reforça a necessidade de estratégias voltadas para a conservação e restauração florestal da vegetação nativa dessa região.

Palavras-chave: Ecologia da paisagem; Mata Atlântica; Geoprocessamento; Floresta nativa.

INTRODUCTION

In north of the Espírito Santo State, São Mateus River basin lies within a considerable area of the Brazilian Atlantic Forest. The Atlantic Forest is an ecological hotspot with great global importance for containing different levels of richness, endemism, and species composition (Martini et al., 2007; Rezende et al., 2018). Due to anthropic impacts, especially in the conversion of forests to agricultural and pasture lands, the Atlantic Forest currently has only 12.40% of its original cover (Fundação SOS Mata Atlântica, 2021; Lima et al., 2021). This

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transformation caused several changes in the structure of landscape and its ecological balance, which led to the formation of vegetation fragments (Liu et al., 2019).

Fragmentation process results from deforestation of forests and it is characterized by changing the configuration or arrangement of the forest cover (Hermosilla et al., 2019). Forest loss on a global scale is associated with commodity production, shifting agriculture, forestry, wildfire and urbanization (Curtis et al., 2018). In recent years, these factors have been growing due to the increase in population, food consumption and commercial practices (Slattery & Fenner, 2021). As a result, fragmentation causes complex changes and lasting effects on biodiversity of forest remnants, with loss of species and alteration of the functional diversity of communities (Zambrano et al., 2020).

Landscape ecology can address, among other issues, the importance of composition and spatial configuration of vegetation fragments in the ecological processes (Silva et al., 2021) and plays a key role in integration of different scales of biodiversity (Liu et al., 2019). Several authors used analysis of spatial distribution through the study of landscape ecology using pre-established metrics and geospatial technologies for identification of landscape patterns (Santos et al., 2018; Hermosilla et al., 2019; Yu et al., 2019; Silva et al., 2021).

The use of remote sensing provides reliable and accurate results in analyzes of forest cover (Portillo-Quintero et al., 2012). Geographic Information Systems (GIS) combined with remote sensing can be widely used in landscape ecology to measure forest fragmentation and its change over time (Hermosilla et al., 2019), in addition to assessing the environmental fragility of forest remnants of different phyto-physiognomies (Silva et al., 2021). The assessment of the landscape using these tools allows to diagnose management problems, estimate future influences (Calegari et al., 2010) and to propose the necessary interventions for biodiversity conservation.

Analyzing the structure of forest landscape becomes important for the region of the São Mateus River basin, which is considered one of the basins with low levels of native forest cover and with greater needs for restoration in Espírito Santo (Espírito Santo, 2017). These factors coupled with the lack of studies on this subject make it essential to know the spatial pattern of fragmentation in the region. Therefore, the aim of this study was to determine and analyze landscape ecology metrics for characterization of spatial pattern of fragments of native forest in the São Mateus River basin.

MATERIAL AND METHODS

1.1. Study area

The study was carried out in São Mateus River basin, located in the Espírito Santo State, Southeastern Brazil (Figure 1). In Espírito Santo (ES), the basin belongs to the Northern region of the state and has a drainage area of 8,237 km^2 (Agência Estadual de Recursos Hídricos, 2018). The main tributaries of the basin are Cotaxé and Cricaré Rivers, both originating in Minas Gerais State (MG) and uniting in the municipality of São Mateus (ES) to form the São Mateus River. Its territorial extension covers 11 municipalities (Água Doce do Norte, Barra de São Francisco, Boa Esperança, Conceição da Barra, Ecoporanga, Jaguaré, Mantenópolis, Nova Venécia, Ponto Belo, São Mateus and Vila Pavão) (Agência Estadual de Recursos Hídricos, 2018), with an estimated total population of 375,393 people in 2021 (Instituto Brasileiro de Geografia e Estatística, 2018).

The region where the basin is located is characterized by pasture, monoculture of eucalyptus, sugar cane and fruit growing areas (Agência Estadual de Recursos Hídricos, 2020). Considering water use, the largest consumption demand is from the agriculture sector (93.90%), mainly due to irrigation activity. Other uses of water are public supply (2.90%), livestock (2.50%), industry (0.60%) and aquaculture (0.10%) (Espírito Santo, 2018).

According to the Köppen classification, the climates in the region are tropical monsoon (Am) and tropical with dry winter (Aw). Average temperature and precipitation in the basin municipalities are 23ºC and 1,262 mm, respectively (Alvares et al., 2013). The main types of soil are yellow oxisol, yellow ultisol and red oxisol (Cunha et al., 2016). All municipalities are in a Dense Ombrophilous Forest, part of the Atlantic Forest. Exception occurs on the coastline, where there is a predominance of pioneer formations, with the presence of mangroves and saline fields (Martins & Cavararo, 2012). Topography is characterized by rugged relief in the interior and western sites and plains on the coast (Agência Estadual de Recursos Hídricos, 2018).

Figure 1. Geographical location of the São Mateus River basin, Espírito Santo State, Brazil. Abbreviations for Brazilian states names are: BA = Bahia, ES = Espírito Santo, MG = Minas Gerais, RJ = Rio de Janeiro.

1.2. Landscape ecology analysis

The vegetation cover and land mapping of the Espírito Santo State Institute for Environment and Water Resources (IEMA) was used. This mapping was carried out from photointerpretation of ortho-photo mosaics from the period of 2012-2015, with a spatial resolution of 0.25 m and a precision of 1:10,000 (Espírito Santo, 2015). To create the map of forest fragments, "native forest" class was selected and the fragments were quantified according to their area sizes. So, the fragments were divided into classes called C1 (<5 ha), C2 (5-25 ha), C3 (25.10-50 ha) and C4 (>50 ha).

Landscape ecology metrics were determined with the extension Vector-based Landscape Analysis Tools 2.0 (V-Late 2.0) in ArcGIS® (version 10.8) software. Metric processing was performed as proposed by McGarigal & Marks (1994) (Table 1). Metrics were grouped according to their nature in (i) area and density, (ii) edge, (iii) shape, (iv) central area and (v) proximity.

Table 1. Landscape ecology metrics processed by the extension V-Late 2.0 for fragments of native forest from the São Mateus River basin, Espírito Santo State, Brazil.

Group	Metrics	Acronym (unit)
Area and Density	Class area	CA (ha)
	Mean fragments size	MPS (ha)
	Number of fragments	NP (no unit)
	Fragments size standard deviation	PSSD (ha)
	Fragments size coefficient variation	PSCoV (%)
Edge	Total edge	TE (m)
	Edge density	ED (m ha^{-1})
Shape	Mean shape index	MSI (no dimension)
	Fractal dimension	MFRACT (no dimension)
Central area	Total central area	TCA (ha)
	Number of central areas	NCA (no unit)
	Mean central area	MCA (ha)
	Total central area index	TCAI (%)
	Standard deviation of central area	DPCA (ha)
Proximity	Mean nearest-neighbor distance	MNN (m)

Source: Adapted from McGarigal & Marks (1994).

The calculation of central area was simulated for edge distances of 20, 40, 80, 100 and 140 m to obtain different scenarios. Regarding shape metrics, circle shape was adopted to calculate the mean shape index (MSI), with values closer to 1 indicating more regular shapes (close to circular) (Moser et al., 2002).

RESULTS AND DISCUSSION

The spatial analysis allowed to verify that native forest is present in only 7.80% of the basin's total area and it is distributed in 4,286 fragments (NP) (Figure 2). Fragments of classes C1 and C2 represented 43.20% and 43.50% of the total number, respectively. Fragments of class C4 were observed in small amounts (5.30%), despite occupying 41.10% of the total area of native forest cover (Table 2). The mean fragments size (MPS) and their respective deviations (PSSD) indicated that most of the fragments of classes C2 and C3 have sizes closer to the lower limits of the class (Table 2). Class C4 showed the most variability in fragment size, demonstrated by the value of its proportional variability (PSCoV) (Table 2).

These values showed that the São Mateus River basin has undergone changes over time that made it highly fragmented, with 94.70% of native forest remnants smaller than 50 ha. Our results show a more critical situation than that found by Ribeiro et al. (2009), who identified that the native forest cover throughout the Atlantic Forest was composed of 83.40% of fragments with less than 50 ha. This configuration of forest cover in the basin reflects the intense process of degradation caused by the expansion of the farming activities and logging in recent decades in northern Espírito Santo State (Thomaz, 2010).

The environmental adequacy of rural properties based on Brazilian Native Vegetation Protection Law (Law No. 12,651/2012) is essential for the expansion of forest cover, as it requires the regularization of Permanent Preservation Areas (APP) and Legal Reserves (RL). The law also provides for the establishment of technical support programs and financial incentives, including payment for environmental services (PES) (Brasil, 2012). In Espírito Santo, Reflorestar Program is an important PES initiative of the state government aimed at conservation and restoration of native vegetation in municipalities in the state (Benini et al., 2016). Despite its incentives, Reflorestar Program is not always available across the basin and/or there are bureaucratic procedures that make it difficult to access it (Agência Estadual de Recursos Hídricos, 2020). Based on the results released by Espírito Santo State Secretary for Environment and Water Resources (SEAMA) (Espírito Santo, 2021) and the mapping carried out in this study, Nova Venécia, for example, was the municipality with the highest

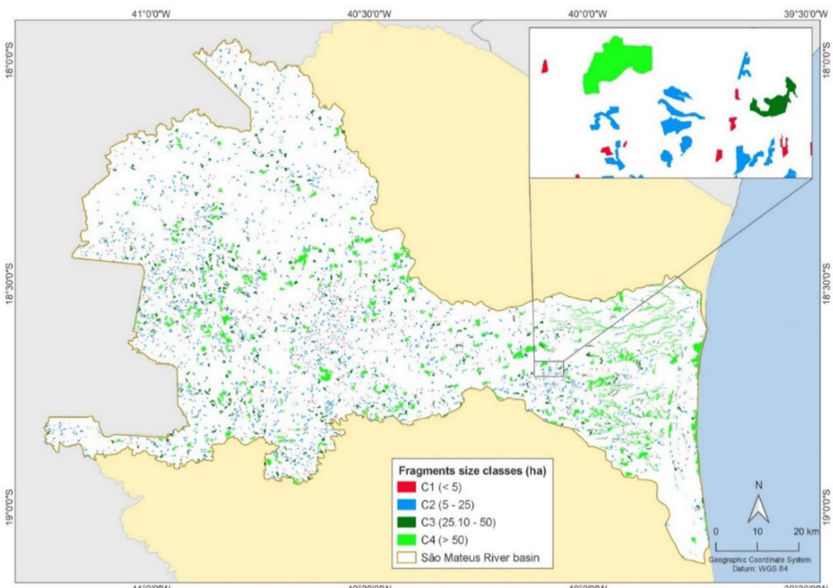

Figure 2. Distribution of native forest fragments considering size classes (in ha) in the São Mateus River basin, Espírito Santo State, Brazil.

participation of producers, but only 2.10% of the municipality's native forest is recognized with PES. In this way, Ramirez-Reyes et al. (2018) reinforces that PES schemes helped to reduce forest fragmentation in Mexico at a regional and national level, with a decrease in the number of forest fragments and edges.

Table 2. Landscape ecology metrics for different size classes of native forest fragments from the São Mateus River basin, Espírito Santo State, Brazil.

Group	Metrics	Size classes (ha)			
		C1 (< 5)	C2 (5 - 25)	C3 (25.10 - 50)	C4 (> 50)
Area and Density	CA (ha)	4,775.24	21,035.17	11,877.21	26,271.65
	MPS (ha)	2.58	11.28	34.63	116.25
	NP (no unit)	1,852	1,865	343	226
	PSSD (ha)	1.28	5.19	6.83	106.99
	PSCoV (%)	49.60	46.00	19.70	92.00
Edge	TE (m)	1,403,493.10	3,709,226.10	1,586,306.70	2,775,796.60
	ED (m ha^{-1})	293.91	176.33	133.56	105.66
Shape	MSI (no dimension)	1.38	1.68	2.22	3.13
	MFRACT (no dimension)	1.32	1.30	1.32	1.33
Proximity	MNN (m)	661.09	576.41	1,562.92	1,477.07

Due to their greater number, fragments of classes C1 and C2 showed higher proximity, expressed by MNN metric, while fragments of classes C3 and C4 showed greater isolation (Table 2). This greater proximity between small fragments is important to provide the formation of functionally interconnected forest mosaics, capable of contributing to regional connectivity (Ribeiro et al., 2009; Diniz et al., 2021), which allows for a greater gene flow between fauna and flora species (Aizen & Feinsinger, 1994). Although the area of a fragment is an important parameter to explain the species richness of fauna (Zungu et al., 2020), smaller fragments increase habitat accessibility for species that could have their persistence threatened by isolation (Diniz et al., 2021). For edge metrics, the fragments of classes C2 and C4 presented the highest TE values, while fragments of classes C1 and C3 presented the lowest values (Table 2). Even with the lowest total edge value, the fragments of class C1 showed a higher edge/area ratio (ED) (Table 2).

ED is important to facilitate a comparison of edge effect in landscapes with different sizes (Gonçalves et al., 2019). The greater number of forest fragments in the smaller size classes (classes C1 and C2) led to higher edge density. It is noteworthy that the high number of fragments with areas between 5 ha and 25 ha determined class C2 as the one with the highest amount of edge (TE) (Table 2). A greater amount of edge provides a high exposure to winds and greater microclimatic differences, which facilitate anthropic interventions and cause several physical and biological impacts (Haddad et al., 2015; Rezende et al., 2018). According to Haddad et al. (2015) more than 40% of forest remnants of the Atlantic Forest present its inner area with less than 100 m from an edge, which can reduce biodiversity in these areas by up to 75% and alter essential ecosystem functions such as decreasing biomass and altering nutrient cycles.

Regarding shape, MSI values were higher with the increase in fragment areas, which indicates that the fragments of classes C3 and C4 presented more irregular shapes as they are less circular (Table 2). Average fractal dimension (MFRACT) presented similar values in all size classes, which demonstrates that the use of this metric was not representative to assess the shape of the fragments in this basin.

Table 3 shows the values of central area metrics (TCA, NCA, MCA, TCAI and DPCA) for different edge distances. Overall, increasing the edge led to a decrease in central area metrics for all classes (Table 3). Fragments of classes C1 and C2 were the ones that showed the greatest reduction in values with increasing edge. The central area is usually conditioned by the size of the fragment; the larger the fragment size, the larger its central area (Silva et al., 2021). However, fragments with the same size may have central areas with significant differences due to irregularity in their shape (Calegari et al., 2010). Even with considerable reduction, fragments of classes C2, C3 and C4 maintained central areas for an edge effect of 140 m. Fragments of the C4 class had the highest values for TCA at all edge distances. On the other hand, the fragments of class C2, which presented the second largest TCA at distances of 20 and 40 m, reduced its edge value considerably at 80 m. In the C1 class as the edge distance increases, the central area values decrease dramatically, reaching the total central area index (TCAI) value of 0.30% at the edge of 80 m. Otherwise, the fragments of class C4 presented TCAI values of 37.90% at the same edge distance of 80 m (Table 3). These results demonstrate that the smaller fragments are totally influenced by the productive matrix.

In addition to impacts on biodiversity, the decrease in forest cover leads to a loss of quantity and quality of water resources (Araujo et al., 2015; Mello et al., 2018) and causes great impacts on the economy and society (Lele et al., 2008). In some places in São Mateus River basin, 17.40% of water availability is already compromised by current demands (Puppin et al., 2019). Furthermore, water availability is expected to worsen in the coming years in this region due to the projected increase in consumption, especially in irrigated agriculture (Puppin et al., 2019). Allied to this worrying water scenario, the spatial pattern of the fragmentation of native forest in São Mateus River basin area reinforces the importance of conservation, expansion, and connection of native forest patches.

Table 3. Landscape ecology metrics for the central area group for different size classes of native forest fragments from the São Mateus River basin, Espírito Santo State, Brazil.

Edge distance (m)	C1 (<5 ha)				
	TCA (ha)	NCA (no unit)	MCA (ha)	TCAI (%)	DPCA (ha)
20	2,338.67	2,089	1.12	48.97	0.88
40	838.75	2,015	0.42	17.56	0.47
80	14.43	1,853	0.01	0.30	0.03
100	0.11	1,852	0	0	0
140	0	0	0	0	0
Edge distance (m)	**C2 (5 - 25 ha)**				
	TCA (ha)	**NCA (no unit)**	**MCA (ha)**	**TCAI (%)**	**DPCA (ha)**
20	14,086.78	2,570	5.48	66.97	4.66
40	8,610.72	2,803	3.07	40.93	3.29
80	2,389.23	2,230	1.07	11.36	1.63
100	1,062.22	2,002	0.53	5.05	1.07
140	147.18	1,876	0.08	0.70	0.33
Edge distance (m)	**C3 (25.10 - 50 ha)**				
	TCA (ha)	**NCA (no unit)**	**MCA (ha)**	**TCAI (%)**	**DPCA (ha)**
20	8,843.72	676	13.08	74.46	12.88
40	6,309.62	771	8.18	53.12	9.42
80	2,901.33	653	4.44	24.43	5.44
100	1,858.63	574	3.24	15.65	4.17
140	654.08	406	1.61	5.51	2.34
Edge distance (m)	**C4 (>50 ha)**				
	TCA (ha)	**NCA (no unit)**	**MCA (ha)**	**TCAI (%)**	**DPCA (ha)**
20	20,881.92	723	28.88	79.48	61.53
40	16,224.35	1,079	15.04	61.76	42.45
80	9,967.36	829	12.02	37.94	33.05
100	7,904.43	665	11.89	30.09	32.35
140	5,036.95	433	11.63	19.17	28.55

CONCLUSIONS

Only 7.80% of the basin area is composed of native forest cover (Atlantic Forest). In total, 4,286 fragments were identified, with a predominance of fragments with more regular shapes, small (<25.10 ha) and, consequently, with greater edge effect. For the region, the central area of fragments smaller than 5 ha are not considered when using edge distance above 100 m. The spatial pattern of native forest distribution in the São Mateus River basin, determined by landscape ecology metrics, has shown that it is highly fragmented, which reinforces the need for actions aimed at forest conservation and restoration of degraded forests in this region.

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