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Native forest cover dynamics in the Guandu River hydrographic basin, Espírito Santo state, Brazil

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Abstract

Objective: We aimed to evaluate the temporal dynamics of the native forest cover in the Guandu River hydrographic basin (GRHB) between the years 1985 and 2020, using landscape ecology metrics.
Methodology: The land cover and land use values from the MapBiomas project in the years 1985 and 2020 were used. The native forest fragments were classified according to their size, as C1 (< 5 ha), C2 (5-25 ha), C3 (25.1-50 ha), and C4 (> 50 ha). Landscape ecology metrics were calculated using the V-Late 2.0 extension in ArcGIS®.
Originality/Relevance: Study of the temporal dynamics of forest cover of hydrographic basins is essential to define strategic forest conservation and restoration actions aimed at protecting water resources.
Results: The native forest cover of the GRHB increased by approximately 12%, with an increase in the number and average area of fragments. In general, the forest remnants became closer to each other and demonstrated a higher edge density. A high number of small fragments (< 5 ha) was verified and the largest fragments (> 50 ha) were the main factor responsible for the expansion of the native forest cover in the basin.
Social/management contributions: Forest restoration actions in the GRHB should prioritize the connectivity of smaller fragments. In addition to supporting forest restoration projects, the results contribute to the application of methodologies to implement water resource management instruments, helping to define practices and policies for sustainable water use.

Keywords: Atlantic Forest, water resources, forest restoration, recovery, landscape ecology.

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DINÂMICA DA COBERTURA FLORESTAL NATIVA NA BACIA HIDROGRÁFICA DO RIO GUANDU, ESPÍRITO SANTO, BRASIL

Resumo

Objetivo: Avaliar a dinâmica temporal da cobertura florestal nativa da bacia hidrográfica do Rio Guandu (GRHB) entre os anos de 1985 e 2020 por meio do uso de métricas de ecologia da paisagem.

Metodologia: Foi utilizado o uso e ocupação do solo do projeto MapBiomas nos anos de 1985 e 2020. Os fragmentos de floresta nativa foram classificados de acordo com seu tamanho em C1 (< 5 ha), C2 (5-25 ha), C3 (25,1-50 ha) e C4 (> 50 ha). O cálculo das métricas de ecologia da paisagem foi realizado a partir da extensão V-Late 2.0 no ArcGIS®.

Originalidade/Relevância: O estudo da dinâmica temporal da cobertura florestal de bacias hidrográficas é primordial na definição de ações estratégicas de conservação e restauração florestal visando a proteção dos recursos hídricos.

Resultados: A cobertura florestal nativa da GRHB aumentou aproximadamente 12%, com acréscimo no número e área média dos fragmentos. No geral, os remanescentes florestais ficaram mais próximos entre si e com maior densidade de borda. Foi verificado elevado número de fragmentos pequenos (< 5 ha) e os maiores fragmentos (> 50 ha) foram os principais responsáveis pela ampliação da cobertura florestal nativa da bacia.

Contribuições sociais/para a gestão: As ações de restauração florestal na GRHB devem priorizar a conectividade de fragmentos menores. Além de apoiar projetos de restauração florestal, os resultados auxiliam na aplicação de metodologias para implementação dos instrumentos de gestão de recursos hídricos, contribuindo para definir práticas e políticas de uso sustentável da água.

Palavras-chave: Mata Atlântica, recursos hídricos, restauração florestal, recuperação, ecologia da paisagem.

DINÁMICA DE LA COBERTURA DE BOSQUES NATIVOS EN LA CUENCA HIDROGRAFICA DEL RÍO GUANDU, ESPÍRITO SANTO, BRASIL

Resumen

Objetivo: Evaluar la dinámica temporal de la cobertura de bosque nativo de la cuenca del río Guandu (GRHB) entre los años 1985 y 2020 mediante métricas de ecología del paisaje.

Metodología: Fueron utilizados los datos de uso y ocupación de suelo de los años 1985 y 2020 del proyecto MapBiomas. Los fragmentos de bosque nativo se clasificaron según su tamaño en C1 (< 5 ha), C2 (5-25 ha), C3 (25,1-50 ha) y C4 (> 50 ha). El cálculo de las métricas de ecología del paisaje se realizó utilizando la extensión V-Late 2.0 en ArcGIS®.

Originalidad/Relevancia: El estudio de la dinámica temporal de la cobertura forestal de las cuencas hidrográficas es fundamental para la definición de acciones estratégicas de conservación y restauración forestal encaminadas a proteger sus recursos hídricos.

Resultados: La cobertura de bosque nativo de GRHB aumentó aproximadamente un 12%, incrementandose en el número y área promedio de fragmentos. En general, los remanentes de bosque se acercaron unos a otros y con mayor densidad de borde. Se verificó un alto número de fragmentos pequeños (< 5 ha) y los fragmentos más grandes (> 50 ha) fueron los principales responsables de la expansión de la cobertura de bosque nativo de la cuenca.

Contribuciones sociales /de gestión: Las acciones de restauración forestal en GRHB deben priorizar la conectividad de fragmentos más pequeños. Además de apoyar proyectos de restauración forestal, los resultados ayudan en la aplicación de metodologías para la implementación de instrumentos de gestión de recursos hídricos, contribuyendo a definir prácticas y políticas para el uso sostenible del agua.

Palabras-clave: Mata Atlántica, recursos hídricos, restauración forestal, recuperación, ecología del paisaje.

Introduction

Access to water in adequate quantity and quality is one of the major challenges of our time (Şenol et al., 2023). According to the World Health Organization (WHO), over 30 million people still lack access to safely managed drinking water services in Brazil (WHO, 2020). In addition to economic and social factors, the climate issue has a significant influence on access to potable water (Pokhrel et al., 2021). Considering the last 60 years, the majority of Brazilian regions experienced the most severe and intense droughts between 2011 and 2019, impacting water supply and economic activities in various areas (Cunha et al., 2019). This issue underscores the importance of studying both anthropogenic and natural factors that affect water availability and quality.

Forests have the capacity to maintain water quality in hydrographic basins and to regulate the flow of springs and watercourses (Mello et al., 2018; Ramião et al., 2020). Forests can potentially increase local precipitation by providing atmospheric moisture through evapotranspiration (Zhang & Wei, 2021). In addition to protecting water resources (Lopes et al., 2020), forests serve functions such as biodiversity maintenance, carbon sequestration, and mitigation of global climate change (Bonan, 2008).

Despite the variety of ecosystem services provided by forests, human activities have intensely degraded forested areas in recent decades, primarily through conversion into agricultural and pasture areas (Gibbs et al., 2010; Maracahipes-Santos et al., 2020). The current scenario of environmental degradation and the close relationship of water resources with vegetation highlight the importance of evaluating forest cover in naturally forested areas within hydrographic basins and the dynamics over time. In this regard, the use of landscape ecology metrics can be employed to assess forest cover and identify spatial patterns (Ponte et al., 2017; McGarigal & Marks, 1995; Mendes et al., 2022; Pirovani et al., 2014; Santos et al., 2018; Yu et al., 2019).

Remote sensing and Geographic Information Systems (GIS) are commonly used in landscape ecology studies (Yu et al., 2019). In addition, in recent years, various tools have been developed for obtaining landscape ecology metrics (Lang & Blaschke, 2009), which can be employed, for example, in quantifying forest cover and fragmentation (Mendes et al., 2022; Yu et al., 2019). Furthermore, landscape ecology is used for studying the delineation of ecological corridors (Santos et al., 2020; Saito et al., 2016; Santos et al., 2018).

The Brazilian National Water Resources Policy (Federal Law 9.433/1997) encompasses norms and principles for water resource management, placing the hydrographic basin as the basic territorial unit for implementing the policy (Brazil, 1997). In the basin space, it is possible to understand more clearly the interrelations of environmental components such as vegetation, soil, climate, and water resources (Almeida, 2012). Characterization of a hydrographic basin can assist in understanding anthropogenic conflicts and the dynamics of ecosystems at the local and regional levels (Almeida, 2012; Teodoro et al., 2007).

Situated in the lower stretch of the Rio Doce basin, the GRHB presents a considerable degree of environmental degradation and unplanned water use, with a high deforestation rate (Consórcio Ecoplan - Lume, 2010), vulnerability to droughts, and intensification of conflicts over water use (Batista Júnior, 2012). According to data from the Brazilian Institute of Geography and Statistics (IBGE), it is estimated that the GRHB is inhabited by around 85 thousand people, mainly engaged in agricultural activities (IBGE, 2021b).

In light of the above, studying the dynamics of forest cover in the GRHB in recent decades is crucial for defining strategic actions for forest conservation and restoration to protect water resources in this region. Thus, the objective of the current study was to assess the temporal dynamics of native forest cover in the GRHB between 1985 and 2020 through the use of landscape ecology metrics.

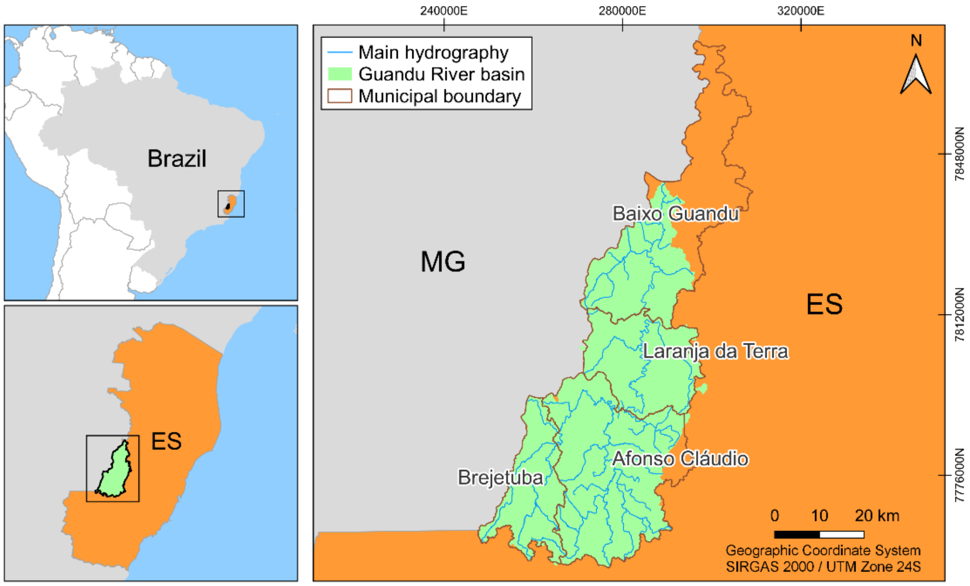
Methodology

Study area

The study was conducted in the GRHB, located in the mountainous central region of the State of Espírito Santo (ES), Brazil. The basin encompasses the municipalities of Afonso Cláudio, Baixo Guandu, Brejetuba, and Laranja da Terra (Figure 1). As part of the hydrographic network of the Rio Doce basin, the Guandu River stretches approximately 160 km from its spring in Afonso Cláudio to its mouth in Baixo Guandu (Batista Júnior, 2012), draining an area of approximately 2,149 km² (IBGE, 2021a).

Figure 1

Location of the Guandu River basin in the state of Espírito Santo, Brazil. ES = Espírito Santo, MG = Minas Gerais



Source: Authors (2023).

The primary land use activity in the GRHB region is farming (Consórcio Ecoplan - Lume, 2010), with a focus on the cultivation of coffee, tomatoes, yams, and bananas, as well as cattle ranching. The Municipal Human Development Index values are 0.656 (Brejetuba and Laranja da Terra), 0.667 (Afonso Cláudio), and 0.702 (Baixo Guandu) (IBGE, 2010).

According to the Köppen classification, the climates in the region are Aw - tropical with dry winter (Baixo Guandu and Laranja da Terra), Cfa - humid subtropical with hot summer (Afonso Cláudio), and Cfb - humid subtropical with temperate summer (Brejetuba). The annual average temperature values in the four municipalities of the basin range from 18.2 to 21.8°C, and the annual average precipitation varies between 1,231 and 1,269 mm (Alvares et al., 2013). The dominant vegetation in the basin is the Atlantic Forest, with a prevalence of Dense Ombrophilous Forest and Seasonal Semideciduous Forest formations (IBGE, 2012).

The topography of the GRHB region is characterized by strongly undulating to mountainous terrain (Consórcio Ecoplan - Lume, 2010), with soils mainly of the Red Argisol, Haplic Cambisol, and Red-Yellow Latosol types according to the Brazilian Soil Classification System (Santos et al., 2018). Regarding hydrogeology, approximately 96% of the basin is situated over fractured aquifer systems in crystalline rocks, while 4% is over granular or porous aquifers (Batista Júnior, 2012).

Landscape Ecology Metrics

Land use and land cover data for the years 1985 and 2020 were obtained from the land cover database of the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas), Collection 6.0. MapBiomas classification utilizes Landsat satellite imagery with a spatial resolution of 30 meters, accessible on the Google Earth Engine platform (MapBiomas, 2021). Vector files provided on the IBGE website (IBGE, 2021a) were employed for basin delimitation.

The land use and land cover classes in the GRHB from MapBiomas were reclassified into Forest (forest formation and savanna formation), Farming (forest plantation, pasture, mosaic of agriculture and pasture, other temporary crops, and coffee), Non-Vegetated Area (urban infrastructure and other non-vegetated areas), Non-Forest Natural Formation (wetland and rocky outcrop), and Water (river, lake, and ocean) (Table 1).

Table 1

Description of land use and land cover classes occurring in the Atlantic Forest biome.

Class	Subclass	Description
Forest	Forest Formation	Dense Ombrophilous Forest, Open Ombrophilous Forest, Mixed Ombrophilous Forest, Semideciduous Seasonal Forest, Deciduous Seasonal Forest, and Pioneer Formation.
	Savanna Formation	Steppe, Forested Savanna, Wooded Savanna.
Farming	Forest Plantation	Tree species planted for commercial purposes, such as eucalyptus and pine.
	Pasture	Pasture area, predominantly planted, linked to livestock production activities. Natural pasture areas are predominantly classified as grassland formation that may or may not be grazed.
	Mosaic of Agriculture and Pasture	Farming areas where it was not possible to distinguish between pasture and agriculture.
	Other Temporary Crops	Areas occupied with short or medium-term agricultural crops, generally with a vegetative cycle of less than one year, which after harvesting need to be planted again to produce.
	Coffee	Areas cultivated with coffee plantation.
Non-vegetated Area	Urban Infrastructure	Urban areas with predominance of non-vegetated surfaces, including roads, highways and constructions.
	Other Non-vegetated Areas	Non-permeable surface areas (infrastructure, urban expansion or mining) not mapped into their classes and regions of exposed soil in natural or crop areas.
Non-Forest Natural Formation	Wetland	Wetlands with fluvial influence.
	Rocky Outcrop	Naturally exposed rocks without soil cover, often with the partial presence of rupicolous vegetation and high slope.
Water	River, Lake, and Ocean	Rivers, lakes, dams, reservoirs, and other water bodies.

Source: MapBiomas (2021)

For the quantification and characterization of forest fragments within the Forest class, landscape ecology metrics were employed. The fragments were categorized based on their size into C1 (< 5 ha), C2 (5-25 ha), C3 (25.1-50 ha), and C4 (> 50 ha). Landscape ecology metric calculations were performed using the Vector-based Landscape Analysis Tools 2.0 (V-Late 2.0) extension (Lang & Tiede, 2003) in ArcGIS® (version 10.8).

The metrics of class area (CA), mean fragment size (MPS), number of fragments (NP), fragment size standard deviation (PSSD), fragment size coefficient variation (PSCoV), edge density (ED), and mean nearest-neighbor distance (MNN) were calculated according to McGarigal & Marks (1995). The metrics were grouped according to their nature into area and density, edge, and proximity (Table 2).

Table 2

Landscape ecology metrics calculated for native forest fragments within the Guandu River hydrographic basin, Espírito Santo, Brazil

Group	Metric	Description
Area and Density	Class area (CA)	The class area (in hectares) is a measure of landscape composition and represents the proportion of the landscape composed of a particular fragment type. It is the sum of all areas belonging to a specific class. This metric is important in various ecological applications, such as the quantitative study of habitat fragmentation.
	Mean fragment size (MPS)	The mean fragment size (in hectares) indicates the average size of fragments within a particular class. The MPS can serve as an index of habitat fragmentation, although with some limitations that may reduce its utility in this regard.
	Number of fragments (NP)	The number of fragments refers to the sum of the fragments belonging to a particular class. The NP of a specific habitat type can influence a variety of ecological processes, depending on the landscape context.
	Fragment size standard deviation (PSSD)	The fragment size standard deviation (in hectares) is a measure of absolute variation. It is a function of the mean fragment size and the differences in size between the fragments. While the PSSD provides information about the variability in fragment size, it is a parameter that can be challenging to interpret without taking into account the mean fragment size.
	Fragment size coefficient variation (PSCoV)	The fragment size coefficient variation (in %) measures relative variability around the mean and not absolute variability. Therefore, it is not necessary to know the mean fragment size to interpret the coefficient of variation. PSCoV is generally better than the standard deviation for comparing variability between landscapes. However, PSCoV can be misleading regarding landscape structure in the absence of information about the number of fragments or fragment density and other structural characteristics.
Edge	Edge density (ED)	The edge density (in m ha^{-1}) comprises the relationship between the total length of the edge and the total area of fragments within a specific class. ED standardizes the edge on a per-unit area basis, facilitating comparisons across landscapes of various sizes. Calculated ED values should not be compared between images with different resolutions, as ED is influenced by resolution.

Proximity	Mean nearest-neighbor distance (MNN)	The mean nearest-neighbor distance (in meters) measures the spatial pattern of the landscape. A higher value indicates a greater distance between fragments of the same type, resulting in a more dispersed distribution. At the class level, MNN can be calculated only if at least two fragments of the corresponding type occur. At the landscape level, the MNN considers only fragments with neighbors.

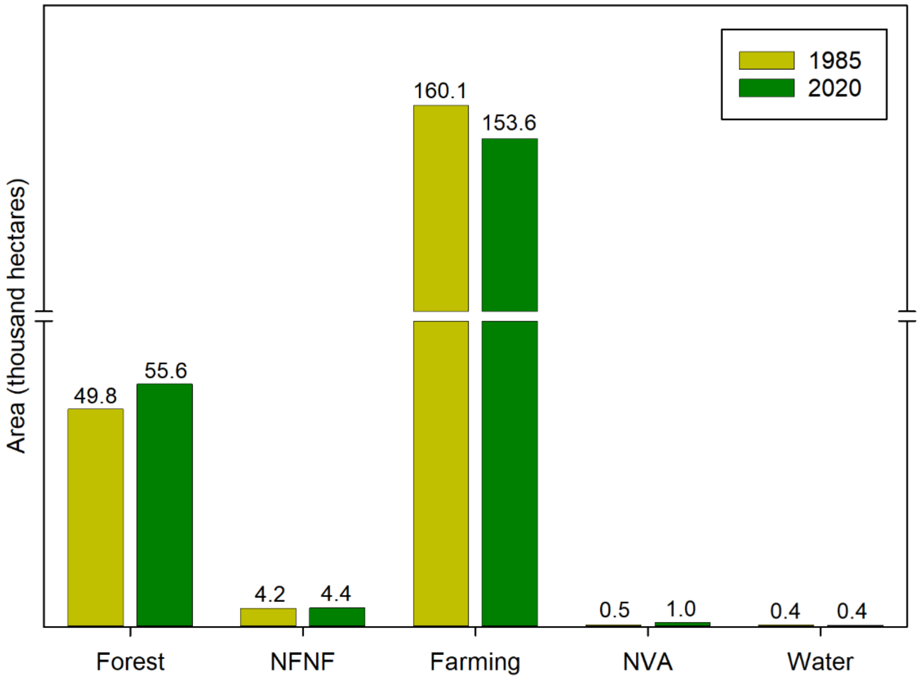
Source: McGarigal & Marks (1995).

Results and discussion

In the GRHB, there was an increase in native forest areas (5,764 ha), non-forest natural formations (153 ha), and non-vegetated areas (549 ha) (Figure 2). Conversely, there was a decrease in areas designated for farming (6,422 ha), and no changes were observed in water bodies. The expansion of native forest areas and non-forest natural formations occurred predominantly in areas previously used for farming activities. The heightened environmental regularization requirements for rural properties with the implementation of Brazilian Federal Law 12,651/2012 (Brazilian Forest Code) (Brazil, 2012) may have contributed to the increase in native vegetation cover in the basin (Klein et al., 2015; Parras et al., 2020). The rise in non-vegetated areas is likely associated with the urbanization and population growth observed in the municipalities of GRHB in recent years (IBGE, 1997, 2010).

Figure 2

Land use and land cover in the Guandu River hydrographic basin for the years 1985 and 2020, Espírito Santo, Brazil. NFNF = Non-Forest Natural Formation, NVA = Non-Vegetated Area



Source: Authors (2023).

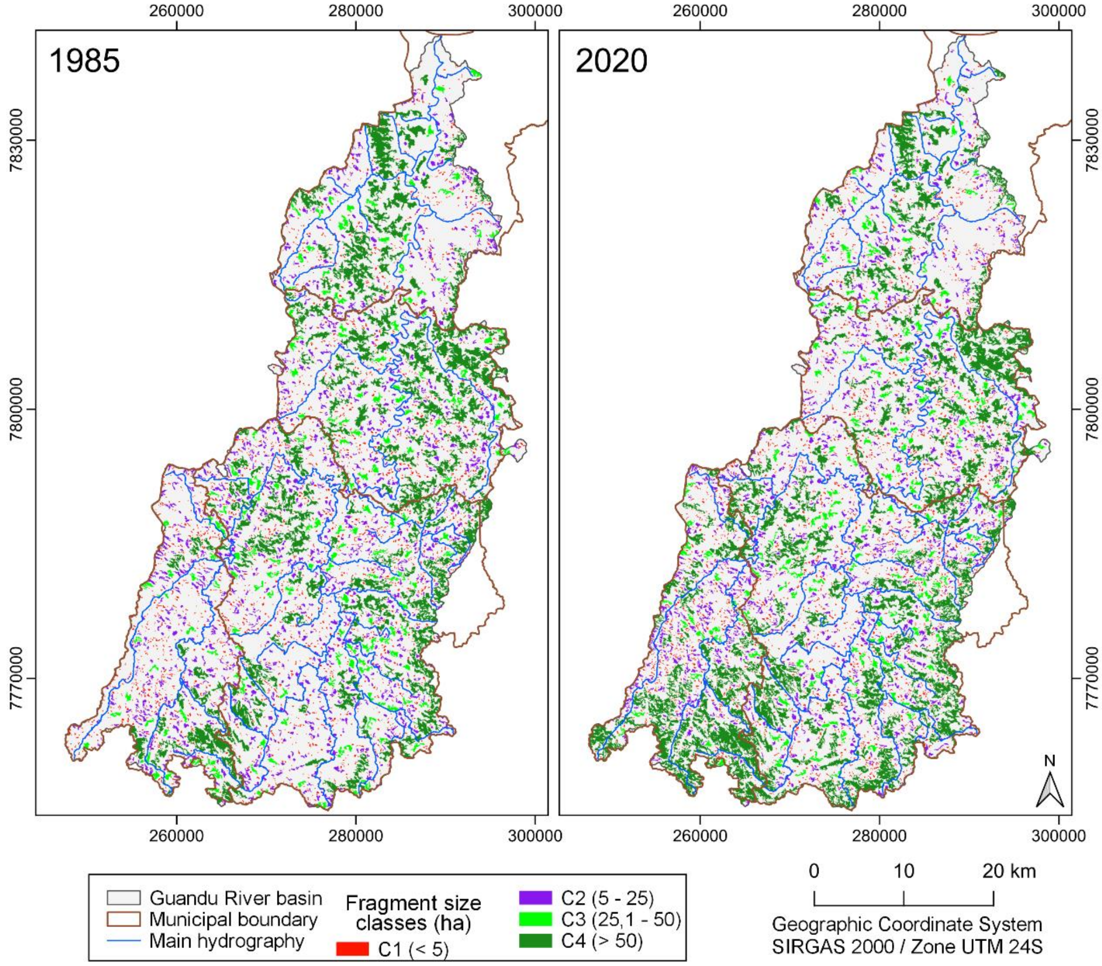
In 2020, areas with native vegetation (Forest and Non-Forest Natural Formations) accounted for approximately 28% of the total area of the basin (Figure 2). According to the Brazilian Forest Code, every rural property in the Atlantic Forest biome is required to maintain at least 20% of native vegetation as a Legal Reserve (Brazil, 2012). However, Permanent Preservation Areas (PPA) should also be taken into account. According to the Consórcio Ecoplan – Lume (2010), in 2006, over 40% of the basin's springs were not protected by forests, and more than 80% of the banks of rivers, streams, lakes, and ponds did not have well-preserved riparian vegetation. In hillside areas, this situation was even worse, especially in the municipalities of Afonso Cláudio and Baixo Guandu, where protection was less than 2%.

The Brazilian Forest Code also envisions the establishment of technical support programs and financial incentives, such as Payment for Environmental Services (PSA) (Brazil, 2012). In Espírito Santo, the Reflorestar Program, initiated in 2012, is a PSA initiative aimed at the recovery and conservation of forest vegetation to ensure water availability and the conservation of soil and biodiversity (Benini et al., 2016). In the municipalities of GRHB, the Reflorestar Program was responsible for compensating producers for the conservation and restoration of over 2.1 thousand hectares from 2015 to 2019 (SEAMA, 2021).

In both years, the spatial analysis of native forest cover demonstrated the predominance of small fragments (< 5 ha), although large fragments (> 50 ha) occupy the majority of the forested area in GRHB (Figure 3 and Table 3). Increases in NP and CA occurred in the C1 and C4 classes, while C2 and C3 experienced a decrease in values over the analyzed years. For MPS, a small decrease in values was observed in C1 and C3, stability in C2, and an increase of over 30 ha in C4. In both 1985 and 2020, PSCoV values showed greater relative variability in fragment areas in C1 and C4.

Figure 3

Native forest fragments in the Guandu River hydrographic basin for the years 1985 and 2020, Espírito Santo, Brazil



Source: Authors (2023).

The total values of NP, CA, and MPS increased between the analyzed years by approximately 7%, 12%, and 4%, respectively (Table 3). The overall increases in CA and MPS are primarily reflective of the growth in these metrics in the C4 class, which has high representation in the total area of native forests. C4 fragments accounted for 55% and 62% of the native forest cover in the basin in 1985 and 2020, respectively. Taken together, the total increases in NP, CA, and MPS suggest a decrease in the degree of fragmentation of the forest landscape in the GRHB between 1985 and 2020.

Table 3

Landscape ecology metrics for native forest fragments in the Guandu River hydrographic basin for the years 1985 and 2020, Espírito Santo, Brazil. CA = Class area, MPS = Mean fragment size, NP = Number of fragments, PSSD = Fragment size standard deviation, PSCoV = Fragment size coefficient variation, ED = Edge density, MNN = Mean nearest-neighbor distance

Year	Group	Metric	Size class (ha)				Total
			C1 (< 5)	C2 (5-25)	C3 (25,1-50)	C4 (> 50)	
1985	**Area and Density**	CA (ha)	5,350.7	10,903.1	6,059.6	27,482.5	49,795.8
		MPS (ha)	1.7	10.9	35.6	151.0	11.1
		NP*	3,142	1,002	170	182	4,496
		PSSD (ha)	1.20	5.21	7.16	159.38	43.75
		PSCoV (%)	70.5	47.9	20.1	105.5	395.0
	Edge	ED (m ha^{-1})	437.0	240.8	177.4	143.4	200.4
	Proximity	MNN (m)	227.8	312.6	1,108.3	364.6	285.5
2020	**Area and Density**	CA (ha)	5,709.5	9,932.3	5,446.5	34,471.0	55,559.3
		MPS (ha)	1.6	10.9	34.0	182.4	11.6
		NP*	3,553	908	160	189	4,810
		PSSD (ha)	1.2	5.2	6.9	256.7	61.9
		PSCoV (%)	73.9	47.7	20.1	140.7	536.0
	Edge	ED (m ha^{-1})	467.9	258.5	198.2	160.8	213.5
	Proximity	MNN (m)	201.7	333.2	941.5	369.2	257.8

* no dimension
Source: Authors (2023).

ED decreased among size classes with the increase in fragment area (Table 3). Between 1985 and 2020, the total ED value increased by approximately 7%, with an increase in all four class sizes. The highest increase in ED occurred in C1, the class with fragments smaller than 5 ha, which also presented the highest number of new fragments in 2020. Higher ED values represent a greater edge effect (McGarigal & Cushman, 2002). The increase in edge effect of forest remnants has negative ecological effects, as it induces modifications in abiotic conditions and facilitates anthropogenic interventions in the fragments (Haddad et al., 2015).

The lowest MNN values in both years were observed in C1, directly related to the higher NP in this class (Table 3). The greatest increase in proximity between fragments during the analyzed period occurred in C3 (approximately 167 m). In contrast, C2 and C4 showed a decrease in fragment proximity, although to a lesser extent. The closer proximity between smaller fragments highlights their importance in connecting larger fragments in the landscape (Moreira et al., 2018). Overall, the average distance between landscape fragments decreased by 27.8 m between 1985 and 2020. This decrease signifies an increase in the proximity of forest remnants in the basin, although they still remain quite distant from each other (MNN > 200 m). Greater proximity between native forest fragments promotes the formation of functionally interconnected mosaics (Diniz et al., 2021). Furthermore, desirable resilience in forest restoration processes is favored when the area to be restored is closer to native vegetation remnants that can provide propagules of different species (Safar et al., 2020).

The coverage of native forest in the GRHB (25.8%) presents a conservation scenario that is supposedly better than in other basins in ES. In the Itapemirim River basin in the southern region of ES, forest coverage was 17% (Pirovani et al., 2014), and in the São Mateus River basin in the northern part of the state, only 7.8% of the basin was composed of native forest (Mendes et al., 2022). The higher level of forest conservation in the GRHB may be associated with anthropogenic and natural factors. The steeper terrain in the GRHB and the Itapemirim River basin, when compared to the São Mateus River basin, for example, helps explain their better forest coverage indices. The rugged topography and difficulty of access generally hinder land-use changes. Topography has been considered not only to explain forest coverage but also the diversity of species in the Atlantic Forest (Freitas et al., 2010).

It is estimated that only 15.3% of the ES territory is covered by remnants of native forest (Santos et al., 2020). Public initiatives such as the "Espírito Santo 2030 Development Plan" are essential for the conservation and expansion of Atlantic Forest coverage in the state. With this plan, the state government aims to increase Atlantic Forest coverage in ES by 8% by 2030 through the efficient implementation of reforestation and spring recovery programs, with emphasis on the Reflorestar Program (Espírito Santo, 2013).

The deficit in native forest coverage in ES is part of a broader context of Atlantic Forest biome degradation, considered a global biodiversity hotspot (Rezende et al., 2018). Faced with a high degree of deforestation, the Atlantic Forest has become one of the most exploited and fragmented Brazilian ecosystems (Araujo et al., 2015). Despite this, forest remnants in degraded landscapes have significant environmental relevance (Garcia et al., 2021; Mesa-Sierra et al., 2022). Highly fragmented tropical regions are important for maintaining landscape functionality and providing essential ecosystem services, such as carbon sequestration (Mesa-Sierra et al., 2022).

Recent studies have emphasized the need to conserve and restore native vegetation in basins with a high percentage of anthropogenic areas, as in the case of the GRHB. The type of land use and occupation around springs and watercourses can reflect indicators of water quality (Fierro et al., 2017; Mello et al., 2018; Ramião et al., 2020; Tolkkinen et al., 2020). Forest cover is the most important land use type for maintaining water quality in lower-order watercourses (Mello et al., 2018). Besides influencing water quality, land use and occupation in riparian areas are essential for reducing nutrient export to downstream ecosystems (Ramião et al., 2020).

On the other hand, there is concern in the scientific community about how forest restoration may interfere with water availability (Filoso et al., 2017; Jones et al., 2022; Zhang & Wei, 2021; Zhao et al., 2020). Models indicate that water availability may also decrease in restored forest areas (Hoek van Dijke et al., 2022). A study conducted in part of a basin with forest restoration in southeastern Brazil demonstrated that streamflow was not altered in the initial years (Ferraz et al., 2021). However, more research is needed on the relationship between forest restoration and water availability in Brazil, especially long-term studies. In this sense, it is also important to note that besides protecting water resources (Lopes et al., 2020), the establishment of forest species provides benefits, such as biodiversity maintenance (Pillay et al., 2022) and carbon removal from the atmosphere (Morais Junior et al., 2020; Milagre et al., 2023).

For the protection of water resources in the GRHB, it is essential to expand forest restoration strategies to accelerate the increase in native vegetation coverage. The choice of native vegetation restoration techniques should also take into account the degree of degradation, the potential for natural regeneration, and the matrix in which the area to be restored is located (Rodrigues et al., 2009), as well as economic and social aspects (Castro et al., 2021; Elias et al., 2022; Fleischman et al., 2022). The selection of native species for forest restoration projects should consider the ecological characteristics of the species (Morais Junior et al., 2020; Giannini et al., 2017; Rodrigues et al., 2009) and their relationship with other ecosystem components, such as soil (Mendes et al., 2021), fauna (Giannini et al., 2017), and water resources (Zhao et al., 2020).

Conclusions

The use of landscape ecology metrics allowed for the quantification of native forest coverage in the GRHB and the assessment of temporal dynamics, facilitating the characterization of forest fragmentation. Between 1985 and 2020, native forest coverage increased by approximately 12%, primarily due to the expansion of the number and area of fragments larger than 50 ha. Despite the enlargement of native forest areas, the high number of small fragments (< 5 ha) underscores the need for conservation and forest restoration efforts in the GRHB.

Forest restoration actions aimed at safeguarding the water resources of the GRHB should prioritize degraded PPA in springs and watercourses, aiming to establish connectivity among fragments of native vegetation, in order to create interconnected mosaics. In addition to providing insights for recovery and forest restoration projects in the GRHB, the findings of this study assist in implementing methodologies for water resource management instruments, contributing to the definition of practices and policies for sustainable water use.

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