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Linkages Between Environmental Attributes and Biotic Integrity in Atlantic Forest Patches

Conexões entre atributos ambientais e integridade biótica em manchas de Mata Atlântica

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ABSTRACT

Anthropogenic pressures are major drivers of environmental degradation and biodiversity loss worldwide, with forest fragmentation representing one of the most pervasive outcomes of human land-use change. Assessing the biotic integrity of forest patches is therefore essential for supporting biodiversity conservation and restoration planning in fragmented landscapes. However, comprehensive evaluations of ecosystem integrity are often costly and time-consuming, even when rapid field-based approaches are employed. In this context, remote sensing (RS) has emerged as a complementary tool for characterizing environmental attributes that may influence forest structure and integrity. This study investigated the relationships between environmental variables derived from RS and field-based indicators of forest structure and integrity obtained through a Rapid Ecological Assessment (REA) approach, expressed as a Biotic Integrity Index (BII). Environmental predictors included the Normalized Difference Vegetation Index (NDVI), obtained from an Unmanned Aerial Vehicle (UAV) survey, altitude, distance to the patch edge, and distance to the hydrographic network. Redundancy Analysis (RDA) was applied to explore multivariate associations between environmental and biotic variables. The results revealed statistically significant but weak relationships between the two data domains, indicating limited explanatory power of the selected environmental predictors. Nonetheless, consistent and ecologically coherent patterns were identified, particularly the positive association between BII and mean NDVI and the influence of edge proximity on disturbance-related indicators. These findings highlight both the potential and the limitations of integrating REA with remotely sensed data, emphasizing the complexity of biotic–environmental interactions in fragmented tropical forests and pointing to the need for incorporating additional landscape-scale variables in future studies.

Keywords: Rapid ecological assessment; ecosystem health; forest structure; fragmented landscape; multivariate analysis.

RESUMO

As pressões antrópicas são importantes vetores da degradação ambiental e da perda de biodiversidade em escala global, e a fragmentação florestal é um dos efeitos mais marcantes das mudanças no uso da terra. A avaliação da integridade biótica de manchas florestais é, portanto, essencial para subsidiar ações de conservação da biodiversidade e o planejamento da restauração ecológica em paisagens fragmentadas. No entanto, avaliações abrangentes da integridade dos ecossistemas são frequentemente custosas e demoradas, mesmo quando metodologias rápidas de campo são empregadas. Nesse contexto, o sensoriamento remoto (SR) tem se consolidado como uma ferramenta complementar para a caracterização de atributos ambientais que podem influenciar a estrutura e a integridade florestais. Este estudo investigou as relações entre variáveis ambientais derivadas do SR e indicadores de estrutura e integridade florestal obtidos em campo por meio de uma abordagem de Análise Ecológica Rápida (AER), expressos por um Índice de Integridade Biótica (IIB). As variáveis ambientais consideradas incluíram o Índice de Vegetação por Diferença Normalizada (NDVI) derivado de levantamento com Aeronave Remotamente Pilotada (ARP), altitude, distância à borda da mancha e à rede hidrográfica. A Análise de Redundância (RDA) foi empregada para explorar as associações multivariadas entre variáveis ambientais e bióticas. Os resultados indicaram relações estatisticamente significativas, porém fracas, entre os dois conjuntos de dados, o que reflete o poder explicativo limitado das variáveis ambientais selecionadas. Ainda assim, padrões ecologicamente consistentes foram identificados, destacando-se a associação positiva entre o IIB e o NDVI médio, bem como a influência da proximidade à borda sobre indicadores relacionados a distúrbios. Esses achados evidenciam tanto o potencial quanto as limitações da integração entre avaliações ecológicas rápidas e dados de sensoriamento remoto, ressaltando a complexidade das interações bióticas e ambientais em florestas tropicais fragmentadas e apontando para a necessidade de incorporar variáveis adicionais em escala de paisagem em estudos futuros.

Palavras-chave: Avaliação ecológica rápida; saúde do ecossistema; estrutura florestal; paisagem fragmentada; análise multivariada.

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Introduction

Anthropogenically induced pressures on natural ecosystems drive environmental degradation and biodiversity loss worldwide (Ferreira et al., 2019; Havlíček et al., 2022; Morales and Valente, 2025), particularly when human-related land uses replace natural vegetation cover (Cabernard et al., 2024; Pickens et al., 2025). Thus, different environments have been experiencing disturbances such as forest fragmentation, habitat and functionality loss, and species richness decline (Ferreira et al., 2019), undermining their capacity to provide essential ecosystem services (ES) for critical areas such as water supply, climate regulation, pollination, biodiversity, and carbon sequestration (Hao et al., 2017; Jones et al., 2019; Gatti et al., 2021; Maeda et al., 2021).

Within this global context of anthropogenic pressure on natural ecosystems, the Atlantic Forest stands out as one of the most diverse and ecologically complex tropical forest domains in the world (Marques and Grelle, 2021). Originally extending along the eastern portion of South America, this biome encompasses a wide range of climatic, topographic, and vegetation gradients and is characterized by exceptionally high levels of species richness and endemism. At the same time, the Atlantic Forest has a long history of human occupation and land-use transformation, which has profoundly shaped its current landscape configuration (Rosa et al., 2021).

As a result of successive economic cycles associated with agriculture, urban expansion, infrastructure development, and industrialization, the Atlantic Forest has experienced extensive habitat loss, structural simplification, and spatial fragmentation (Vancine et al., 2024). Currently recognized as a global biodiversity hotspot under severe anthropogenic pressure (Calaboni et al., 2018), the biome retains only a small fraction of its original forest cover, which is now distributed predominantly in isolated and heterogeneous forest patches embedded within human-modified landscapes (Marques and Grelle, 2021; Dias et al., 2023). This scenario has stimulated increasing scientific interest in understanding the ecological consequences of habitat loss and fragmentation and in developing effective strategies for biodiversity conservation and ecological restoration (Crouzeilles et al., 2019; Martinez Pardo et al., 2023).

Within this broad methodological scope, the use of geotechnologies, particularly RS and Geographic Information Systems (GIS), has become central to the acquisition, integration, and analysis of spatially explicit environmental data. RS-based approaches have been extensively used to characterize vegetation structure and condition, support forest inventories and biomass estimation, map land use and land cover (LULC) dynamics, and derive spectral indices related to vegetation vigor and disturbance (Lussem et al., 2019; Marcial-Pablo et al., 2019; Mohan et al., 2021; Ecke et al., 2022). When integrated within GIS environments, these data allow multi-scale analyses that link local ecological information to broader landscape patterns, thereby strengthening decision-making processes in conservation, restoration, and land-use planning.

In tropical forests, components such as the remaining forest patches are frequently evaluated in studies focused on landscape structure and ecological functioning (Arroyo-Rodríguez et al., 2023), addressing aspects such as their structural attributes (Magnago et al., 2015; Pires et al., 2016; Guedes et al., 2020; Dias et al., 2023), functionality (Riva and Fahrig, 2022; Martinez Pardo et al., 2023; Repullés and Galán-Acedo, 2025), and species composition (Magnago et al., 2014; Wagner et al., 2020; Mangueira et al., 2021).

Understanding the biotic integrity of forest patches is essential for revealing the contribution of these communities to conservation and identifying the ecological filters that interfere with their successional trajectories. Likewise, understanding the environmental characteristics that affect the structure of these ecosystems can increase the effectiveness of ecological restoration and genetic enrichment efforts.

Assessing the environmental integrity of ecosystems is a challenging task that requires significant human and financial resources (Graciano-Silva et al., 2018). However, in many situations, there is insufficient time for long-term scientific inventories to implement ecological conservation and restoration projects (Medeiros and Torezan, 2013). Rapid assessment methodologies are practical frameworks used by conservationists and managers to define conservation strategies based on indicators observable in the field. Rapid Ecological Assessment (REA) methodologies, for instance, consist of flexible surveys that are accelerated and directed toward indicator species and vegetation types (Medeiros and Torezan, 2013).

This practical approach allows for more efficient and timely conservation efforts. In addition, approaches that use RS data help to characterize these environments, given their strong capacity to provide information about the territory. As highlighted by Singh and Frazier (2018), RS data at its different resolutions (i.e., spatial, spectral, radiometric, and temporal) has provided valuable information for a wide range of landscape features such as relief (Arabameri et al., 2020), hydrography (Guidolini et al., 2020; Morales and Valente, 2023), land-use and land cover (Souza et al., 2020), spectral indices for vegetation analysis (Marcial-Pablo et al., 2019; Ecke et al., 2022) and climate data (Cavalcante et al., 2020; Andrade et al., 2024), including time-series analysis to monitor phenomena that occur on a spatial and temporal scale (Laipelt et al., 2021; Dias et al., 2023; Diksha et al., 2023).

As Kurtz et al. (2018) highlighted, using high-resolution RS images for habitat mapping can significantly assist conservationists in monitoring endangered species, particularly those in inaccessible or dangerous regions. The recent increase in Unmanned Aerial Vehicle (UAV) use has enabled the acquisition of high-resolution images for environmental monitoring without the temporal limitations imposed by orbital platforms. UAVs also allow for different combinations of sensors and spectral bands, enhancing the effectiveness of environmental monitoring (Albuquerque et al., 2022).

In this context, we propose an integrated analysis that links site-specific biotic integrity data obtained using the REA approach with high-resolution RS data from aerial photogrammetric UAV surveys in the evaluated forest patches, and with mappings derived from RS orbital imagery produced at the landscape scale for the characterization of the relief and hydrography. Thus, we used a multivariate approach with Redundancy Analysis (RDA) to assess whether environmental variables (i.e., obtained from RS) correlate with the biotic integrity of forest patches (i.e., obtained from REA surveys).

Material and methods

The methodological procedure employed RDA as a multivariate approach to identify relationships between explanatory environmental variables derived from aerial and orbital remote sensing images and biotic response variables reflecting the structure and composition of the evaluated forest patches.

We conducted a field survey campaign to assess the biotic integrity status of forest patches and to proceed with the photogrammetric survey. Sample plots (n = 24) were demarcated within the 10 examined forest patches and several vegetation and forest structure attributes were evaluated to obtain the BII (Graciano-Silva et al., 2018) of each plot.

The plots had the geographic coordinates of their vertices determined using Global Navigation Satellite System (GNSS) receivers, enabling subsequent spatialization and integration with remote sensing data. Below, we detail our study area and the procedure used to obtain the BII (i.e., biotic response variables), the explanatory remote sensing environmental variables, and the RDA.

Study area

We assessed ten forest patches in the third-order watershed called *'Godinhos'* (see Figure 1), part of the Sarapuí River Basin. The *Godinhos* watershed is an agricultural area where small farms primarily cultivate horticultural crops such as onions, pumpkins, cucumbers, and strawberries, as well as hardwood (Mello et al., 2018).

This landscape is representative of a significant portion of the Sarapuí River basin, where human activities, mainly agricultural and urban expansion, pose constant threats to forested areas. Initially covered by Atlantic Forest, predominantly Dense Ombrophylous Forest (IBGE, 2012), the basin is now characterized by a diverse land-

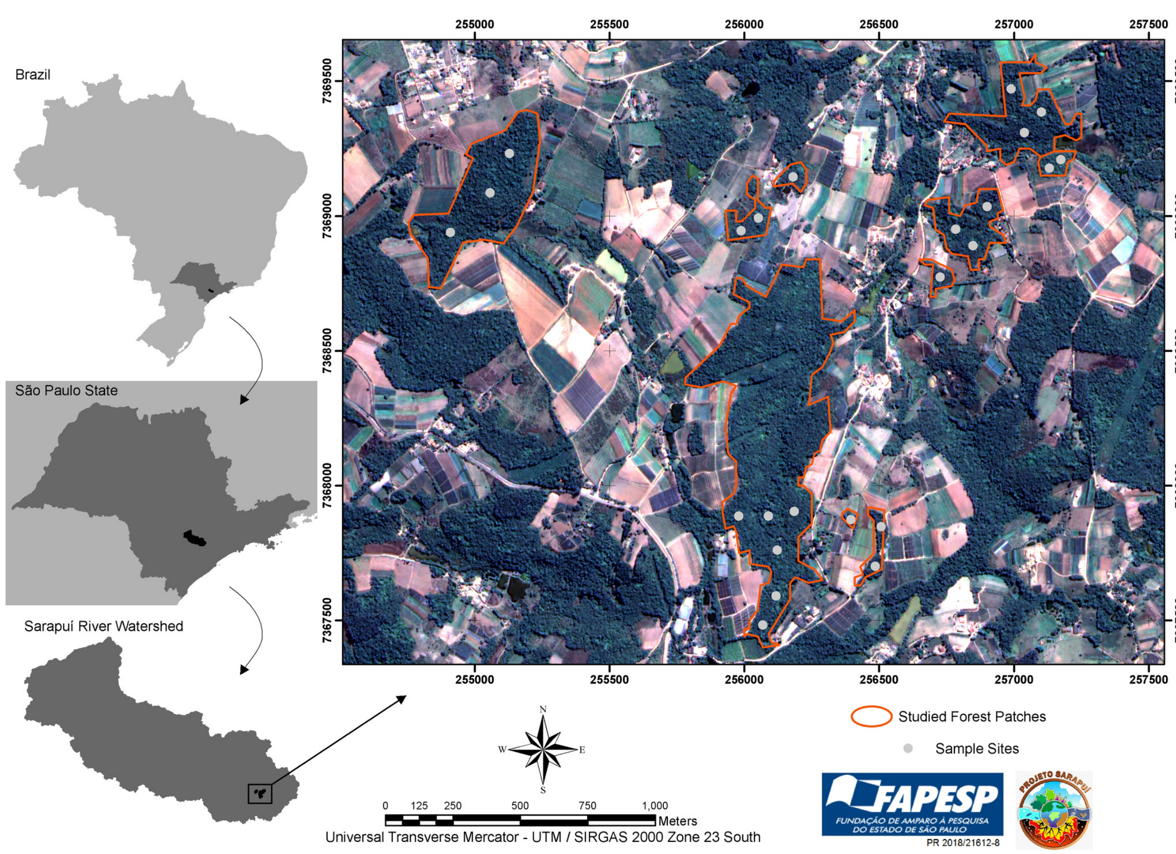

Figure 1 – Forest patch location and sample plots used in the study in the Sarapuí River basin, SP, Brazil.

scape including agriculture, pasture, forestry, urban sites, and highly fragmented native vegetation (Valente et al., 2023).

Biotic response variables

To assess the biological attributes of the evaluated plots, we applied the REA method proposed by Medeiros and Torezan (2013), which provides the BII for each sampling plot. The BII is an index based on an integrity scale derived from the evaluation of 12 biotic indicators (Table 1), which are easily detectable in the field and reflect vegetation structures, regeneration, and disturbance signals. The method was specifically designed to be simple, flexible, and applicable across different forest contexts, and has been successfully used to evaluate the conservation status of forest patches in diverse Brazilian landscapes (Medeiros and Torezan, 2013; Graciano-Silva et al., 2018).

The biotic indicators included in the BII encompass attributes associated with both ecosystem integrity and disturbance processes. Indicators such as litter cover, vascular epiphytes, orchids, palm trees, tree ferns, and late-successional canopy and understory species are primarily associated with structural complexity, regeneration capacity, and successional advancement, and therefore reflect positive aspects of biotic integrity. In contrast, indicators such as the presence of exotic grasses, exotic woody species, tangled lianas and vines, forest gaps, and dead trees are commonly associated with disturbance intensity and edge-related processes, particularly in fragmented forest patches. This dual composition allows the BII to integrate signals of conservation status and anthropogenic pressure within a single synthetic index.

Thus, the BII integrates the individual scores assigned to each biotic indicator into a single composite value for each sampling plot. This composite score is interpreted using a standardized integrity classification scale (Table 2), which assigns plots to five integrity classes based on predefined score intervals (Graciano-Silva et al., 2018).

Table 1 – Indicators that composed the Biotic Integrity Index in Dense Ombrophylous Forest.

Indicator	Integrity Scale				
	1	2	3	4	5
Litter (coverage)	Absent/Exposed Soil	25%	50%	75%	100%
Dead trees[1]	> 3	3	2	1	Absent
Exotic grasses (coverage)	> 50%	25-50%	Up to 25%	Up to 10%	Absent
Exotic wood species[2]	> 3	3	2	1	Absent
Lianas and vines	> 3 tangled (thin)	2 tangled (thin)	Absent or 1 tangled (thin)	Thick (up to 4cm diam.)	Woody (above 4cm) diam.)
Forest gaps	> 50%	25-50%	Up to 25%	Up to 10%	Absent
Vascular epiphytes[1]	Absent	1	2-4	5-9	>10
Orchids[1]	Absent	1	2	3	>3
Palm trees[1,5]	Absent	Only regenerants	1 adult individual	2 Adult individuals	>2 Adult individuals
Tree ferns	Absent	1	2	3	4 or more
Late and/or threatened canopy species[2,3]	Absent	1	2	3	4 or more
Late and/or threatened understory species[2,4]	Absent	1	2	3	4 or more

[1]Consider the number of individuals; [2]Consider the number of species; [3]Consider *Cariniana estrellensis* (Jequitibá), *Cedrela fissilis* Vell. (Cedro), *Copaifera langsdorffii* Desf. (Copaíba); *Aspidosperma polyneuron* Müll.Arg. (Peroba-rosa); [4]Consider individuals in the *Rubiaceae, Myrtaceae,* and *Meliaceae* families; [5]Consider *Euterpe edulis* (Palmeira Jussara). Source: Medeiros and Torezan (2013); Graciano-Silva et al. (2018).

Table 2 – Scores and their respective classifications according to the Biotic Integrity index.

Score	BII Classification
50 – 55	Very high
40 – 49.9	High
30 – 39.9	Regular
20 – 29.9	Low
11 – 19.9	Very Low

A field sampling campaign for BII assessment was conducted within forest patches selected to represent the range of patch conditions present in the local landscape, including variation in size, shape, and conservation status. Within each forest patch, the locations of sampling plots were determined primarily by field accessibility, given the study area's rugged, mountainous topography, which imposes substantial logistical constraints on movement and plot establishment. Whenever feasible, sampling plots were positioned as far as possible from patch edges in order to minimize direct edge effects.

Sampling was carried out using rectangular plots of 100 m² (5 × 20 m). Within each plot, all arboreal individuals with a circumference at breast height (CBH) ≥ 15 cm were recorded. Tree species were identified in the field whenever possible; when field identification was uncertain, botanical material was collected for subsequent laboratory identification, following standard taxonomic procedures. In addition to the biotic indicators that compose the index (Table 1), the CBH and height were also sampled for the individual trees.

In addition, the geographic coordinates of plot vertices and centroids were recorded using a GNSS receiver, thereby supporting both UAV flight planning and the accurate spatial representation of sampling plots in the cartographic materials.

Remote sensing explanatory variables

In this study, a set of environmental variables derived from remote sensing was selected to represent site and landscape characteristics potentially associated with biotic integrity at the plot scale. These variables included the Normalized Difference Vegetation Index (NDVI), obtained through a UAV survey and mapping, terrain attributes (altitude and slope), proximity to forest patch edges, and distance to the hydrographic network. The selection of these variables was based on their documented influence on vegetation structure, microclimatic conditions, regeneration processes, and species persistence in human-modified tropical landscapes, as well as on their frequent use as proxies for environmental constraints affecting biotic integrity (Magnago et al., 2015; Şekercioğlu et al., 2015; Borda-Niño et al., 2020; Yan et al., 2025).

Within this framework, environmental variables derived from RS were used to explore landscape and forest patch characteristics related to biotic integrity and its indicators. This study evaluated variables, including NDVI, across four fractions (minimum, average, maximum, and standard deviation) per plot. This index indicates vegetation vigor as it represents the photosynthetically active area (Dutra et al., 2020; Santos et al., 2021) and is often used to classify native vegetation (Quesada et al., 2017; Käfer and Rex, 2019) and estimate habitat quality (Silveira et al., 2017; Vanderley-Silva and Valente, 2023).

In addition to vegetation-related metrics, the study assessed terrain variables, including altitude and slope. These metrics are commonly associated with a greater presence of native vegetation in human-altered landscapes (Borda-Niño et al., 2020), greater natural regeneration rates (Precinoto et al., 2022), and a greater propensity for land abandonment (Sloan et al., 2016; Calaboni et al., 2018).

To account for spatial position within forest patches, the influence of the plot's location in relation to the forest area in which it is embedded was also evaluated to assess the potential occurrence of edge effects on plot-level biotic integrity. Edge effects are well documented in the literature (Magnago et al., 2015; Precinoto et al., 2022; Harper et al., 2023). Forest patches commonly experience edge-related disturbances, including biodiversity and functional losses (Precinoto et al., 2022), increased susceptibility to wind exposure, reduced humidity, increased luminosity and temperature, and pronounced microclimatic contrasts between patch edges and core areas (Magnago et al., 2015).

Finally, the spatial relationship between sampling plots and the regional hydrographic network was considered, given the potential influence of water availability and riparian environments on biotic integrity. Proximity to drainage networks was evaluated based on the assumption that water resources can increase organism survival rates (Borda-Niño et al., 2020) and that hydrographic corridors may act as dispersal pathways for a wide range of species (Şekercioğlu et al., 2015), thereby favoring the maintenance of biodiversity and biotic integrity.

For the NDVI, data were acquired via aerial surveys of the study sites using a UAV platform equipped with a camera adapted to capture the red, green, and near-infrared bands (660, 550, and 850 nm, respectively). The UAV platform was the Mavic 2 PRO multi-rotor, equipped with a MAPIR Survey 3W camera.

The flights were conducted at 120 meters of altitude from the take-off point, enabling a spatial resolution of six centimeters per pixel. Flight lines were planned to achieve a longitudinal overlap of 75% and a lateral overlap of 70%. The images were initially obtained in RAW format (12-bit) and converted to TIFF format using the sensor-processing software MAPIR Camera Control (MCC). This conversion was essential to differentiate the three bands of the electromagnetic spectrum captured by the sensor and to enhance the radiometric resolution from 12 to 16 bits.

Subsequently, the images underwent radiometric calibration based on images obtained from the sensor calibration target before each flight. This calibration was performed using linear regression equations relating the digital numbers (DN) in the calibration target images to their corresponding reflectance values (Gomes et al., 2021).

Georeferenced ortho-mosaics were generated for each band based on the calibrated images from each survey using *Agisoft Metashape Professional* software version *1.5.0*. This ortho-mosaic creation process entailed image alignment and the generation of a dense point cloud, a digital elevation model (DEM), and the georeferenced ortho-mosaic itself (Gomes et al., 2021).

The NDVI was calculated following the formulation originally proposed by Rouse et al. (1973), which relates reflectance values in the near-infrared (NIR) and red spectral bands (Equation 1).

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad (1)$$

NDVI values theoretically range from −1 to +1, where positive values are commonly associated with vegetated surfaces, while values close to zero or negative typically correspond to non-vegetated features such as bare soil, water bodies, or artificial surfaces. This spectral behavior is explained by the interaction between electromagnetic radiation and plant tissues, where chlorophyll strongly absorbs radiation in the red region for photosynthesis, while the internal structure of leaves promotes high reflectance in the near-infrared region due to multiple scattering processes within the mesophyll (Rouse et al., 1973; Tucker, 1979; Yan et al., 2025).

Based on this spectral behavior, NDVI was used in our framework as a relative indicator of the presence and condition of native vegetation in the plots, in accordance with its use in the literature for analyses and characterizations of native forest cover (Käfer and Rex, 2019; Dutra et al., 2020; Vanderley-Silva and Valente, 2023).

Environmental variables representing terrain topography (altitude and slope) and the distance to the drainage network were derived from morphometric analyses of the Sarapuí River basin conducted by Morales and Valente (2023).

These analyses are based on DEM data from the Advanced Land Observing Satellite (ALOS) satellite, equipped with the Phased Array L-Band Synthetic Aperture Radar (PALSAR) sensor, provided by the Alaska Satellite Facility (ASF) with a spatial resolution of 12.5 meters. The average values of plot pixels were considered for each of these variables.

Lastly, the variable linking plot location to distance from the patch edge was obtained by measuring the distance between the centroid of the sample plot and the fragment edge, as determined by digitizing Sentinel-2A satellite images freely available from the European Space Agency (ESA). These images have a 10 meters spatial resolution.

Multivariate analysis of environmental and biotic parameters

The data were organized into two tables, one referring to environmental data (remote sensing) and the other referring to biological data (BII). The environmental data considered for each plot were (1) Minimum NDVI value, (2) Average NDVI value, (3) Maximum NDVI value, (4) NDVI Standard Deviation, (5) Altitude, (6) Slope, (7) Distance from the plot to the fragment edge, and (8) Distance from the plot to the drainage network. The biological data considered for each plot were the 12 indicators used in the BII and their respective sum.

Subsequently, these two groups of variables were analyzed using RDA, a multivariate method that combines linear regression and principal component analysis (PCA) for the joint analysis of two distinct groups of characteristics (Borcard et al., 2011).

To assess multicollinearity among the explanatory variables and thus eliminate redundant characteristics, the Variance Inflation Factor (VIF) was calculated, as described by Gómez et al. (2016), and the criterion of eliminating the environmental characteristic with VIF > 4 was adopted. Afterward, the model underwent a sensitivity analysis, where each variable was individually removed, and the resulting p-value, R^2, and adjusted R^2 for each model were analyzed. This process is crucial for refining the explanatory model and selecting the relevant variables.

All analyses were performed using R version 4.2.1 (R Core Team, 2024) and the VEGAN Community Ecology Package (Oksanen et al., 2016), with the environmental variables standardized and the biotic variables log-transformed.

Results and discussion

The results of the REA campaigns indicate that none of the 24 sampled plots exhibited BII values classified as either very high or very low. Most plots were classified within the high and regular BII classes, accounting for 12 and 11 plots, respectively. Only one plot deviated from this general pattern, with a BII value of 28, placing it within the low biotic integrity class.

Table 3 summarizes the field-based indicator scores used to derive the BII values, as well as the average tree DBH and height for each plot. The mean BII across all plots was 32.20, a value comparable to those reported by Medeiros and Torezan (2013) and Graciano-Silva et al. (2018) in REA studies conducted in Atlantic Forest landscapes dominated by Semi-deciduous Seasonal Forest and Dense Ombrophylous Forest, respectively.

Similarly, our results suggest that forest patches embedded in agricultural landscapes may still retain moderate to relatively high levels of biotic integrity, despite long-term and increasing anthropogenic pressure. This pattern reflects the capacity of remnant forest patches to maintain some structural and functional attributes even under persistent matrix influence, although such integrity is often threatened and spatially heterogeneous.

Figure 2 illustrates the spatial distribution of the sampled plots and their respective BII class assignments across the study area. Although landscape metrics were not explicitly quantified in this study, a visual inspection of the spatial arrangement of plots suggests that variation in biotic integrity may be influenced by patch size, shape, and proximity to edges. In particular, plots located within larger and more spatially compact forest patches tend to be associated with higher BII values, whereas plots situated in smaller or more elongated patches, or closer to patch boundaries, more frequently fall within the regular or low integrity classes.

All plots located within the smallest forest patches (plots 1–3, 10, 12–14, and 24) were classified as having regular biotic integrity. Notably, plot 10, classified as high integrity within this group, presented a BII score of 40 (Table 3), which is close to the lower threshold of the high integrity class (Table 2). This pattern reinforces the idea that a small patch area may limit the capacity to sustain structurally complex and diverse forest communities, as reduced habitat availability and increased exposure to external disturbances can constrain species persistence and regeneration processes in fragmented landscapes (Hending et al., 2023).

In contrast, plots located within bigger and more compact patches, such as those encompassing plots 18–23, consistently exhibited high BII values. Compact patch configurations are commonly associated with a lower edge-to-area ratio, which may reduce the penetration of edge-related disturbances and help maintain internal for-

Table 3 – Scores obtained for each BII indicator and their respective summed values, for each plot evaluated.

Plot	LIT	DTR	EXG	EXW	LIA	GAP	EPF	TRF	EUT	LSC	LSU	DBH	HEI	BII
1	5	1	5	4	3	3	3	1	1	1	3	2.69	10.57	35
2	5	3	4	4	1	3	2	1	1	1	3	2.54	12.29	33
3	3	2	5	4	4	3	2	1	5	1	3	2.92	12.78	38
4	4	3	4	5	5	3	4	5	3	3	3	3.69	15.33	48
5	5	2	5	5	5	3	3	1	3	3	5	3.54	17.29	46
6	5	2	5	5	5	3	2	1	1	1	5	3.08	11.24	40
7	5	1	5	5	5	3	2	1	1	1	5	3.00	11.02	39
8	5	3	5	4	4	3	1	1	2	2	5	3.08	13.24	40
9	5	3	4	4	3	3	2	1	1	1	3	2.69	12.77	35
10	5	1	4	4	5	3	1	1	1	2	5	3.08	24.77	40
11	5	1	5	5	1	3	1	1	1	1	3	2.46	12.19	32
12	5	1	4	4	4	3	1	1	1	1	4	2.62	14.25	34
13	5	1	5	5	4	3	2	1	1	1	5	2.92	12.28	38
14	5	2	4	4	4	3	2	1	2	1	4	2.85	10.22	37
15	5	1	5	5	4	3	3	1	2	3	4	3.15	10.03	41
16	5	1	5	5	4	4	2	1	1	1	5	3.00	11.89	39
17	4	1	3	3	4	3	1	1	1	1	1	2.15	12.95	28
18	5	5	5	4	4	3	1	1	4	2	5	3.38	13.27	44
19	5	5	5	4	5	3	3	1	1	1	5	3.38	15.23	44
20	5	2	5	4	4	3	5	1	1	1	3	3.08	10.85	40
21	5	4	5	4	4	3	5	1	1	2	5	3.46	16.28	45
22	5	1	5	5	4	3	5	1	1	1	5	3.15	10.27	41
23	5	5	5	5	4	3	5	1	1	2	5	3.54	11.81	46
24	5	1	5	5	3	3	2	1	1	1	5	2.92	18.26	38

Where: LIT = litter / DTR = dead trees / EXG = exotic grasses / EXW = exotic wood species / LIA = lianas and vines / GAP = forest gaps / EPF = vascular epiphytes / TRF = tree ferns / EUT = *Euterpe edulis* / LSC = late canopy species / LSU = late understory species / DBH = average diameter at breast height / HEI = average tree height

est conditions, even in landscapes dominated by agricultural matrices (Sun et al., 2025).

An illustrative example of potential edge effects is observed within the largest forest patch analyzed. Plots 7 and 9, located closer to patch edges, exhibited lower BII classifications compared to other plots within the same patch, which were positioned farther from edges and consistently classified as high integrity. This spatial contrast visually highlights how edge influence may affect local biotic integrity, reinforcing the well-documented role of edge effects in altering vegetation structure, species composition, and ecological processes in fragmented forest landscapes (Ma et al., 2023).

To complement the spatial patterns of biotic integrity described above and to better contextualize the environmental conditions associated with each plot, Table 4 presents the results for the environmental variables derived from remote sensing data.

NDVI values derived from the sampled plots provide a spectral representation of vegetation conditions by contrasting near-infrared (NIR) and red reflectance. This index serves as a widely accepted proxy for vegetation presence and condition. Its theoretical foundation is based on the interaction between electromagnetic radiation and plant tissues, where chlorophyll strongly absorbs radiation in the red region, while the internal leaf structure promotes high reflectance in the near-infrared region due to multiple scattering processes within the mesophyll (Rouse et al., 1973; Tucker, 1979; Yan et al., 2025).

The NDVI values presented in Table 4 reveal significant contrasts among the sampled plots, particularly in minimum values, which ranged from −0.98 to 0.07 (Table 4). Negative or near-zero NDVI values indicate surfaces with minimal or no photosynthetically active vegetation within portions of the plots. Such values are commonly associated with non-photosynthetic elements, including dead vegetation, woody components, exposed soil, and shaded areas, which contribute weak or negative responses in the near-infrared relative to the red band (Käfer and Rex, 2019; Dutra et al., 2020).

In forest patches affected by structural discontinuities, such as canopy gaps or edge-influenced environments, the proportion of shaded pixels and non-photosynthetic plant parts tends to increase, re-

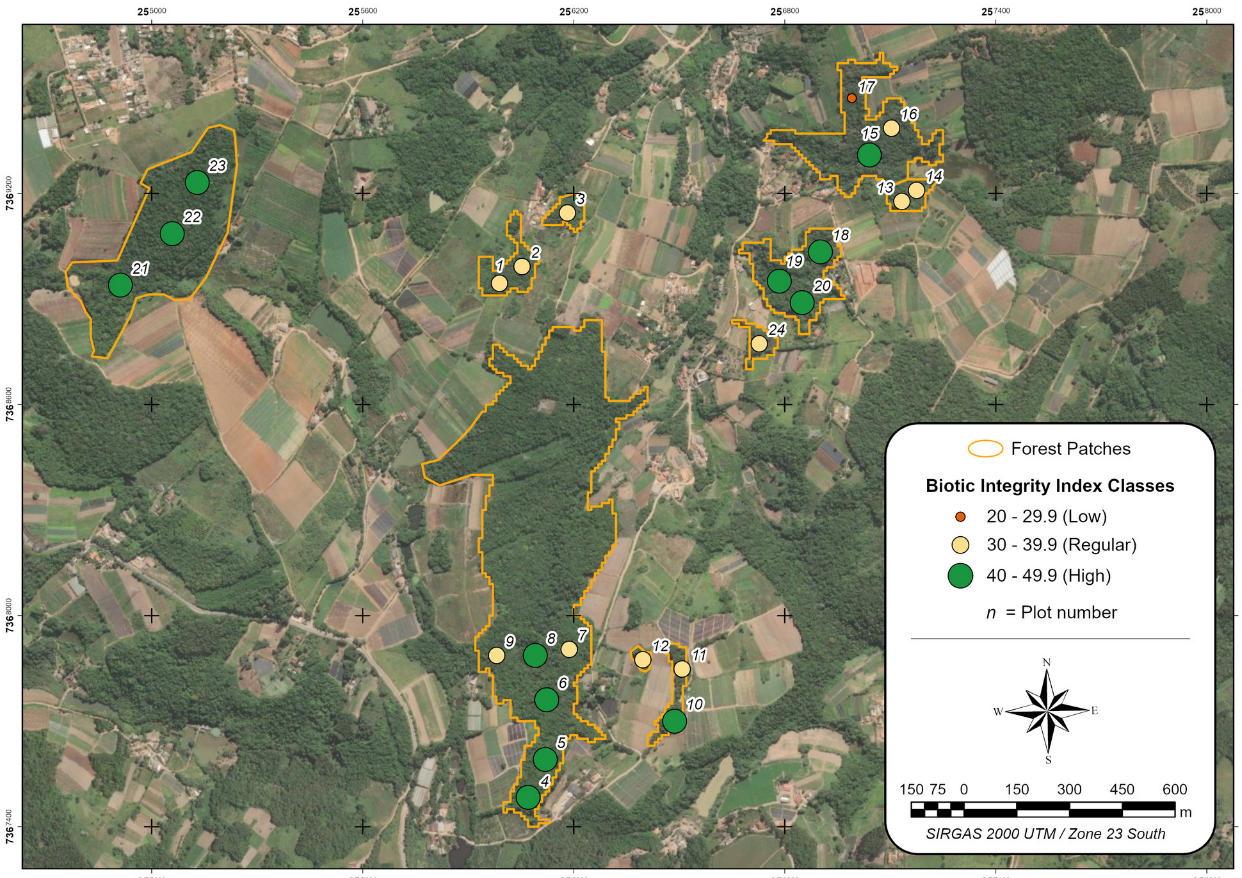

Figure 2 – Location of sampling plots and forest patches in the study area, with plots classified according to BII classes, Sarapuí River basin, Brazil.

Table 4 – Results obtained for the environmental characteristics in the analyzed plots.

Plot	NDVI (min)	NDVI (mean)	NDVI (max)	NDVI (SD)	Altitude (m)	Slope (%)	Distance to edge (m)	Distance to the hydrographic network (m)
1	-0.2	0.30	0.66	0.10	1030.81	15.87	33.04	158.56
2	-0.25	0.30	0.63	0.11	1021.33	27.21	36.17	79.08
3	-0.26	0.31	0.70	0.12	984.60	8.68	24.20	23.50
4	-0.31	0.34	0.60	0.10	1061.22	16.28	32.82	7.91
5	-0.44	0.32	0.83	0.13	1045.59	20.49	42.57	1.03
6	-0.03	0.31	0.63	0.09	1039.86	29.00	69.16	50.06
7	0.07	0.32	0.54	0.06	1010.38	13.10	63.69	48.97
8	0.07	0.32	0.60	0.07	1020.58	36.48	132.58	46.95
9	-0.19	0.32	0.73	0.10	1054.27	11.39	41.64	145.74
10	-0.22	0.32	0.72	0.14	1054.91	2.58	17.42	200.45
11	-0.31	0.29	0.84	0.20	1057.80	12.80	11.82	302.19
12	0.00	0.32	0.66	0.09	1041.14	16.57	19.90	242.76
13	-0.09	0.31	0.59	0.08	1002.50	15.67	26.67	59.10
14	-0.04	0.30	0.56	0.09	995.60	23.86	27.20	19.71
15	0.04	0.32	0.54	0.08	986.28	15.94	59.22	53.92
16	-0.07	0.32	0.56	0.08	1010.90	24.85	47.58	139.37

Plot	NDVI (min)	NDVI (mean)	NDVI (max)	NDVI (SD)	Altitude (m)	Slope (%)	Distance to edge (m)	Distance to the hydrographic network (m)
17	-0.01	0.30	0.53	0.05	996.08	32.62	29.98	194.07
18	-0.10	0.34	0.58	0.09	1001.69	21.81	44.31	244.79
19	-0.05	0.31	0.52	0.08	972.82	22.81	48.80	196.22
20	-0.04	0.32	0.57	0.07	990.32	24.92	44.20	281.57
21	-0.23	0.34	0.72	0.13	1001.76	16.17	58.37	19.30
22	-0.98	0.32	1.00	0.14	1039.70	21.63	110.73	168.56
23	-0.97	0.34	0.97	0.16	1060.71	6.04	85.82	317.66
24	-0.24	0.32	0.73	0.10	987.69	26.61	27.38	183.61

sulting in reduced NDVI values even where vegetation is present. In this context, low but positive NDVI values may still reflect vegetation with limited photosynthetic activity, whereas negative values are more consistently indicative of surfaces lacking photosynthetically active tissues, a distinction that is particularly relevant in fragmented and edge-dominated forest landscapes (Magnago et al., 2015; Harper et al., 2023).

Additional insight is provided by plot 11, which exhibited the highest NDVI standard deviation among all sampled plots (SD = 0.20; Table 4). This elevated variability suggests pronounced spectral heterogeneity within the plot, indicating the simultaneous presence of photosynthetically active foliage, shaded areas, woody components, and exposed surfaces. Visual inspection of Figure 2 shows that plot 11 is located within a narrow forest patch, where edge effects likely dominate most of the plot area. In such spatial configurations, increased spectral heterogeneity is expected, as edge-influenced environments tend to exhibit canopy discontinuities, increased light penetration, and a higher proportion of non-photosynthetic elements (Magnago et al., 2015; Harper et al., 2023).

Maximum NDVI values across the plots ranged from 0.52 to 1.00, indicating dense, vigorous vegetation in portions of the forest canopy. Values exceeding 0.5 are commonly reported for closed-canopy tropical forests and are consistent with areas dominated by photosynthetically active foliage (Dutra et al., 2020). However, these high values were spatially restricted within each plot and did not dominate the overall spectral response.

Mean NDVI values, which integrate the spectral contribution of all pixels within each plot, showed a narrower range (0.29–0.34) and were systematically lower than those typically reported for forested areas using orbital multispectral sensors. This pattern is strongly influenced by the centimetric spatial resolution of the UAV-derived imagery. At this scale, individual pixels capture fine-grained heterogeneity within the canopy, including shadows, gaps, branches, and other non-photosynthetic elements that are commonly mixed within a single pixel at coarser spatial resolutions. As a result, mean NDVI values derived from centimetric-resolution imagery tend to be lower, as they incorporate a greater proportion of non-photosynthetically active surfaces within the plot footprint (Nijland et al., 2014; Santos et al., 2021).

Consequently, the relatively low mean NDVI values observed in this study should not be interpreted as indicative of poor vegetation condition, but rather as a reflection of the increased sensitivity of high-resolution imagery to structural and compositional heterogeneity within forest canopies. This characteristic reinforces the need to interpret NDVI values in light of spatial resolution and acquisition context, particularly when comparing UAV-based products with NDVI values derived from orbital platforms.

This outcome aligns with findings from other researchers employing similar sensors (Gomes et al., 2021; Santos et al., 2021). The authors suggested that the sensor's origin, stemming from a modified RGB camera capturing images from three bands in a single sensor, impacts signal capture for each band due to the inability to adjust shutter opening individually (Gomes et al., 2021). As a result, absolute NDVI values obtained from modified RGB sensors tend to be lower and more compressed than those derived from calibrated multispectral sensors.

Nijland et al. (2014) demonstrated that in modified RGB cameras, including the one used in this study, the red band not only captures red wavelengths but also a portion of radiation in the NIR spectrum. This increased reflectance in the red band consequently diminishes NDVI values. Thus, it is crucial to emphasize that NDVI values obtained from sensors utilizing modified RGB cameras should not be directly compared with those from multispectral sensors, whether attached to orbital or aerial platforms. Nevertheless, within a single study and acquisition workflow, relative differences among plots remain informative for identifying spatial gradients in vegetation vigor and canopy condition.

Beyond spectral properties, terrain-related variables also exhibited marked variability among the sampled plots. As anticipated, altitude varied slightly across the sampling sites due to their proximity, ranging from 972 to 1061 meters above sea level. In contrast, slope values exhibited a wider range, spanning 2% to 36%, indicating shifts from flat to undulating terrain (EMBRAPA, 2006; IBGE, 2013). In this context, such variables represent unfavorable landscape characteristics for high-intensity agricultural exploitation (Barlow et al., 2016), which may indirectly favor the persistence of native vegetation in certain topographic positions (Borda-Niño et al., 2020).

Regions with high altitude and steep slopes are commonly considered marginal for mechanized agriculture, favoring forest conservation and restoration actions (Meli et al., 2019; Borda-Niño et al., 2020). Moreover, such landscape characteristics can even lead to the establishment of natural regeneration processes (Rezende et al., 2015).

Notably, in the studied region, there is low- and medium-intensity agricultural exploitation, conducted mainly by family farmers who produce annual vegetable crops such as onions, pumpkins, and cucumbers (Mello et al., 2018), highlighting the need for educational actions in these communities to promote the conservation of remaining forest patches.

The distance from the plots to the patch edge exceeded 100 meters in only two sample plots, as only one of the patches exhibited a substantial core area. This result is of great relevance in evaluating the biotic integrity of remaining patches, considering that edge regions are susceptible to various disturbances, such as higher temperatures, increased light exposure, low humidity, and higher wind speeds (Harper et al., 2023), which commonly lead to biodiversity and functionality loss (Magnago et al., 2014).

In tropical forests, such as the Atlantic Forest, studies indicate that a forest patch is impacted by edge effects at distances greater than 100 meters from the edge (Magnago et al., 2015), presenting a different structure than its core, with low canopy cover and height, low density of all sizes of trees, and greater abundance of graminoids (Harper et al., 2023).

Thus, our results reflect the adverse effects related to the edge areas of the patches since none of the analyzed plots presents BII characterized as very high, which is relevant information for environmental planning in the context of forest conservation and restoration (Harper et al., 2023) since it reflects a considerable part of the Atlantic Forest, where, due to its high degree of fragmentation (Marques and Grelle, 2021; Dias et al., 2023), edge effects are highly pronounced (Magnago et al., 2015).

Furthermore, the fact that the sample plots are in regions highly influenced by edge effects may partly explain the lower-than-expected NDVI averages, as edge-related structural simplification and microclimatic stress can reduce canopy continuity and photosynthetic performance.

Finally, the hydrological context also contributed an additional dimension of environmental variability among plots. The distance to the hydrographic network showed greater variability than the other environmental variables, ranging from 1.03 to 317.66 meters. Notably, even plots without a direct stream presence were situated near the hydrographic network, a characteristic attributed to the high drainage density within the basin (Morales and Valente, 2023).

In forest conservation, proximity to river networks is closely linked to legal issues, as several countries have adopted forest restoration policies and prohibitions on other land uses in riparian regions (Schweizer et al., 2022). In this context, riparian areas possess a degree of intrinsic conservation value, given that they often have steep terrain and high susceptibility to flooding, among other environmental risks (Monteiro et al., 2016).

In the biotic sphere, the relationship between biotic integrity, or an increase in fragment structure, and its proximity to a watercourse still requires further study (Borda-Niño et al., 2020). However, studies such as that of Şekercioğlu et al. (2015) demonstrate that watercourses act as seed dispersers and supply water and nutrients to riparian regions.

For the multivariate analysis, RDA was initially performed with all explanatory variables. Subsequently, multicollinearity was assessed using VIF values. As shown in Table 5, high VIF values were observed for the NDVI minimum, maximum, and standard deviation, indicating strong multicollinearity among these metrics. Therefore, these variables were excluded, and the analysis was re-run using the remaining explanatory variables.

The variance analysis indicated that the reduced model was statistically significant ($p = 0.008$). To further improve model performance, a sensitivity analysis was conducted, sequentially removing explanatory variables and evaluating changes in significance (*p-value*), R^2, and adjusted R^2 (Table 6). The best-performing model excluded the slope variable, yielding a significant result ($p = 0.001$) and the highest R^2 (0.14).

Table 5 – VIF values in determining multicollinearity from the analysis containing all explanatory characteristics and after eliminating the characteristics with the highest inflation.

VIF	NDVI (min)	NDVI (mean)	NDVI (max)	NDVI (SD)	Altitude (m)	Slope (%)	Distance to edge (m)	Distance to hydro. network (m)
Initial	6.11	1.51	10.59	4.8	1.62	1.97	1.96	1.14
Final	-	1.33	-	-	1.24	1.58	1.5	1.05

Table 6 – p-value, R^2, and adjusted R^2 for the RDAs carried out within the scope of the sensitivity analysis.

Model	p	R^2	adjusted R^2
without NDVI	0.22	0.19	0.03
without Altitude	0.005	0.27	0.12
without Slope	0.001	0.29	0.14
without Dist. to edge	0.009	0.26	0.10
without Dist. to hydro.	0.004	0.28	0.12

Although modest, the adjusted R^2 obtained in this study falls within the range commonly reported in investigations that relate biotic attributes to environmental variables in heterogeneous and fragmented tropical landscapes, where high ecological complexity and strong local variability tend to constrain the explanatory capacity of multivariate models (Magnago et al., 2015; Arroyo-Rodríguez et al., 2017; Martinez Pardo et al., 2023).

The exclusion of slope from the final model is consistent with findings reported by Harper et al. (2023), who observed that topographic variables often exhibit limited explanatory power for variation in forest structure and diversity when compared to factors related to fragmentation and disturbance. Nevertheless, other studies emphasize that topographic position, rather than slope alone, may influence regeneration dynamics and species establishment in Atlantic Forest landscapes (Rezende et al., 2015). Thus, while slope did not emerge as a key predictor in the present analysis, terrain-related factors may still exert indirect effects on biotic integrity through accessibility, land-use history, and disturbance gradients.

The final RDA ordination (Figure 3) reveals a structured organization of biotic indicators along the main environmental gradients represented by average NDVI, distance to the patch edge, and altitude. The first constrained axis (RDA1), which explains most of the constrained variation, primarily reflects a gradient of vegetation vigor and structural development. In contrast, the second axis (RDA2) captures additional variation related to edge exposure and topographic position.

Forest gaps are associated with shorter distances to the patch edge and lower NDVI values, indicating that plots more strongly influenced by edge conditions tend to exhibit greater canopy discontinuities and reduced photosynthetic activity. A similar pattern is observed for exotic grasses, which show a clear association with proximity to patch edges, reinforcing their role as indicators of edge-related disturbance commonly linked to adjacent agricultural matrices.

The BII shows a strong positive association with average NDVI, highlighting the close relationship between overall vegetation vigor and integrated measures of biotic condition. Lianas and vines also align positively with NDVI, a pattern that likely reflects their substantial green biomass, despite their ecological interpretation as disturbance-associated indicators in fragmented forests.

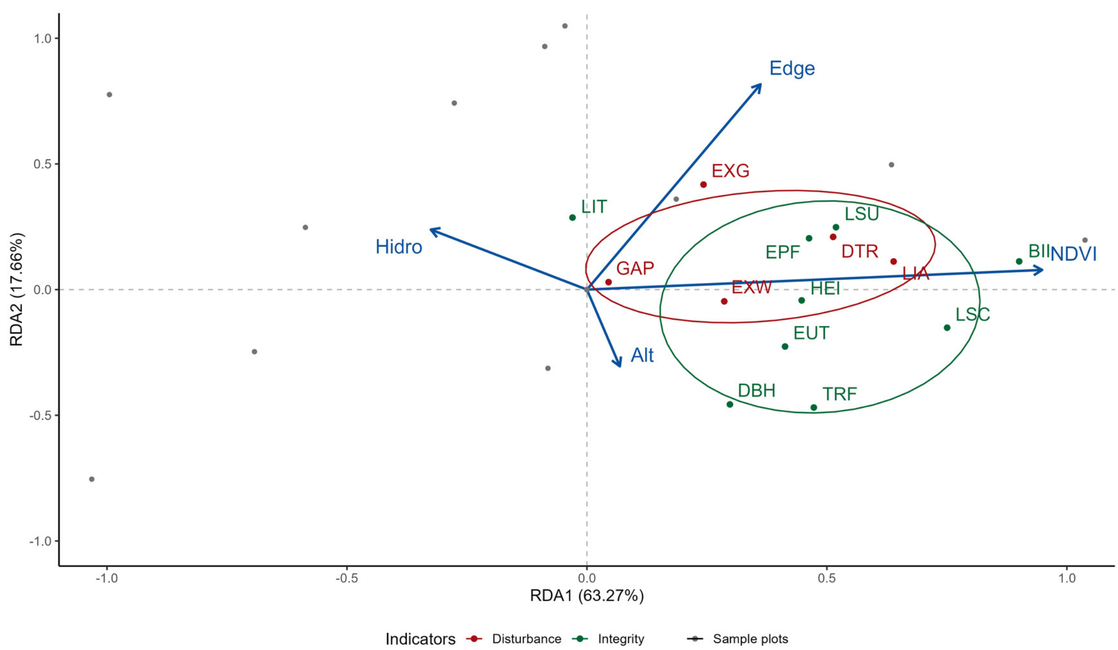

Figure 3 – RDA ordination of the relationships between biotic indicators and environmental variables in Atlantic Forest patches. Environmental variables are shown as arrows, biotic indicators as points.
Where: LIT = litter / DTR = dead trees / EXG = exotic grasses / EXW = exotic wood species / LIA = lianas and vines / GAP = forest gaps / EPF = vascular epiphytes / TRF = tree ferns / EUT = *Euterpe edulis* / LSC = late canopy species / LSU = late understory species / DBH = average diameter at breast height / HEI = average tree height.

Indicators related to forest regeneration and structural complexity in the understory, such as late-successional understory species and vascular epiphytes, are positioned toward regions of the ordination space associated with higher NDVI values and greater distance from patch edges. This configuration suggests that these attributes tend to occur in plots less affected by edge influence and characterized by more favorable microclimatic and structural conditions.

Late-successional canopy species, together with altitude, the presence of *Euterpe edulis*, tree ferns, and larger diameter trees, form a coherent group associated with higher NDVI values and elevated terrain. This pattern indicates that plots located at higher altitudes and exhibiting greater photosynthetic activity tend to support more structurally developed forest components and late-successional elements, likely reflecting lower accessibility, reduced disturbance intensity, and more advanced successional stages.

Overall, the ordination suggests that biotic indicators associated with edge-related disturbance processes tend to occupy different regions of the ordination space than those linked to vegetation vigor, structural complexity, and successional advancement. Although these patterns are not sharply delineated, the RDA offers useful insights into how groups of biotic indicators covary with key environmental gradients in fragmented Atlantic Forest patches, despite the model's limited explanatory power.

Conclusions

The diagnosis carried out using the BII proved useful for a rapid and structured field-based assessment of forest patches, with indicators that were representative of local conditions and readily identifiable during field surveys. In turn, the environmental variables derived from remote sensing enabled partial characterization of landscape attributes relevant to biotic integrity, particularly through high-resolution NDVI data from UAV surveys, which captured fine-scale variability in vegetation condition across the sampled plots.

The multivariate analysis revealed statistically significant but weak relationships between biotic integrity and environmental predictors, with distance to patch edge, mean NDVI, and altitude emerging as the most influential variables. Although the explanatory power of the final model was limited, these results indicate that vegetation vigor and edge-related processes help shape biotic integrity patterns within highly fragmented Atlantic Forest landscapes. At the same time, the modest model performance reflects intrinsic ecological complexity, the predominance of edge-influenced conditions, and methodological constraints associated with aggregating field observations into discrete BII scores, which inevitably leads to some loss of biological information.

Additional limitations are associated with the use of NDVI derived from a modified RGB camera, as absolute values are not directly comparable to those obtained from true multispectral sensors. Nevertheless, relative variation among plots proved informative for capturing gradients in vegetation condition at very fine spatial resolution. Furthermore, the restricted set of environmental predictors evaluated in this study limits the model's explanatory power, suggesting that incorporating additional variables, such as surrounding land-use and land-cover context, patch configuration, and detailed topographic position, would likely improve future analyses.

Overall, the patterns observed in this study illustrate the inherent ecological complexity of fragmented Atlantic Forest landscapes, where biotic integrity emerges from the interaction of multiple local and landscape-level processes. In this context, the results point to relevant environmental gradients and indicate directions for future investigations that may further refine the understanding of biotic–environment relationships in these systems.

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