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Enhancing biodiversity monitoring in impact assessment follow-up through landscape metrics

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ABSTRACT
Field-based monitoring may be insufficient to detect biodiversity trends across scales, especially in projects that have the potential to impact extensive areas. Despite its importance, landscape-scale data collection is rare in impact monitoring practice. In this research, we tested landscape metrics to evaluate their contribution to enhancing forest biodiversity monitoring in the EIA follow-up process, using a case study of a bauxite mine in the Brazilian Amazon. The research combined literature review and a case study to select, apply, and compare landscape metrics with local-scale field-based biodiversity monitoring. Metrics related to the amount and quality of habitats, fragmentation, edge effect extent and connectivity of landscape were selected and evaluated. We found that they can be easily incorporated into EIA follow-up, as they rely on readily available remote sensing time series, enabling the construction of historical baselines even prior to project approval. Also, landscape metrics can complement field-based surveys by detecting spatial patterns and offering opportunities for integrated multi-scale biodiversity assessments. Furthermore, they provide valuable inputs for identifying, planning, and spatially allocating offsets and additional conservation actions, thereby contributing to more effective impact mitigation and supporting stronger biodiversity outcomes.

KEY POLICY HIGHLIGHTS
- Landscape metrics can detect spatial land cover patterns that affect biodiversity, complementing field-based monitoring.
- These metrics can be integrated into impact assessment and monitoring, as they allow the construction of baselines and time series using satellite imagery, encompassing areas that are difficult to access on the ground.
- Landscape metrics can support the assessment of indirect and cumulative impacts and the design of mitigation strategies under the hierarchy.

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Landscape Ecology; habitat fragmentation; no net loss; forest conservation; bauxite mining

1. Introduction

As the loss of biodiversity increases (WWF 2024), biodiversity monitoring is essential to provide information on its trends and responses to anthropogenic pressures. Monitoring supports decision-making processes aimed at conservation (Watkins et al. 2015) as well as sustainability-oriented development, in particular for environmental impact assessment – EIA (UN 2021). Project-based EIA has been increasingly called upon to raise its ambition regarding how it addresses impacts on biodiversity, shifting from a paradigm of managed loss toward a stronger emphasis on impact avoidance (Bull et al. 2022) and on achieving no net loss, net gain, and, more recently, Nature Positive outcomes (Morrison-Saunders and Sánchez 2024).

Follow-up is an important component of the EIA process, providing information on actual impacts and effectiveness of mitigation. Follow-up comprises monitoring, evaluation, management, engagement and communication, and governance (Morrison-Saunders et al. 2022). Monitoring is a key element of EIA follow-up, involving collecting data on environmental conditions related to the project activities and the implementation of mitigation measures, thus enabling the evaluation of project compliance and performance across time (Morrison-Saunders et al.). Biodiversity monitoring is also important for detecting unpredicted or underestimated impacts at early stages, informing corrective actions (Sánchez 2012) and additional conservation strategies (Santini et al. 2017) as well as stakeholders, offering support for decision-making processes (Margarido et al. 2025).

Biodiversity has increasingly become a central theme for monitoring, particularly in the context of mining. Due to the spatial coincidence between mineral deposits and areas of high biodiversity value,

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such as tropical forests (Murguía et al. 2016; Giljum et al. 2022), mining often entails not only direct, but also indirect impacts on highly biodiverse areas (Sonter et al. 2014; Siqueira-Gay and Sánchez 2020) by facilitating access to otherwise intact and previously undisturbed forest areas (Lloyd et al. 2023).

Despite its importance for detecting trends in biodiversity, especially because impacts can manifest at different scales (Sonter et al. 2018), landscape-scale monitoring is still rare in practice (Lindenmayer et al. 2022). In many cases, biodiversity monitoring relies primarily on field data collected near the project's area, with limited consideration of broader-scale biodiversity threats that could affect project performance (Watkins et al. 2015; Lindenmayer and Likens 2018). Landscape Ecology is a scientific field focused on the study of spatial patterns within landscapes and their influence on ecological processes (Harker et al. 2021). The integration of Landscape Ecology and its respective landscape metrics into EIA can contribute to understanding the impacts at multiple spatial and temporal scales (Dabiri and Blaschke 2019; Harker et al. 2021). Landscape metrics have been recommended and applied to support EIA practice in different contexts (Koblitz et al. 2011; Dalloz et al. 2017; Gonçalves et al. 2022), including mining, to assess indirect and cumulative impacts (Siqueira-Gay et al. 2020) and to study the effectiveness of offsets (Rosa et al. 2022). However, to the best of our knowledge, no study has yet explored the advantages of applying landscape metrics in biodiversity monitoring.

Building on these considerations, the present research proposes and tests a set of landscape metrics for biodiversity monitoring to address the question: how can landscape metrics provide additional and useful information to understand a project's impacts and enhance biodiversity monitoring? We selected metrics that represent important landscape features for tropical forests and tested their applicability and contribution to monitoring impacts on forest ecosystems using a case study of a large-scale mine with documented impacts on biodiversity. In the following sections, we present a short description of the study area and detail the research methods (Section 2), present the results (Section 3), discussion (Section 4), and conclusions, also featuring implications for practice and future research (Section 5).

2. Methods

For the development of the research, the methodology comprised four stages: (i) selection of a case study, (ii) selection and calculation of landscape metrics for application in the study area, (iii) review of environmental monitoring reports related to the case, and (iv) an analysis of relationships between field-based data and landscape metrics. The case study under analysis, the Juruti bauxite mine, was selected for its relevance to discussions on mining in forest areas, given its location in the Brazilian Amazon.

2.1. Landscape metrics

In Brazil, the area of influence of projects is typically divided into three according to the extent of the potential impacts: directly affected (project footprint), direct influence and indirect influence areas (Sánchez 2020). The analysis was conducted in the area of indirect influence of the mine, as considered in the environmental impact study – EIS (CNEC 2004), comprising about 480,000 hectares.

To calculate the landscape metrics, land cover data of the study area was obtained from the Tropical Moist Forest (TMF) cover change provided by the European Commission's Joint Research Centre,[1] available for free (Bourgoin et al. 2024). These data are derived from Landsat imagery with a spatial resolution of 30 meters (Vancutsem et al. 2021). The TMF dataset was selected due to its superior spatial differentiation between 'Undisturbed Forest' and 'Degraded Forest' classes (Bourgoin et al. 2024), being particularly relevant because there is growing concern about not only deforestation, but also the degradation of the Amazonian Forest (Lapola et al. 2023). The years 2002, 2008, 2015, and 2022 were chosen to represent the pre-implementation, implementation, and two subsequent operational phases of the mining project, respectively.

The metrics chosen were those that could represent phenomena of interest to biodiversity in the forest context, such as habitat loss and fragmentation, edge effect, and reduced connectivity (Liu and Yang 2015; Issii et al. 2020; Siqueira-Gay et al. 2020; Barwicka and Milecka 2021), and that best fit the objectives of the research following the guide of McGarigal and Marks (1995) software FRAGSTATS (Table 1). The metrics chosen are presented in Table 1. The phenomena presented can be detected through more 'comprehensive' visualizations of the spatial patterns of the landscape, which are offered by landscape metrics (Barwicka and Milecka 2021), are of great importance for conservation (Sonter et al. 2018) and can then be adopted for monitoring. All metrics were calculated for the study area using FRAGSTATS, a widely adopted software for landscape analysis (McGarigal and Marks 1995; Cardille and Turner 2017).

2.2. Study area

The study area encompasses the Juruti bauxite mine, in the western region of Pará, currently the leading bauxite-producing state in Brazil. The mine began to be implemented in 2006 and to be operated in 2009 by Alcoa World Alumina Brazil (Alcoa 2022a). Operations

Table 1. Selected landscape metrics and their rationale.

Metric	Rationale
Percentage of Landscape (PLAND)	Indicates percentage of area occupied by a given class (land use or land cover). Variations in the area occupied by forest classes within a landscape contribute to understanding the amount of habitat available for biodiversity (McGarigal and Marks 1995; Barwicka and Milecka 2021). For this context, the metric was chosen because it indicates the variation in the area occupied by 'undisturbed forest'.
Number of Patches (NP)	It represents the number of patches present within the landscape, which can help to understand the degree of landscape fragmentation. NP can respond to several ecological processes, given that it is related to habitat, in addition to being necessary for the calculation of other metrics (McGarigal and Marks 1995; Liu and Xang 2015; Siqueira-Gay et al. 2020). The metric was chosen to indicate the occurrence of fragmentation of the 'undisturbed forest' class.
Mean Patch Size (MPS)	Represents the mean size of the patches of a given class (Issii et al. 2020). Along with the Class Area and NP, the MPS helps to assess landscape fragmentation, indicating whether the landscape is dominated by many small fragments or a few large ones (McGarigal and Marks 1995, Liu and Xang 2015; Siqueira-Gay et al. 2020). MPS has a relationship with the fragility of the patches, since smaller patches tend to be less resistant to anthropogenic pressures, setting up an interesting metric to explore in this context.
Total Edge (TE)	Refers to the sum of all boundaries between patches of different classes within a landscape. The metric is an important indication of the occurrence of the edge effect (McGarigal and Marks 1995; Liu and Xang 2015). Quantifying the area occupied by edges in forest mosaics is important for several ecological processes, since patches are influenced by their neighborhood, such as degradation by the edge effect.
Total Core Area (TCA)	It represents the total core areas of the patches, excluding the influence of the edges. TCA can indicate the quality of the habitat available in the landscape, since it considers only the internal areas of the forest patches, which are more conserved and can house more specialized species, setting up an interesting metric to explore in terms of biodiversity (McGarigal and Marks 1995).
Connectance Index (CONNECT)	Percentage of connections between the patches of the same type at a distance less than or equal to the threshold distance determined according to the ecological group of interest (Issii et al. 2020). Evaluating the connectivity between patches of 'undisturbed' forest helps to understand the isolation of vegetation patches in a landscape, the dispersal capacity of the individuals presents, as well as the resilience of the forest environment against anthropogenic actions. The functional connectivity metric used a threshold distance of 800 meters, as this represents an intermediate seed dispersal range by animals in the Amazon Rainforest (Castro et al. 2020).

Source: Adapted from McGarigal and Marks (1995).

in Juruti comprise an opencast mine, an ore processing plant, tailings ponds and storage yards, as well as a railway and a harbor (Figure 1).

The field-based monitoring, as a part of the follow-up, is conducted by the company according to a plan developed in the EIA. Results are reported to the state environmental agency through the Annual

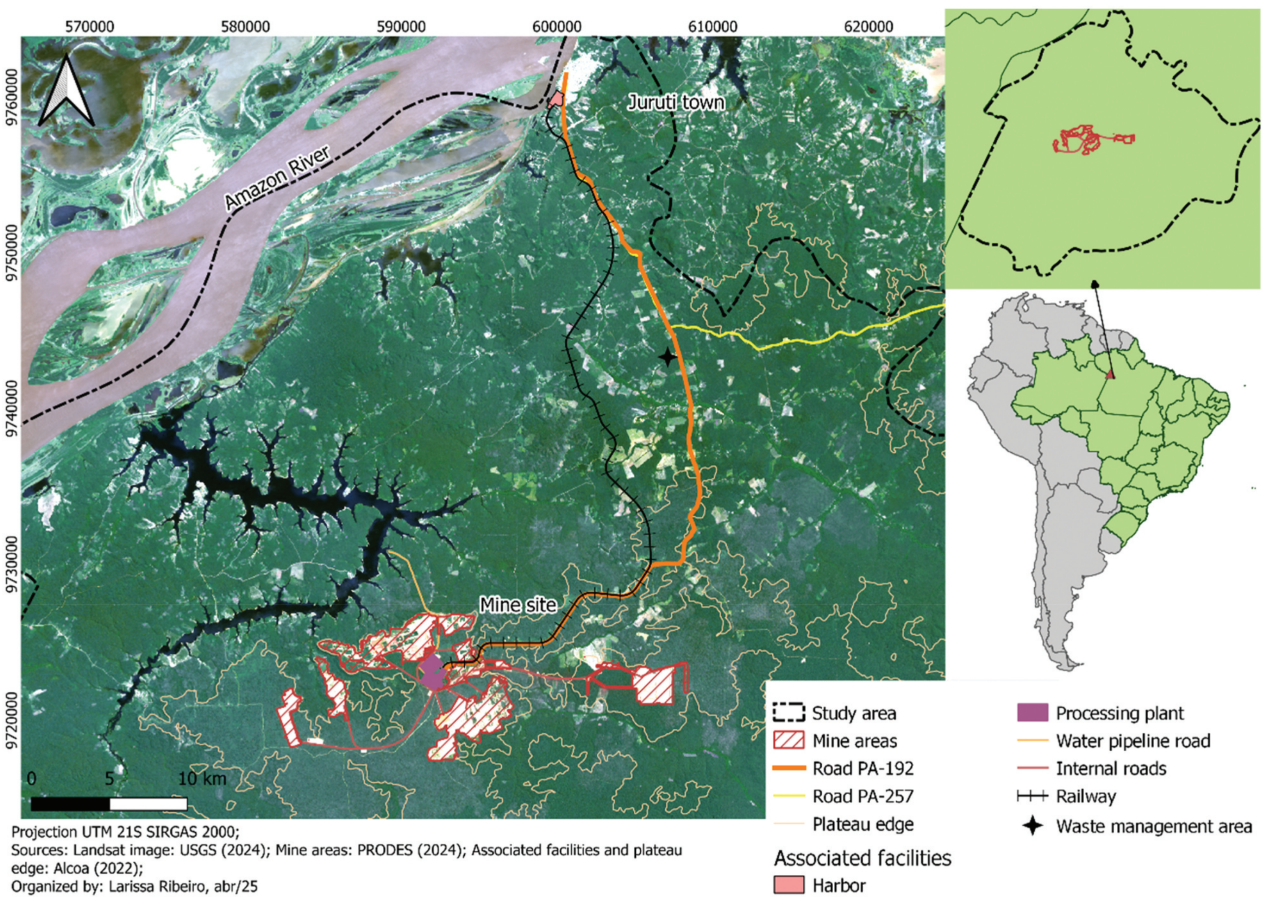


Figure 1. Location of Juruti town and Juruti mine with its main structures.

Environmental Information Report (RIAA, from Portuguese – *Relatório de Informações Ambientais Anual*). This report encompasses the monitoring of all activities related to the project's environmental impacts. However, the present research focuses specifically on vegetation monitoring. We reviewed eight reports (2016 to 2023) to organize a database containing the monitored parameters, results, location of monitoring stations, and data collection and methods, registering if and how they changed over time, specifically regarding spatial features, such as the location of monitoring stations.

For this analysis, two field-based monitoring programs that are part of EIA follow-up were chosen, given their relationship with impacts on vegetation: (1) Flora Conservation Program – including two subprograms, Secondary Forest Monitoring and Threatened Species Monitoring; (2) Rehabilitation Program (PRAD, from Portuguese – *Plano de Recuperação de Áreas Degradadas*). Both programs involved local-scale data collection. Vegetation is the component most directly affected by mining activities and can serve as a proxy for impacts on other components, such as soil (Lausch et al. 2015) and fauna, due to habitat loss (Cares et al. 2023). To support the analysis, the available literature on the topics of vegetation monitoring in mining and Landscape Ecology were consulted. The Juruti's sub-programs that aim to monitor the vegetation condition – the Monitoring of Secondary Forest and of Threatened Species – had their sampling points guided by the area of indirect influence delimited in the EIS. On the other hand, in rehabilitation monitoring, the plots are implemented according to the progress of the rehabilitation works. The EIS of the Juruti mine provides the vegetation baseline, based on surveys conducted in 2002 across seven plots (CNEC 2004).

Field-based monitoring in Juruti is essential for identifying the species present in the area, supporting the construction of inventories, and monitoring rare and/or endangered species, as conducted under the scope of the Monitoring of Threatened Species program (Alcoa 2023). Within the rehabilitation process, species identification is also necessary to evaluate whether the methodologies employed can promote the natural regeneration of the area (Alcoa 2013). However, the field-based monitoring results are highly dependent on the sampling effort applied.

The Secondary Forest Monitoring is held every six months (dry and rainy season), to gauge the state of secondary vegetation, as well as the degree of anthropogenic interference. Currently, five permanent plots of 1 hectare each are monitored, to represent different land covers found in the region (Table 2).

The Threatened Species Monitoring subprogram aims to identify endemic, rare, and threatened flora species (Alcoa 2022b) and to understand the dynamics of these species, providing subsidies for mine rehabilitation and conservation actions (Alcoa 2023). Six tree target species (*Aniba rosiodora*, *Bertholletia excelsa*, *Dicypellium caryophyllaceum*, *Manilkara huberi*, *Manilkara excelsa*, *Manilkara paraeneses*) are monitored every six months (dry and rainy season) in seven permanent plots of 10 hectares each, divided into 50x50m (Alcoa 2022b). The parameters assessed are presented in Table 2.

Legally required for mining, the PRAD aims at the rehabilitation of mined areas or areas deforested due to mining activities for future uses (Alcoa 2010). Monitoring is conducted every six months (dry and rainy season) for the parameters presented in Table 2. The permanent plots are installed according to the progression in the recovering areas, and changes in location and amount of plots are inherent to this program.

2.3. Analysis – landscape metrics vs field-based parameters

Given that spatial landscape patterns can interfere with ecological processes, an analysis was conducted. We compared the calculated landscape metrics to one parameter obtained from the field-based monitoring programs, to understand how the landscape patterns correlate with the local monitoring and whether the landscape metrics can complement the regulatory monitoring, as part of follow-up. The selected field-based parameter was species richness (from the Secondary Forest Monitoring). The choice was based on their consistent adoption across all sampling

Table 2. Summary of vegetation parameters monitored in Juruti.

Monitoring Program	Parameters	Sampling points
Flora Conservation – Secondary Forest Monitoring Subprogram	Species richness, abundance, diameter, bole height, total height, geometric wood volume, basal area, aboveground biomass of ombrophilous forests, mortality rate, similarity, diameter at breast height.	Five permanent plots of 1 hectare each, covering different vegetation formations of the region, during 2002–2022.
Flora Conservation – Monitoring Threatened Species Subprogram	Circumference at breast height, height, phenology, abundance or density, cross-sectional area, dominance, absolute dominance, volume.	Seven permanent plots of 10 hectares each, during 2008–2022
PRAD – Rehabilitation Program	Diameter at ground level, height, species richness of planted and regenerating species, degree of similarity between planted and regenerating species, annual mortality rate, annual recruitment rate of regeneration.	Plots are installed as rehabilitation progresses, in 2022 they were 80 plots installed between 2014 and 2022.

campaigns, ensuring comparability. For the purposes of this analysis, the highest species richness values recorded at each monitoring campaign were considered, for better representing the number of species in the landscape.

The analysis was conducted from the results of species richness organized through the elaboration of scatter plots, which can demonstrate the relationship between two sets of values in Microsoft Excel, with the richness values being considered the dependent variable. The value of R^2 was recorded for each of the relationships, as well as the p-value.

3. Results

The results of the landscape metrics used in this research are presented below. Subsequently, the information about the spatial features of the monitoring programs, and the comparison between the metrics and the field-based measurements are shown.

3.1. Landscape metrics analysis

Using the data provided under the Tropical Moist Forest project (Figure 2), the landscape metrics were calculated for undisturbed forest (Table 3).

The landscape metrics applied to the study area of the Juruti Mine, specifically for forested-related land

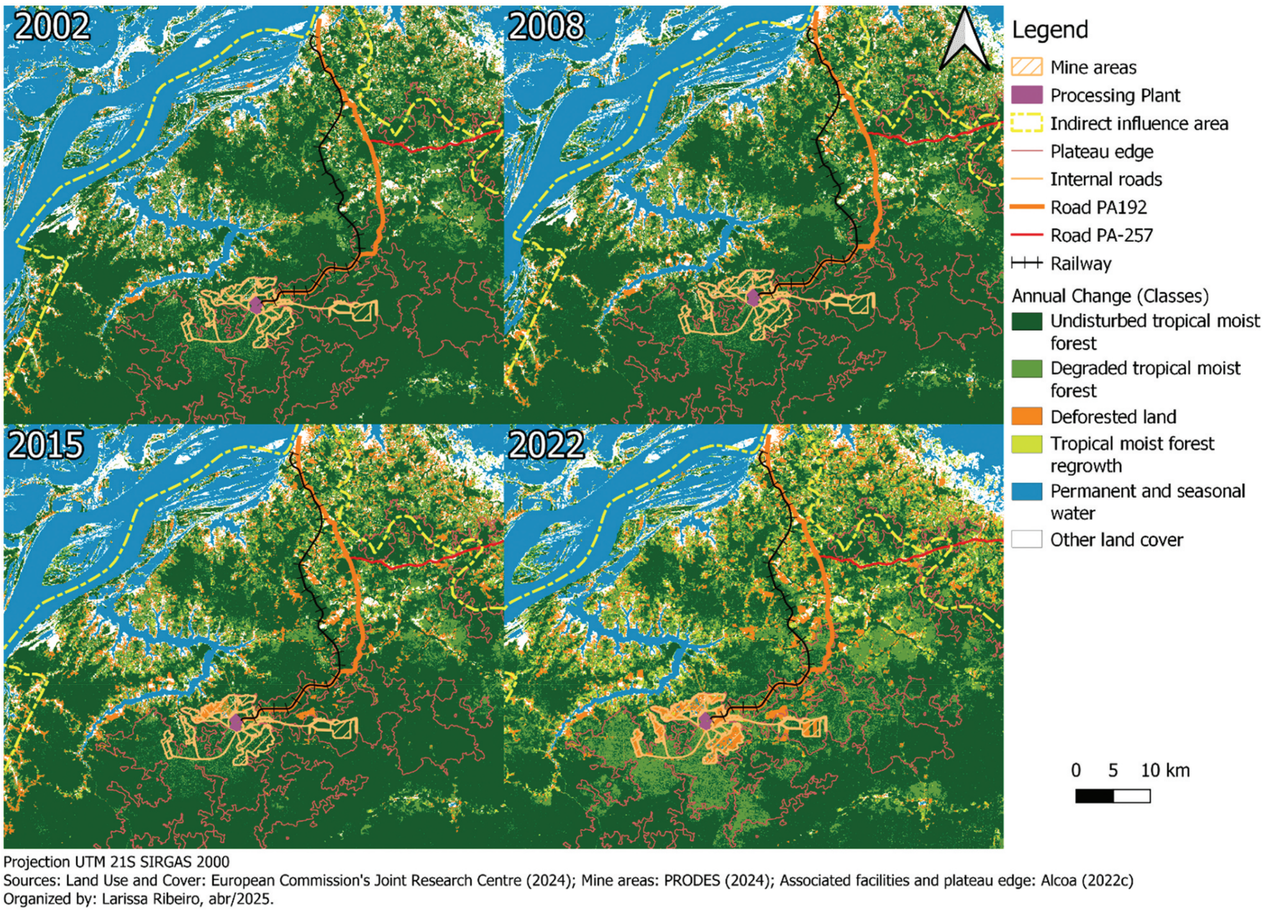


Figure 2. Land use and land cover maps of the study area around Juruti mine for the years 2002, 2008, 2015 and 2022.

Table 3. Landscape metrics results in the study area for undisturbed forest.

Metric	Unit	2002	2008	2015	2022	Result interpretation
Percentage of Landscape (PLAND) -	%	80.18	78.50	76.13	67	The PLAND decreased over the period, especially after 2015.
Number of Patches (NP)	–	8249	8201	8316	14401	The NP increased over the period, especially after 2015.
Mean Patch Size (MPS)	ha	46.86	46.15	44.14	22.40	The MPS decreased over the period, especially after 2015.
Total Edge (TE)	m*10000	1793.51	1800.40	1865.34	2700.12	The TE increased over the period especially after 2015.
Total Core Area (TCA)	ha	17.52	15.85	12.68	3.21	The TCA decreased over the period, especially after 2015.
Connectance Index (CONNECT)	%	25.5	24.5	24.2	19.3	The connectivity percentage slightly decreased between 2002 and 2015 and there was a steeper decrease between 2015 and 2022.

cover classes, indicate that the landscape within this area has now less undisturbed forest, a greater number of forest fragments, of smaller size, with more edge lenght, and less connectivity than in 2002.

The Percentage of Landscape (PLAND) metric alongside the reduction in the Mean Patch Size (MPS) reflects the reduction in the area classified as 'undisturbed forest'. The observed increase in the Number of Patches (NP) indicates higher fragmentation in the area. These metrics indicate that the mine's area of indirect influence has lost undisturbed forest and presents more and smaller forest fragments in 2022, when compared to 2002.

The increased fragmentation favors higher edge effects, and this is what happened indeed: the Total Edge (TE) metric showed consistent increase across time. This makes the edge vegetation more exposed to environmental stressors, such as wind, temperature fluctuations, and fires. The reduction in the Total Core Area (TCA) metric observed in the study area indicates a decline in the quality of the fragments. This reflects the decrease in MPS and relates to the increase in TE. This trend suggests that patches are increasingly vulnerable to stressors related to edge effects and with less shelter area in their interior for sensitive species.

The Connectance Index (CONNECT) metric indicated a decline in functional connectivity, considering the flora as the focus group. This implies a reduction in the species' potential to disperse in the landscape, which may hinder flora species population interchange, seed dispersal and, ultimately, faunal movements and other ecological processes.

3.2. Field-based monitoring analysis

Monitoring of vegetation conditions underwent changes in the sampling design, particularly regarding the plots tracked over time. In both programs, the plots monitored in the initial years were not maintained in subsequent assessments (Alcoa 2022b). The Monitoring of Threatened Flora Species included sampling points in other municipalities, but these were discontinued after the first monitoring campaigns. Only a few parameters were monitored consistently, namely species richness in the Monitoring of Secondary Forest (Figure 3) and the number of individuals in the Monitoring of Threatened Species (Figure 4). There have been difficulties in accessing some of the permanent plots over time. In 2022, for example, only two plots were monitored for Secondary Forest, and no plot was monitored for Threatened Species, compromising the construction of the database. It is noteworthy that access difficulties to plots in both sub-programs primarily stem from the lack of landowner authorization for entry (Alcoa 2022b). It should be noted that for the Monitoring of Threatened Species no data were identified for the year 2002 and the data regarding the implementation of the PRAD begin in 2012.

A total of 80 plots were installed between 2014 and 2022 to monitor the progress of rehabilitation efforts for PRAD. The method used for many years was nucleation, which seeks to induce natural regeneration to get as close as possible to the initial condition (Alcoa 2022b). Evaluation of the mortality rate by the company led to a modification of rehabilitation methods (Alcoa 2024) (Figure 5).

Regarding the conclusions of the reports, the *Secondary Forest Monitoring* reports present the number of species identified (Figure 3), but only indicate trends of stability in species number in the last monitoring campaigns, not indicating the occurrence of other relevant phenomena. Similarly, the *Threatened Flora Species* program quantified the number of individuals but was inconclusive regarding the detected impacts. Both reports indicate the occurrence of wildfires in areas adjacent to the mine, which resulted in alterations to the monitored parameters. The *Rehabilitation Program*, in turn, reports mortality rates, which are now considered to be within acceptable levels (Alcoa 2023).

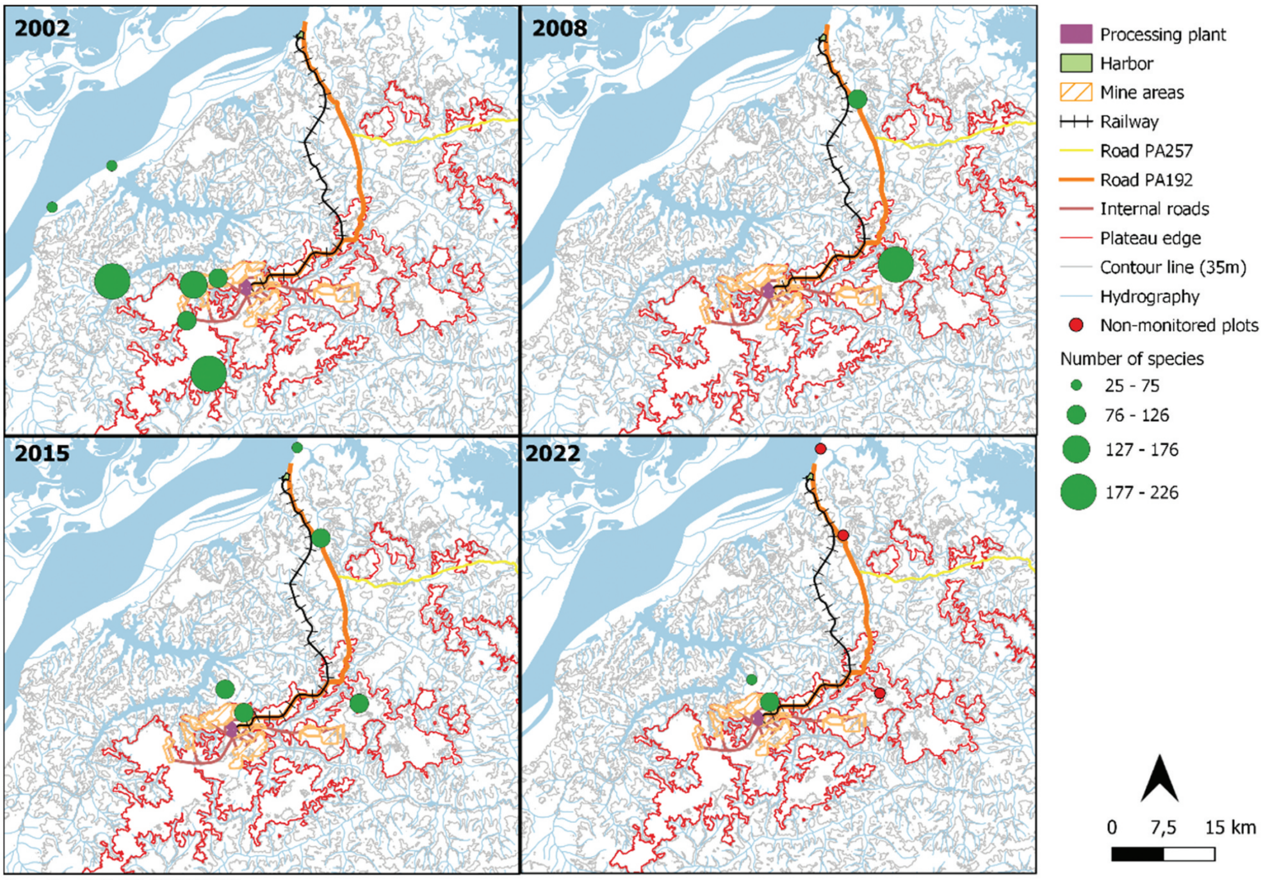
These results are currently informing future directions in the company's offset planning. In the recent Biodiversity and Ecosystem Services Action Plan for the Juruti mine, Alcoa established a clear commitment to achieving no net loss by 2030, with specific goals linked to operational indicators (Alcoa 2025). Complementary tools may be useful to strengthen the monitoring framework and support this goal.

3.3. Field-based monitoring vs landscape metrics

Drawing on the results of the landscape metrics analysis and the case study's current field-based monitoring, Table 4 presents a comparison of the main features of both approaches. While the current monitoring strategy emphasizes species richness and site-level indicators, integrating landscape metrics (e.g. habitat amount, fragmentation, and connectivity) could enhance future assessments by providing a broader perspective on ecological function and regional-scale biodiversity outcomes, aligning with recent literature on biodiversity offsets and spatial planning (Sonter et al. 2018; Rosa et al. 2022; Borges-Matos et al. 2025).

The use of these landscape metrics can complement field-based monitoring indicators by offering insights into landscape dynamics and, consequently, the potential influence of mining on forest structure. The relationships between species richness data from the Secondary Forest Monitoring and the calculated landscape metrics were tested in an analysis (Figure 6).

A direct relationship was observed between richness and the TCA metric ($R^2 = 0.812$), which can also



Projection UTM 21S SIRGAS 2000
Sources: Mine areas: PRODES (2024); Hydrography: IBGE (2024); Topographic Contour: EMBRAPA (2024); Associated facilities, plateau edge and monitoring data: Alcoa (2022c);
Organized by: Larissa Ribeiro, abr/2025.

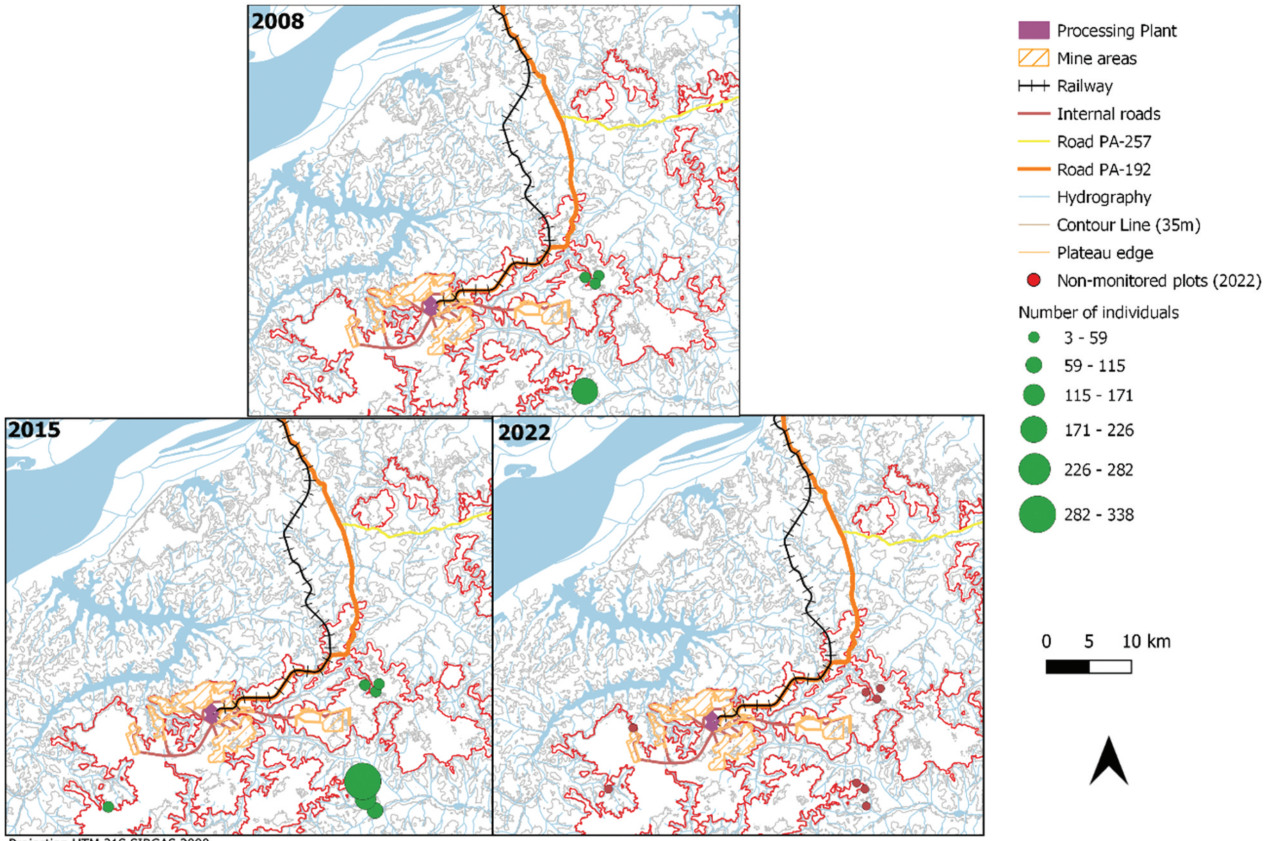
Figure 3. Changes in the secondary forest monitoring sampling points and species richness (number of tree species) over time. The EIA sampling points are shown in the 2002 quadrant. The 2008 quadrant shows the two points sampled along roads for monitoring in 2007 and 2008. The bottom quadrants show the five sampling points monitored since 2009 until today, highlighting the three points that were not monitored in 2022.

be observed for PLAND ($R^2 = 0.7796$) and CONNECT ($R^2 = 0.677$). It is noteworthy that despite the relationship observed through the R^2 values, only TCA was considered statistically significant at a 90% confidence level. This may have occurred due to the small size of the samples considered, not allowing for too many inferences at this level of confidence. The TCA and PLAND metrics are related to the area occupied by forest and the phenomenon can be better represented by TCA, given the higher value of R^2. This finding suggests that these metrics, particularly TCA, can serve as reliable proxies for flora species richness, and can thus complement field-based monitoring when it presents gaps. However, the other metrics showed limited sensitivity to gradual declines in richness, responding significantly only after 2015, when a large-scale fire occurred in the region. This pattern suggests that while TCA and CONNECT can reflect subtle changes over time, the other metrics appear to respond markedly only to high-magnitude disturbance events. These results illustrate the potential for integrating field-based indicators and landscape metrics in biodiversity monitoring. Future studies could deepen this investigation by considering additional biodiversity variables (e.g. abundance, functional traits), expanding the spatial extent of analysis, and exploring the responsiveness of landscape metrics under different disturbance regimes.

4. Discussion

In the case study analyzed, the follow-up process required by the State environmental agency is limited to field-based monitoring and annual reporting and faces challenges in its implementation. The location of monitoring plots in two main programs (Secondary Vegetation and Threatened Species) has changed over time in relation to the baseline survey, due to access constraints. These interruptions have resulted in gaps in the historical data series making it difficult to track the progression of changes in forest conditions over time. Measuring biodiversity impacts remains a challenge in practice, especially in constructing a comparable and long-term database (Gullison et al. 2015).

Due to the increasing availability of spatial data and satellite images, the use of remote sensing tools offers



Projection UTM 21S SIRGAS 2000
Sources: Mined areas: PRODES (2024); Hydrography and municipal boundaries: IBGE (2024); Topographic Contour: EMBRAPA (2024); Associated facilities, plateau edge and monitoring data: Alcoa (2022c; 2024);
Organized by: Larissa Ribeiro, abr/2025.

Figure 4. Monitoring of threatened flora species sampling points and number of individuals over time. The 2008 quadrant shows the four points sampled in Juruti municipality that year. The 2015 quadrant show the seven sampling points monitored in Juruti. The 2022 quadrant shows the same seven monitoring points, but that were not monitored during that year.

valuable opportunities to enhance biodiversity monitoring (Crowley and Cardille 2020). The access to data from old satellite images at any time stands out, offering an interesting opportunity to complement baseline information even if not collected during pre-approval EIA stages (Dai et al. 2025; Ritter et al. 2017). This facilitates consistent comparisons of environmental conditions before and after project implementation, making it especially useful for long-term monitoring (Mansourian and Stephenson 2023; Uhlhorn et al. 2024), as demonstrated in the present case study. In addition, the possibility of accessing historical data over a long period facilitates the understanding of biodiversity trends, also helping to predict future trends for the region studied (Mulatu et al. 2017; Harker et al. 2021). Landscape metrics can be reassessed and corrected for the same period, given that the source image will remain the same, without the need for large financial resources, unlike field-based indicators (Van der Vliet et al. 2024).

A challenge is that field-based monitoring does not capture relevant landscape-scale patterns that induce changes in biodiversity at this spatial scale, such as habitat fragmentation and the occurrence of edge effect (Rosa et al. 2017). The selected landscape metrics allow for the exploration of key landscape aspects relevant to biodiversity: habitat amount and quality (PLAND, TCA, TE), fragmentation (NP, MPS), edge effect extent (TE), and connectivity (CONNECT). The landscape metrics applied to the Juruti context show an increase in the edge area of forest patches and a reduction in core forest areas, which indicates an important process of degradation in Amazon Rainforest (Lapola et al. 2023; Flores et al. 2024).

The reduction of the areas occupied 'undisturbed forest' class, which corresponds to the best conserved state of vegetation, has important implications for biodiversity, as it signals the loss of high-quality habitat essential for maintaining ecological integrity (Grande et al. 2020; Cares et al. 2023). The reduction of forest MPS combined with the increase in NP and CONNECT reduction endorses the problem of loss and fragmentation of natural habitats in the landscape, which affects landscape connectivity and, consequently, the biodiversity (Gonçalves-Souza et al. 2025). The monitoring of metrics such as TCA is promising for analyzing habitat-quality loss (McGarigal and Marks 1995). These landscape-scale results possibly reflect indirect and cumulative impacts of mining operation, which should be addressed within the EIA follow-up process (Siqueira-Gay et al. 2020).

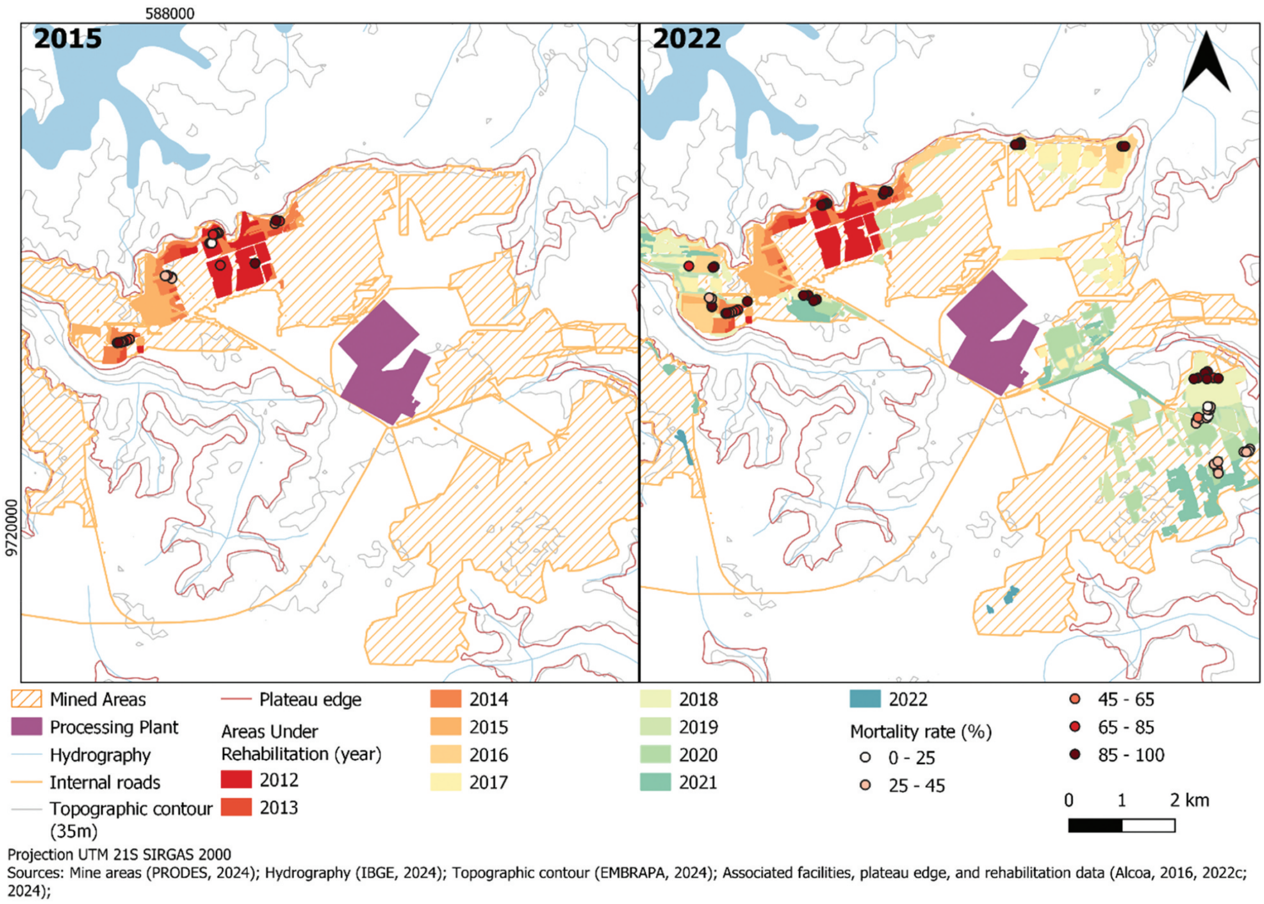


Figure 5. Areas under rehabilitation and seedling mortality rate results for the sampling points. The 2015 map shows the areas under rehabilitation up to that year and the corresponding permanent plots. The 2022 map also shows the progress of restoration and the corresponding monitoring plots.

Table 4. Comparison between field-based and landscape approaches for biodiversity monitoring.

Aspect	Field-Based Approach	Landscape Approach
Spatial coverage	Limited to predefined sample plots; gaps may occur due to inaccessibility (e.g. fire)	Large and continuous spatial coverage; includes inaccessible areas through satellite imagery
Temporal consistency	Subject to logistical constraints	High consistency across time; historical data retrievable via remote sensing
Level of detail	High taxonomic and structural detail	Broad landscape structure and patterns (patch size, connectivity, fragmentation)
Sensitivity to ecological processes	Effective for detecting fine-scale processes (e.g. regeneration, mortality)	Effective for detecting landscape-scale phenomena (e.g. edge effects, habitat loss)
Indicators of habitat quality	Site-specific; influenced by sampling effort	Region-wide indicators of connectivity, core habitat, and edge area
Data collection effort	Labor-intensive; requires trained personnel and field work	Less labor-intensive; low-cost, reliant on GIS and remote sensing
Limitations	Incomplete spatial representation; potential gaps in long-term series	Requires careful selection and interpretation of appropriate metrics

Achieving biodiversity conservation requires assessing the environmental impacts of mining at multiple scales (Sonter et al. 2018), given that it is not possible to capture all biodiversity trends at a single scale (Díaz and Malhi 2022). Different strategies must be adopted, recognizing they are interrelated (Fernandes et al. 2023; Dai et al. 2025). Metzger et al. (2009) indicate that landscape structure is an important factor in explaining the patterns of species richness and abundance, indicators often adopted in EIA for biodiversity monitoring (Santini et al. 2017). Through the analysis between the species richness data (Secondary Forest Monitoring) and the landscape metrics calculated, a strong relationship between the TCA metric and species richness was observed. Thus, the TCA can also be used as a proxy for plant species richness at the landscape level. Although illustrative, the correlation highlights the interdependence between scales, suggesting valuable avenues for further research, given that the field-based monitoring showed a reduction, as well as the metrics, even if not proportionally (Sonter et al. 2018; Díaz and Malhi 2022; Dai et al. 2025).

In the case of the Juruti mine, which has set a target of no net loss, adopting landscape metrics

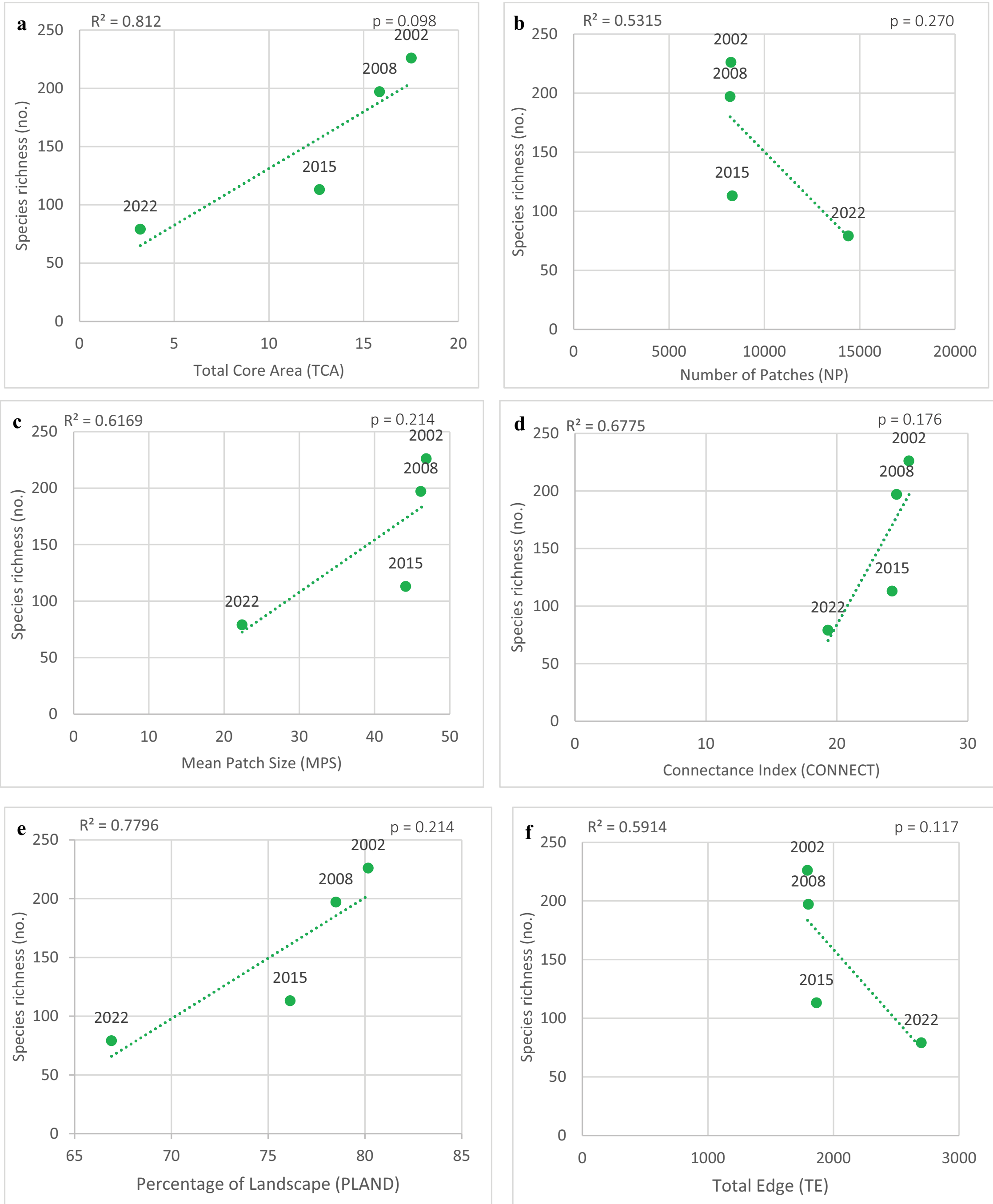


Figure 6. Relationship between the species richness from secondary forest monitoring and the six landscape metrics tested for the study area (species richness x TCA (a), NP (b), MPS (c), CONNECT (d), PLAND (e), and TE (f)). The dotted line represents the trend line of the relationships and R^2 is presented at the upper left corner of each graph, and the p-value at the right corner at a 90% confidence level.

could support better informed decisions across the mitigation hierarchy, helping to minimize residual impacts (Fernandes et al. 2023). As new extraction fronts are yet to be developed, expansion planning can incorporate objectives such as maximizing ecological connectivity and expanding core habitat areas that may be critical for threatened species identified in the region (Rosa et al. 2022), directly addressing the adverse impacts revealed by this research. Accordingly, this approach can contribute to avoiding and preventing additional impacts, while also guiding the planning of offsets that align with the mine's no net loss biodiversity commitment. Located in an area of high biodiversity value, the application of landscape metrics in Juruti has the potential to support the assessment of cumulative effects arising from mining and other anthropogenic activities, such as logging and agriculture, that affect biodiversity balance and the maintenance of ecosystem services (Boldy et al. 2023). The incorporation of landscape metrics into the environmental monitoring process, can contribute to a better understanding of key drivers of Amazon Rainforest degradation, such as edge effect (Lapola et al. 2023).

As broader contributions, the regional analysis provided by Landscape Ecology are relevant for EIA follow-up, as they contribute to identify indirect and cumulative impacts that may not be captured at the local scale, given that changes occurring at one scale can trigger alterations at others (Karlson et al. 2014) and they may manifest at considerable distances from the source (Sonter et al. 2017). Landscape metrics can support earlier and spatially informed decisions within the Mitigation Hierarchy by identifying areas of high ecological value and guiding project adjustments during the planning phase and decisions during operation, as advocated by Fernandes et al. (2023). By enabling the spatially explicit anticipation of impacts, improving the definition of residual losses, and supporting early design of offset areas, landscape metrics can contribute to minimizing the time-lags between biodiversity losses and gains (Fernandes et al. 2023), one of the main challenges for achieving better biodiversity outcomes (Metzger et al. 2009). As mining companies increasingly commit to stronger biodiversity goals such as no net loss, net gain or nature-positive outcomes (Sánchez and Morrison-Saunders 2025), measures taken at the landscape level become necessary (ICMM 2024).

As it is a temporary activity in which the subsequent recovery of the area is necessary, mining has different issues regarding the area rehabilitation and the environmental status of the surroundings can influence the rehabilitation process. In this sense, Landscape Ecology can also present important contributions that can be better explored in new research (Wu et al. 2023). Other approaches that can be the target of new applications in the field of biodiversity monitoring can also be mentioned, such as the Optimal Resource Availability applied by Issii et al. (2020), which represents the optimal availability of forest resources in each landscape and can influence species conservation.

Finally, we consider that this regional approach provided by Landscape Ecology supports key principles of EIA follow-up, particularly promoting continuous learning from experience to improve future practice, facilitating adaptive management, addressing cumulative effects, and considering the overall effects of the project (Morrison-Saunders et al. 2022). This research does not exhaust the range of possible approaches for using landscape metrics, that could contribute to EIA, nor does it fully address the scope of current environmental monitoring programs. Nonetheless, it offers practical insights into how landscape metrics can be applied to strengthen biodiversity monitoring, particularly in complex environments such as tropical forest regions. More robust statistical analysis and hypothesis-driven research are required to confirm the consistency and ecological validity of relationships across spatial and temporal scales.

5. Conclusion

In this research, we tested landscape metrics in an area surrounding a large scale mine in the Brazilian Amazon to assess their potential contribution to biodiversity monitoring in EIA follow-up. While essential, the field-based vegetation monitoring faces several operational challenges, particularly regarding access to the established permanent plots, which compromise the consistency and spatial coverage of biodiversity assessments. Moreover, as it relies solely on local measurements, this type of monitoring does not capture broader spatial patterns in the landscape that can influence biodiversity, such as habitat fragmentation and edge effects.

When applied to the study area, landscape metrics demonstrated their value in contexts where access limitations or resource constraints hinder long-term field-based monitoring. The selected metrics, addressing habitat amount and quality (PLAND, TCA, TE), fragmentation (NP, MPS), edge effect extent (TE), and connectivity (CONNECT), revealed a significant decline in undisturbed forest area, reduced patch size and connectivity, and an increase in edge areas and degraded forest. These outcomes offer distinct and complementary insights to those generated by current field-based monitoring, enriching ecological analysis within the EIA follow-up framework. By providing information on changes in landscape structure and spatial configuration, landscape metrics can help identify project-related impacts and strengthen the overall understanding of landscape dynamics (Liu and Yang 2015; Dalloz et al. 2017).

Beyond methodological innovation and biodiversity monitoring, this integration can have broader strategic implications for project management. Understanding spatial impacts at the landscape level supports better informed decision-making across the mitigation hierarchy, from guiding project adjustments to improving the definition of residual losses and identifying priority areas for offsets (Fernandes et al. 2023). In the context of increasing commitments to no net loss, net gain, and nature-positive outcomes, adopting landscape-scale approaches is essential. Landscape metrics can inform recovery planning, monitor structural ecosystem changes, and help detect cumulative and indirect impacts, which are critical but often missed by site-level assessments during follow-up (Borges-Matos et al. 2023; Morrison-Saunders et al. 2022 ; Harker et al. 2021).

We conclude that the incorporation of landscape metrics into EIA follow-up represents a promising pathway to improve the detection of landscape-scale impacts and promote more effective biodiversity outcomes, particularly in regions like the Amazon where conservation stakes are high. We recommend future research to explore how these metrics can be systematically applied to other environmental components, including freshwater ecosystems. Additionally, further studies should investigate the interrelationships between landscape and field-based metrics, and how they can be more effectively integrated into the design and evaluation of restoration and compensation strategies following the mitigation hierarchy.

Note

1. Tracking long-term (1990–2022) deforestation and degradation in tropical moist forests: Available at: https://forobs.jrc.ec.europa.eu/TMF.

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