Landscape Metrics to Assess Changes in Native Vegetation Patches in the Paraíba Valley, Brazil

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Abstract

Landscape metrics are essential for understanding the spatial patterns associated with land-use change. This study analyzes the correlations among metrics applied to native vegetation in the Paraíba Valley (São Paulo State, Brazil), based on the differences observed between the years 2000 and 2022. Class-level metrics were calculated to represent different dimensions of landscape structure, such as fragmentation, edge, connectivity, and shape complexity. Pearson's correlation analysis was then applied to assess the associations among these metrics. The results showed a positive correlation between Total Edge and Number of Patches ($r = 0.69$), indicating that an increase in the number of fragments leads to a greater total edge length. In contrast, Fractal Dimension Index and Aggregation Index exhibited a negative correlation ($r = -0.31$), suggesting that more aggregated fragments tend to present simpler shapes. These findings reveal a process of spatial reorganization of native vegetation in the study area, driven by secondary regeneration and conservation policies implemented in the region. Therefore, the integrated analysis of metrics contributes to a better understanding of landscape dynamics and provides practical insights for conservation and restoration strategies.

1. Introduction

The Atlantic Forest is one of the most threatened biomes in the world. Only 12.4% of its original forest cover remains in mature fragments (SOS Mata Atlântica, 2024). This severe loss has resulted in a highly fragmented landscape, where most forest remnants are isolated within a predominantly anthropogenic matrix (Ribeiro et al., 2009). Within this biome, the Paraíba Valley region has undergone intense transformations. Agricultural expansion, followed by livestock farming and industrial activities, promoted deforestation that drastically reduced forest cover. In recent years, natural regeneration in abandoned areas, combined with conservation policies, has contributed to a reconfiguration of the landscape (Silva et al., 2017).

With nearly 70% of its area occupied by rural properties, the Paraíba Valley of São Paulo state is a strategic region for conservation policies (Figure 1). One example was the Payment for Environmental Services (PES) program, implemented by the Atlantic Forest Connection in 2018 and concluded in 2023, which aimed to reconcile native vegetation preservation with agricultural production. The program directly involved small landholders, reinforcing the integration of conservation and productive practices (Oliveira et al., 2024).

In this context, understanding the effects of these policies and the recent transformations in the region is essential for guiding future restoration projects. Landscape Ecology, together with Geographic Information Systems (GIS), provides important tools to analyze spatial dynamics and the impacts of forest fragmentation (Bridgewater, 1993). Among these tools, landscape metrics stand out for quantifying patterns of fragmentation, connectivity, and configuration of forest remnants, allowing an objective assessment of landscape structure (McGarigal, 2015).

Therefore, this study analyzes the correlations between changes in landscape metrics calculated for native vegetation between 2000 and 2022. The objective is to understand how these metrics reflect patterns of fragmentation, connectivity, and ecological integrity in the Paraíba Valley of São Paulo over time. The findings are expected to contribute to conservation and ecological restoration strategies, particularly in a region under strong anthropogenic pressure.

2. Materials and methods

2.1 Data

This study used land-use and land-cover (LULC) data from 2000 and 2022, obtained from the MapBiomas Project (Collection 8). The political-administrative boundaries of the municipalities in the Paraíba Valley (São Paulo State, Brazil) were provided by the Brazilian Institute of Geography and Statistics (IBGE, 2023).

2.2 Methods

LULC data were reclassified, and the target class, Natural Vegetation, was defined by grouping the "Forest Formation" and "Wetland" classes. Landscape metrics were calculated using the Fragstats software (McGarigal et al., 2015).

The selected class-level metrics included: Percent of Landscape, Number of Patches, Total Edge, Total Core Area (with a 50 m buffer), Aggregation Index, Cohesion Index, Fractal Dimension Index, Contiguity Index, and Shape Index. Calculations were performed at the class level, using an 8-cell neighborhood rule, with municipality boundaries serving as the spatial grid.

According to McGarigal (2015), Percent of Landscape indicates the proportion of the total landscape occupied by a land-cover class, reflecting its representativeness and contribution to landscape composition. Number of Patches corresponds to the total number of fragments of a class, expressing its degree of fragmentation. Total Edge represents the sum of the perimeter length of all patches of a class in relation to other classes, thus indicating the level of fragmentation and edge exposure. Total Core Area corresponds to the total interior area of patches, excluding a 50 m buffer from the edges, and represents the amount of habitat not affected by edge influence.

The Aggregation Index indicates the degree of aggregation of patches of a class, reflecting internal connectivity. The Cohesion Index measures the physical connectivity among patches of the same class, representing how structurally connected they are within the landscape. The Fractal Dimension Index evaluates patch shape complexity, where higher values represent more irregular geometries. The Contiguity Index measures the internal spatial connectivity of patches, indicating the degree of continuity of the class. Finally, the Shape Index compares patch shape to a square standard, such that values close to 1 indicate regular shapes, while higher values indicate greater irregularity. These metrics complement more direct indicators, such as Number of Patches and Total Core Area, allowing for a more integrated assessment of landscape structure.

The metrics generated in Fragstats were subsequently processed in R (statistical software). For each municipality, the difference between the 2022 and 2000 values of each metric was calculated, representing the change that occurred over the period. Pearson correlation analyses were performed using these change values ($\Delta = 2022 - 2000$), allowing the identification of how variations in the metrics were related. The correlations were visualized in a heatmap to facilitate interpretation.

3. Results and Discussion

The Pearson correlation matrix revealed distinct patterns of association among the landscape metrics calculated for natural vegetation in the Paraíba Valley region (Figure 2). The results illustrate how the changes that occurred between 2000 and 2022 are related, with the analysis interpreted in light of the ecological and socioeconomic processes that shaped the region during this period.

A strong positive correlation between Total Edge and Number of Patches ($r = 0.69$) indicates that increased landscape fragmentation is closely linked to greater edge length across the territory. This result is expected, as the subdivision of forest cover into multiple fragments tends to increase the extent of edges, increasing the interface between the remnants and the anthropic matrix (McGarigal et al., 2015).

This finding reinforces edge effects as a direct consequence of fragmentation, whereby the vulnerability of native vegetation fragments to external pressures becomes even greater (Laurance and Yensen, 1991; Viana and Pinheiro, 1998). Such effects can lead to microclimatic changes, exotic species invasion, and other anthropogenic disturbances that compromise biodiversity and ecological processes (Haddad et al., 2015).

The moderate negative correlation between the Fractal Dimension Index and the Aggregation Index ($r = -0.31$) suggests that more aggregated fragments tend to exhibit simpler geometric shapes. This pattern may reflect recent secondary regeneration processes, contributing to a trend of spatial homogenization in the landscape. In addition, the weak positive correlation between the Patch Cohesion Index and Total Core Area ($r = 0.12$) may indicate that more connected fragments have a greater potential to maintain larger interior areas.

More connected fragments may be associated with landscapes with low-intensity land use, which increases their potential to support biodiversity and ecological functionality (Arroyo et al., 2017). This reinforces the importance of restoration actions and the continuity of conservation incentive programs.

Additionally, Shape Index showed a weak negative correlation with both Total Core Area and Total Edge ($r = -0.12$), suggesting that highly irregularly shaped fragments are associated with smaller core areas and shorter total edge length. This relationship indicates that fragment irregularity hinders the maintenance of stable vegetation cores, reducing the amount of habitat protected from edge effects and, consequently, the ecological quality of native vegetation fragments.

A positive correlation between Percent of Landscape and Total Core Area ($r = 0.68$) further indicates that increases in total vegetation cover are associated with expansion of preserved core zones within fragments.

The expansion of native vegetation increased its proportion and favored the formation of more stable core forest areas. This process reflects a spatial reconfiguration of native vegetation in the region, where forest regeneration contributes to the recovery of ecological integrity.

In the Paraíba Valley, these patterns may be related to the reduction of intensive land-use activities in some areas, combined with conservation policies that have favored the recomposition of forest fragments (Silva et al., 2017). These processes resulted in more continuous and less complex formations, explaining the greater aggregation observed and the geometric simplification of fragments. At the same time, fragment cohesion contributed to the expansion of core areas that are less affected by edge effects.

Similar patterns of regeneration and increasing connectivity have been observed in other areas of the Atlantic Forest (Rezende et al., 2018). Tropical landscapes with a long history of human use tend to exhibit small fragments that are strongly affected by edge effects and embedded in a heterogeneous matrix of pastures, croplands, and regenerating forests. In such contexts, secondary succession plays a central role in restoring connectivity and recovering ecological functions when associated with appropriate management strategies (Arroyo-Rodríguez et al., 2017).

Therefore, these analyses highlight a process of structural reconfiguration of the region's landscape in recent years, in which vegetation fragments are becoming more spatially cohesive, geometrically simplified, and potentially more functional from an ecological perspective.

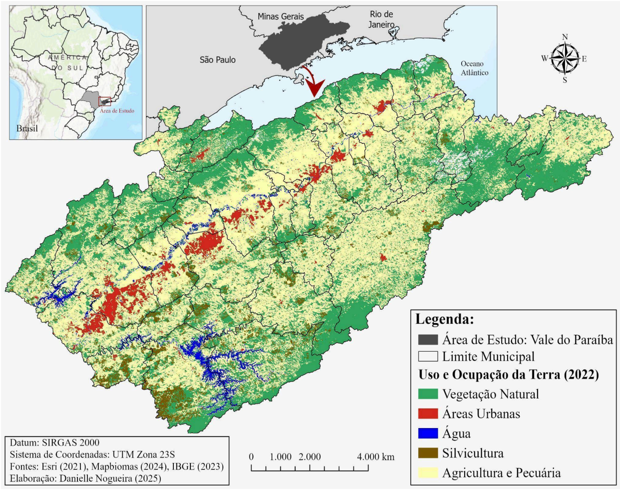

Figure 1. Study area: Vale do Paraíba region.

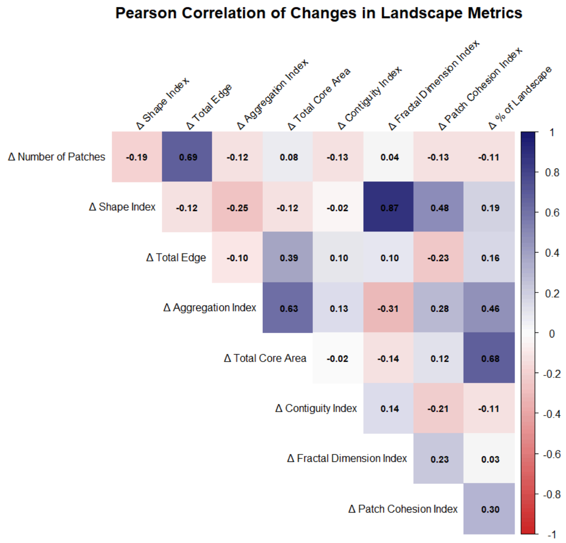

Figure 2. Pearson correlation matrix between landscape metrics for natural vegetation (2000–2022).

4. Conclusions

The analysis of correlations between metrics from 2000 to 2022 revealed significant transformations in the structure of native vegetation in the Paraíba Valley, São Paulo State. Considering the changes between the two periods made it possible to understand not only the current state of the landscape but also the processes of spatial reorganization driven by secondary regeneration and conservation policies. The approach adopted reinforces the importance of landscape metrics as tools to guide conservation actions in areas under anthropogenic pressure.

The use of landscape metrics has been consolidated as an essential tool for monitoring and planning ecological restoration. Recent studies have demonstrated their applicability both in the prioritization of forest fragments for conservation (Toro, Cardoso-Leite, and Valente, 2022) and in the assessment of how landscape structure influences restoration outcomes (San-José et al., 2022). Such analyses have also been used to relate fragmentation, connectivity, and ecological processes at different scales, reinforcing their role in supporting conservation and restoration decisions (Rudge et al., 2022).

Public policies and local initiatives should prioritize restoration actions in areas adjacent to existing fragments, in order to enhance the formation of stable core zones and reduce edge effects. The maintenance and strengthening of programs such as the Payment for Environmental Services (PSA) are fundamental to stimulate forest regeneration and consolidate the positive trends observed.

The results of this study reinforce the relevance of landscape metrics as support tools for environmental planning. When integrated with environmental and socioeconomic data, these metrics can inform decision-making and guide new projects capable of incorporating the outcomes of previous programs, ensuring the continuity of restoration and conservation efforts. In this way, they become essential instruments to reconcile conservation with sustainable land use, amplifying the positive effects on forest restoration in the region.

References

Arroyo-Rodríguez, V., Melo, F.P.L., Martínez-Ramos, M., Bongers, F., Chazdon, R.L., Meave, J.A., Norden, N., Santos, B.A., Leal, I.R., Tabarelli, M., 2017. Multiple successional pathways in human-modified tropical landscapes: new insights from forest succession, forest fragmentation and landscape ecology research. Biol. Rev. 92, 326–340

Bridgewater, P.B., 1993. Landscape Ecology, GIS and nature conservation. In: Haines-Young, R., Green, D.R., Cousins, S., Landscape ecology and spatial information systems. Bristol, Taylor and Francis, 23-36.

Fundação SOS Mata Atlântica, 2024. Atlas dos remanescentes florestais da Mata Atlântica: período 2022/2023, Relatório Técnico. Fundação SOS Mata Atlântica & INPE, São Paulo.

Haddad, N.M., et al., 2015. Habitat fragmentation and its lasting impact on Earth's ecosystems. Science Advances, 1(2), e1500052.

Laurance, W.F., Yensen, E., 1991. Predicting the impacts of edge effects in fragmented habitats. Biological Conservation, 55(1), 77-92.

McGarigal, K., 2015. FRAGSTATS help. University of Massachusetts, Amherst, MA, USA, 182 p.

Oliveira, L.R., et al., 2024. Projeto Conexão Mata Atlântica em São Paulo. SEMIL, São Paulo.

Rezende, C.L., et al., 2018. From hotspot to hopespot: An opportunity for the Brazilian Atlantic Forest. Perspectives in Ecology and Conservation, 16(4), 208-214.

Ribeiro, M.C., Metzger, J.P., Martensen, A.C., Ponzoni, F.J., Hirota, M.M., 2009. The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biology Conservation.

Rudge, M.L.M., et al., 2022. Developing landscape-scale forest restoration targets that embrace spatial pattern. Landscape Ecology, 37(7), 1747-1760.

San-José, M., Werden, L. K., Joyce, F. H., Reid, J. L., Holl, K. D., & Zahawi, R. A., 2022. Effects of landscape structure on restoration success in tropical premontane forest. Scientific Reports, 12(1), 13452.

Silva, R.F.B., Batistella, M., Moran, E.F., Lu, D., 2017. Land changes fostering Atlantic Forest transition in Brazil: evidence from the Paraíba Valley. The Professional Geographer, 69(1), 80-93.

Toro, A.P.S.G.D.D., Cardoso-Leite, E., Valente, R.A., 2022. Prioritization of Atlantic Forest remnants for biodiversity conservation: A patch index development. Research, Society and Development, 11(5), e2811527962.

Viana, V.M., Pinheiro, L.A.F., 1998. Conservação da biodiversidade em fragmentos florestais. Série Técnica IPEF, 12(32), 25-42.