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Papers

Geodiversity and Landscape Structure in the Quarta Colônia Unesco Global Geopark, Brazil: Compositional Richness and Land-Use and Land-Cover Fragmentation

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Abstract
Geodiversity can be understood as the structural foundation of landscapes, playing a significant role in shaping ecological processes and the spatial organization of land uses. In territories recognized as geoparks, the analysis of spatial relationships between abiotic heterogeneity and land occupation can support territorial planning and management strategies. This study aims to quantify the internal statistical consistency of physical landscape components and investigate their spatial associations with land-use and land-cover patterns in the Quarta Colônia UNESCO Global Geopark (Rio Grande do Sul, Brazil). The methodological approach was based on the application of a 2 × 2 km regular grid as the spatial unit of analysis, within which a Geodiversity Index was constructed from the richness of geological, geomorphological, soil, and hydrographic classes. Patterns of anthropogenic occupation were assessed under two metric scenarios: compositional richness of land-use classes (multipart arrangements) and spatial fragmentation (singlepart arrangements), represented by the number of patches. Relationships between variables were evaluated using Spearman's correlation and bivariate Local Indicators of Spatial Association (LISA). Results indicate a strong positive correlation among geodiversity components, particularly between geology, geomorphology, and soil variables, supporting the methodological robustness of the index. Areas with higher abiotic diversity tend to exhibit greater compositional richness of land uses, whereas fragmentation metrics show lower statistical dependence on physical landscape structure. Spatial modelling (LISA) identified zones of co-occurrence and statistical contrast between physical heterogeneity and land-use intensity. This study demonstrates that the integration of abiotic metrics, landscape ecology principles, and spatial statistics enables robust quantitative interpretations with potential applications in territorial planning instruments within geoparks.

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INTRODUCTION

Geodiversity, a concept introduced in the 1990s as the abiotic counterpart to biodiversity (Sharples, 1995; Wiedenbein, 1993), refers to the natural variety of abiotic elements that constitute the Earth's surface, including rocks, minerals, fossils, landforms, soils, and hydrological processes (Gray, 2013). Beyond its physical dimension, geodiversity provides the structural foundation of ecosystems, contributing to landscape development, biodiversity support, and the provision of geosystem services, understood as the direct and indirect benefits derived from abiotic components and processes (Gray, 2011; Hjort; Luoto, 2012; Chakraborty; Gray, 2020).

The attribution of specific values to unique components of geodiversity underpins their recognition as part of the natural and geological heritage. Whereas geodiversity encompasses the full range of abiotic components and processes, natural and geological heritage is restricted to elements of outstanding scientific, educational, cultural, or aesthetic value (Brilha, 2016; Reynard; Brilha, 2018). This recognition has stimulated the development of methodologies for the assessment, mapping, and conservation of these sites, which can be broadly classified into qualitative approaches, based on expert interpretation, and quantitative approaches, founded on numerical metrics and geospatial techniques (Pereira *et al.*, 2013; Zwoliński *et al.*, 2018; Guerini *et al.*, 2024).

Among quantitative approaches, grid-based methods have become particularly prominent, whereby the richness, diversity, and spatial distribution of abiotic elements are quantified by regular spatial cells. Serrano and Ruiz-Flaño (2007) proposed a geomorphological index to assess landform diversity, whereas Pereira *et al.* (2013) used abiotic richness as the basis for geodiversity indices. Forte *et al.* (2018) introduced centroid density as a measure of the spatial concentration of these components.

Subsequent studies refined these approaches by incorporating metrics derived from landscape ecology, such as the Shannon and Simpson indices adapted to quantify abiotic diversity (Manosso *et al.*, 2021; Silva *et al.*, 2024). Lopes *et al.* (2023) further highlighted the influence of grid-cell resolution on the stability and sensitivity of the results, a particularly relevant issue in local and regional analyses.

These indices have been widely employed because they enable the quantification of attributes such as richness, rarity, and integrity, while supporting the development of composite indicators that can be integrated with statistical and geospatial analyses, thereby revealing patterns of spatial heterogeneity that are often difficult to identify using exclusively qualitative approaches (Serrano; Ruiz-Flaño, 2007; Hjort *et al.*, 2015). This perspective is consistent with the principles of landscape ecology, which emphasize the relationships among spatial structure, ecological function, and landscape dynamics (Forman; Godron, 1986; Turner, 1989; Turner *et al.*, 2001).

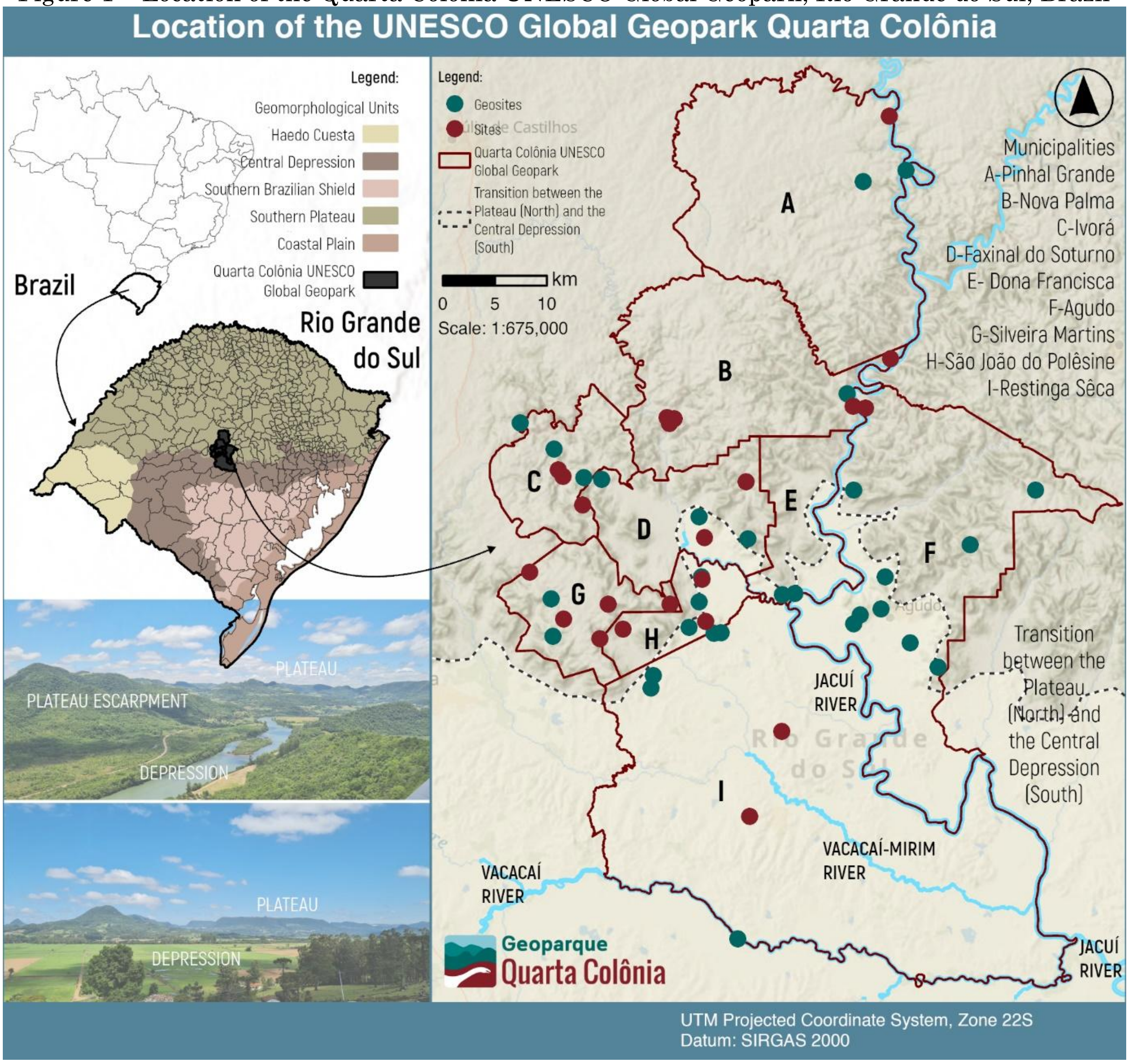
More recently, approaches integrating geodiversity with ecological and territorial dynamics have gained increasing attention, extending its application beyond its traditional relationship with biodiversity. Within this context, the combined analysis of geodiversity and land use and land cover (LULC) has emerged as a valuable framework for understanding landscape organization in relation to its underlying physical structure (Scammacca *et al.*, 2022). In this study, LULC are understood as an integrated concept, encompassing both the biophysical characteristics of the Earth's surface and the human activities associated with its appropriation and transformation (Cihlar; Jansen, 2001; Rawat; Kumar, 2015; Gregorio, 2016). The application of landscape ecology metrics enables the quantification of fragmentation, connectivity, and spatial diversity associated with different land-use patterns, integrating geodiversity studies with landscape configuration analysis (Gomes *et al.*, 2019; Forman; Godron, 1986; Turner, 1989).

Despite its theoretical relevance, empirical studies investigating the spatial relationships between geodiversity and LULC remain relatively scarce. This gap is manifested in several respects: (i) local spatial autocorrelation analyses, such as Local Indicators of Spatial Association (LISA), are generally applied to geodiversity in isolation and are rarely integrated with LULC variables (Souza *et al.*, 2023; Esmaili, 2024); (ii) studies conducted in geoparks rarely consider the geopark territory itself as an integrative analytical unit at the subregional scale, with the majority of studies carried out at broader spatial scales or focused on individual geosites (Scammacca *et al.*, 2022; Tukiainen *et al.*, 2017; Pál; Albert, 2023); (iii) methodological inconsistencies persist due to the overlap between metrics describing abiotic diversity and metrics characterizing landscape spatial configuration, although these quantify fundamentally different phenomena (Danese *et al.*, 2021; Yao *et al.*, 2022); and (iv) the diversity of methods used to quantify geodiversity hinders direct comparisons among studies and across landscapes (Pál; Albert, 2023).

Among the few studies that have advanced this field more directly, the works of Datta (2022) stand out for investigating the correlation between abiotic diversity and LULC diversity. Although not explicitly addressing this relationship, other studies have demonstrated the importance of abiotic heterogeneity in shaping the spatial organization of habitats, land-use patterns, and ecological processes (Jačková; Romportl, 2008; Hjort *et al.*, 2015; Tukiainen *et al.*, 2017). Within the context of geoparks, recent studies indicate that geodiversity remains underutilized and insufficiently integrated into territorial planning frameworks and spatially explicit analyses, a situation that is particularly evident in Brazil (Wilhelm *et al.*, 2025).

Against this background, the Quarta Colônia UNESCO Global Geopark, located in the central region of the state of Rio Grande do Sul, southern Brazil (Figure 1), provides an appropriate case study. Officially designated as a UNESCO Global Geopark in 2023, the territory covers approximately 2,900 km² across nine municipalities and encompasses remarkable geological, geomorphological, pedological, and hydrological diversity. Its landscape results from the interaction of sedimentary formations of the Paraná Basin, basaltic lava flows of the Serra Geral Formation, structural escarpments, deeply incised valleys, fluvial plains, and a hierarchically organized drainage network, forming a highly heterogeneous physical mosaic.

Figure 1 – Location of the Quarta Colônia UNESCO Global Geopark, Rio Grande do Sul, Brazil



Source: Prepared by the authors (2026).

In light of this, this study aims to analyze the statistical and spatial associations between geodiversity and LULC patterns within the Quarta Colônia UNESCO Global Geopark. The central hypothesis is that abiotic heterogeneity exhibits spatial correspondence with distinct patterns of territorial occupation. It is expected that areas of higher geodiversity are associated with multipart scenarios characterized by greater compositional diversity of LULC classes, whereas areas of lower geodiversity tend to correspond to singlepart scenarios, marked by more simplified patterns of land occupation. The study seeks to identify zones of co-occurrence and contrast between these variables through statistical and spatial association analyses, without assuming direct causal relationships.

METHODOLOGY

The spatial analysis was structured through the application of a regular grid composed of 2 × 2 km cells, covering the entire territory of the Quarta Colônia UNESCO Global Geopark, which was adopted as the spatial unit for integrating and comparing environmental and anthropogenic variables. The use of a grid enables the harmonization of heterogeneous datasets, reducing scale discrepancies among different thematic databases and allowing the systematic quantification of abiotic diversity and LULC patterns (Lopes *et al.*, 2023). All cartographic datasets were standardized to a 1:250,000 scale and projected in the SIRGAS 2000 / UTM Zone 22S coordinate system.

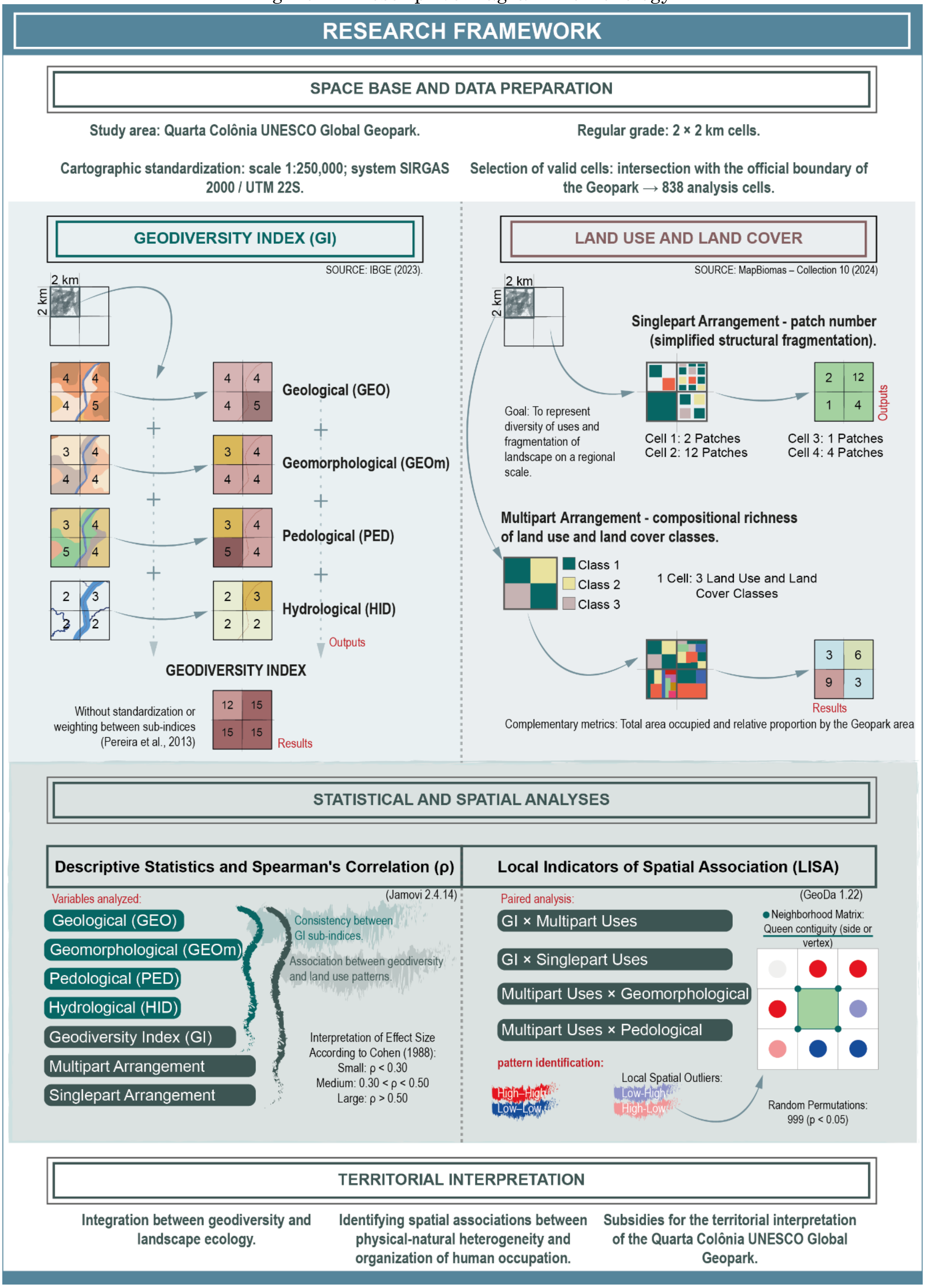
The definition of the 2 × 2 km spatial resolution was based on prior multiscale tests conducted by the authors, in which different grid sizes (500 m, 1 km, 2 km, 3 km, and 5 km) were evaluated in terms of index stability, spatial representativeness of abiotic heterogeneity, and computational performance. The results indicated that the 2 km resolution provides the best balance between spatial detail and analytical stability at the regional scale, while also being compatible with the cartographic scale of the input datasets (1:250,000) and with similar studies conducted in regional geodiversity contexts (Manosso *et al.*, 2021; Lopes *et al.*, 2023).

The regular grid was initially generated continuously over the entire territorial extent and subsequently clipped to the official boundaries of the Geopark using a spatial intersection operation, resulting in 838 analysis cells (Figure 2).

The geodiversity index (IG) was calculated following the approach proposed by Pereira *et al.* (2013), considering four physical landscape components derived from cartographic databases provided by the Brazilian Institute of Geography and Statistics (IBGE, 2023), organized into sub-indices: geological (GEO), geomorphological (GEOm), pedological (PED), and hydrographic (HID) (Figure 2).

The first three components were represented by polygon data, whereas the hydrographic component, originally in linear vector format, was methodologically adapted based on Datta (2022) and Forte *et al.* (2018). The conversion of the hydrographic network into polygons aimed to ensure geometric compatibility with the other geodiversity sub-indices, enabling its integration into the regular grid-based spatial analysis.

Figure 2 – Descriptive diagram Methodology



Source: Prepared by the authors (2026).

For this purpose, buffer zones were defined based on a combination of: (i) the hierarchical ordering of streams according to Strahler (1952); (ii) riparian buffer widths established by the Brazilian Forest Code (BRAZIL, 2012), used solely as a theoretical ecological reference; and (iii) average field-measured widths obtained from representative rivers within the study area.

This methodological adaptation does not aim to represent the legal or actual width of river channels, but rather to construct a functional spatial approximation of hydrographic influence on landscape composition, ensuring geometric compatibility with the other abiotic components.

Within each grid cell, the richness of distinct classes for each component was calculated, and these values were subsequently integrated through simple addition to obtain the Geodiversity Index (IG), according to the following expression:

$$IG = GEO + GEOm + PED + HID$$

The use of simple addition follows the original proposal by Pereira *et al.* (2013) and is based on the assumption that the components represent complementary dimensions of abiotic diversity, without prior assignment of hierarchy or relative importance among them.

In this context, the index is intended to represent the compositional richness of physical landscape elements, rather than to establish weighting of environmental, functional, or heritage importance among the analyzed components. Accordingly, no standardization or weighting was applied across sub-indices, preserving the logic of accumulated thematic richness within each spatial unit.

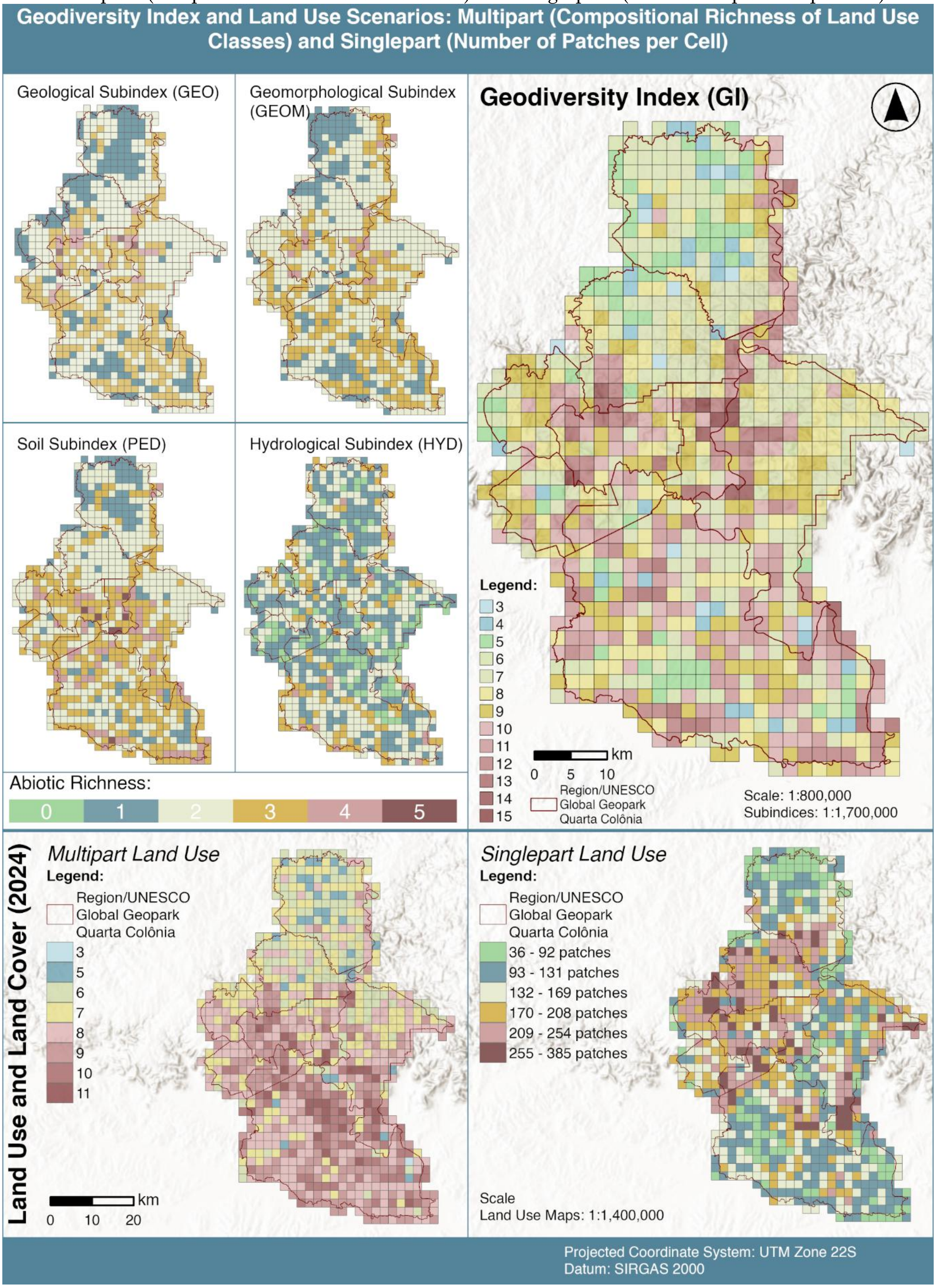
LULC data were derived from MapBiomas Collection 10, 2024 (MapBiomas, 2024) and integrated into the same regular grid, also without standardization, considering structural landscape indicators: (i) compositional richness of LULC classes (multipart), expressed by the number of distinct classes present in each cell, and (ii) simplified structural fragmentation (singlepart), measured by the number of patches (individual polygons) per spatial unit (Figure 2; Figure 3).

In addition, spatial metrics associated with patches were considered – total area occupied and relative proportion per cell –, allowing assessment of both the intensity and the configuration of anthropogenic occupation.

It is recognized that landscape fragmentation is a multidimensional phenomenon, typically analyzed through complementary metrics related to connectivity, edge density, contagion, and patch spatial configuration. In this sense, the number of patches was used as a simplified indicator of structural fragmentation, appropriate for the regional scale of the analysis and for the matrix logic of the adopted regular grid, enabling the identification of general spatial patterns of subdivision and heterogeneity in land occupation.

To verify relationships among variables, statistical analyses were performed using Jamovi software version 2.4.14, (Jamovi, 2024). Data normality was assessed using the Shapiro–Wilk test, which indicated a non-parametric distribution.

Figure 3 – Regular 2 × 2 km grid used to integrate the geodiversity index and two land use scenarios: multipart (compositional richness of classes) and singlepart (number of patches per cell)



Source: Prepared by the authors (2026).

Thus, the Spearman correlation coefficient (ρ) was employed to evaluate the internal consistency of the IG components and their association with LULC patterns under the multipart and singlepart scenarios. As a rank-based method, Spearman's coefficient reduces the influence of scale differences between variables, making it appropriate for association analyses involving non-parametric data and metrics derived from heterogeneous cartographic sources.

The interpretation of correlation strength followed the guidelines by Cohen (1988), classifying coefficients as weak when $\rho < 0.30$, moderate between 0.30 and 0.49, and strong when $\rho \geq 0.50$.

In addition to correlation analysis, LISA was performed using GeoDa software version 1.22.0.4 (Anselin *et al.*, 2024), based on a Queen contiguity matrix (Anselin, 2005), which defines neighbors as all cells sharing at least one edge or vertex, thereby increasing sensitivity in the detection of spatial patterns (Anselin, 1995; Cressie, 1993).

The LISA analysis was conducted in two stages. The first stage examined the pairs IG × Usos_Multipart and IG × Usos_Singlepart, assuming that land-use class richness and fragmentation represent distinct regimes of territorial organization.

The second stage analyzed the pairs Usos_Multipart × Geomorphology and Usos_Multipart × Pedology, aiming to deepen the understanding of spatial relationships between land-use diversity and physical components directly associated with landscape configuration and potential. The selection of these sub-indices is justified by their structuring role in territorial organization, as geomorphological and pedological conditions influence land suitability, human occupation patterns, and land-use distribution, enabling a more direct spatial interpretation of the observed associations.

Statistical significance of local clusters was assessed using 999 random permutations, adopting a significance threshold of $p < 0.05$, following standard procedures implemented in GeoDa. Results were interpreted based on pseudo-significance levels provided by the software, without applying additional corrections for multiple spatial testing. This procedure enabled the identification of statistically significant spatial clusters (High–High, Low–Low) and local outliers, revealing spatial patterns linking abiotic diversity and anthropogenic landscape organization.

Consistent with the Spearman analysis, no prior normalization of variables was applied, as LISA is based on relative spatial relationships between neighboring units rather than absolute magnitudes.

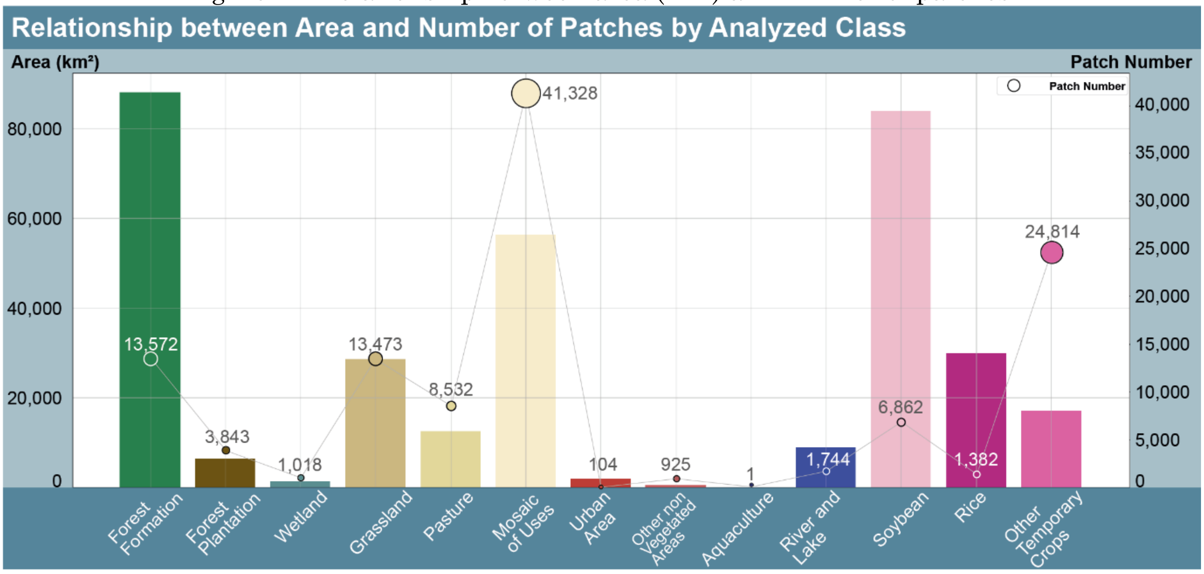
The integration of the geodiversity index with landscape ecology metrics enabled a simultaneous assessment of physical–natural heterogeneity and the spatial structure of human occupation, providing a territorial framework for identifying spatial associations between abiotic heterogeneity and patterns of land-use organization in the Quarta Colônia Geopark.

RESULTS

The distribution of LULC classes within the Quarta Colônia UNESCO Global Geopark reveals a mosaic characterized by the predominance of anthropogenic uses (62.17%) compared to natural uses (37.83%) (Table A1 – Supplementary Material – Wilhelm *et al.*, 2026). Among natural land covers, forest formations occupy 879.45 km² (26.24% of the Geopark), representing the largest class within this group in terms of extent and the dominant natural cover in the Multipart scenario, as illustrated in Figure 4. From the singlepart perspective, forest formations comprise 13,572 patches across the Quarta Colônia territory, while the mean number of patches across all LULC classes is 9,046. They also represent the second-largest continuous patch among all evaluated classes, with 98.40 km². Grassland formations constitute the second most extensive natural land cover, covering 286.3 km² (8.54% of the Geopark) and totaling 13,473 patches.

Within anthropogenic land uses, agricultural activities predominate, accounting for the largest share of territorial occupation (Figure 4). Soybean cultivation represents the most extensive land use in this group, covering 837.2 km² (24.98% of the Geopark) and constituting the primary crop in the Multipart scenario. Its largest individual patch covers 149.1 km². In the singlepart analysis, this class totals 6,862 patches. The land-use mosaic represents the second-largest anthropogenic class in terms of area, covering 563.5 km² (16.82% of the Geopark) and comprising 41,328 patches, corresponding to 35.14% of the total mapped patches in Quarta Colônia.

Figure 4 – Relationship between area (km²) and number of patches



Source: Prepared by the authors (2026).

The application of Spearman's statistical analysis revealed significant associations among most of the evaluated indicators (Table B1 – Supplementary Material – Wilhelm *et al.*, 2026). The strongest correlations were concentrated among the physical landscape components – geology, geomorphology, and pedology –, whose coefficients ranged from $\rho = 0.64$ to $\rho = 0.71$ ($p < 0.001$). IG showed even stronger correlations with these same components ($\rho > 0.80$; $p < 0.001$), a result consistent with its compositional structure.

Associations between geodiversity and land use patterns exhibited distinct behavior depending on the metric applied. In the multipart scenario, correlations ranged from $\rho = 0.27$ (pedology) to $\rho = 0.42$ (hydrography) ($p < 0.001$). The relationship between geodiversity and hydrography fell within this range ($\rho \approx 0.49$; $p < 0.001$).

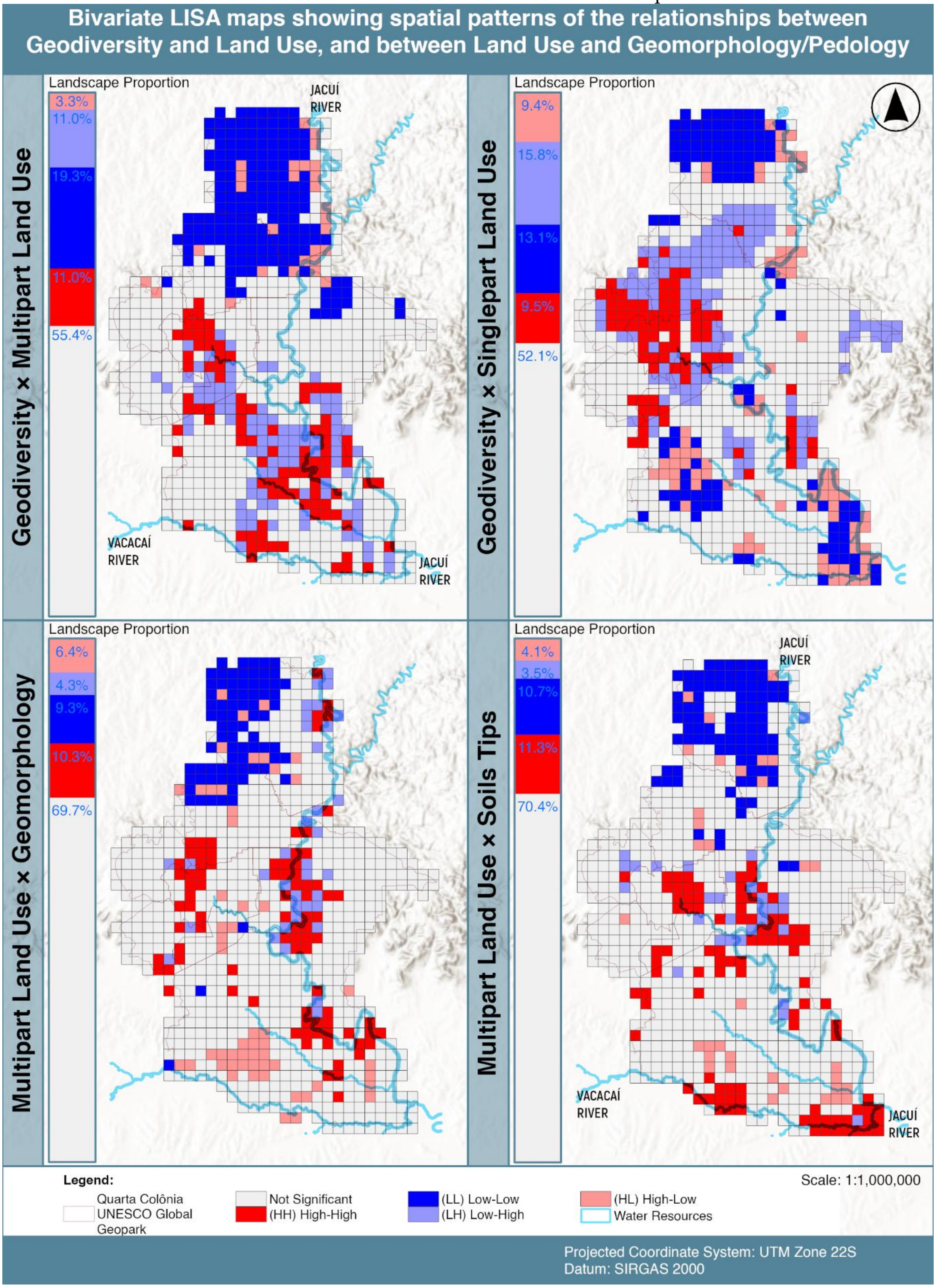
In contrast, the singlepart scenario showed predominantly weak correlations with abiotic components ($\rho \approx 0.08$; $p < 0.05$), as well as a moderate association with Usos_Multipart ($\rho = 0.28$; $p < 0.001$). The relationship between Usos_Singlepart and hydrography showed a negative coefficient ($\rho = -0.15$; $p < 0.001$).

The Global Bivariate Moran's I analysis indicated positive spatial patterns of low to moderate intensity, according to the classification proposed by Anselin (2005), in which I values close to zero indicate absence of spatial autocorrelation, values between 0.1 and 0.3 represent weak to moderate spatial association, and values above 0.3 indicate spatial dependence. In this context, positive associations were observed between geodiversity and Usos_Multipart (I = 0.215), geodiversity and hydrography (I = 0.165), Usos_Multipart and geomorphology (I = 0.167), and, more strongly, between Usos_Multipart and pedology (I = 0.271). Conversely, the relationship between geodiversity and Usos_Singlepart showed a value close to zero (I = –0.014), indicating no meaningful spatial autocorrelation between the variables.

At the local scale, bivariate LISA revealed heterogeneous spatial patterns (Figure 5), with a predominance of non-significant areas (52% to 71% of cells; $p < 0.05$). High–High clusters between geodiversity and Usos_Multipart are mainly distributed in the central-southern portion of the Geopark, while Low–Low clusters predominate in the northern half.

In the geodiversity × Usos_Singlepart relationship, High–High clusters exhibited a sparse and discontinuous distribution, mainly concentrated in the central portion of the territory. In contrast, Low–High patterns occurred predominantly in peripheral sectors and in extensive agricultural areas.

Figure 5 – Bivariate LISA autocorrelation maps for the studied variables and percentage distribution of clusters across the landscape



Source: Prepared by the authors (2026).

In the Usos_Multipart × geomorphology and Usos_Multipart × pedology analyses, High–High patterns are concentrated in the central and southern portions of the territory. In contrast, Low–High clusters correspond to areas characterized by high physical diversity and lower diversity of land uses.

Overall, the results highlight differences between the spatial patterns observed for the multipart and singlepart metrics, particularly regarding the intensity of spatial associations with the physical–natural components of the landscape.

DISCUSSIONS

The LULC distribution in the Quarta Colônia UNESCO Global Geopark reveals a landscape extensively transformed by anthropogenic activities, which occupy more than 60% of the total area. Although this pattern is common in consolidated rural landscapes in southern Brazil, its occurrence within a geopatrimonial territory is particularly significant, as it develops over a physical–natural base characterized by high geological, geomorphological, pedological, and hydrographic heterogeneity.

The results reveal a spatial configuration marked by high fragmentation, expressed by the large number of patches associated with anthropogenic land uses and natural land covers. In agricultural areas and land-use mosaics, discontinuous and heterogeneous spatial patterns predominate, whereas natural formations, although still relevant in the landscape, are also subdivided into multiple fragments. This scenario reinforces the importance of integrated approaches capable of jointly analyzing the physical diversity of the landscape and territorial occupation processes, especially in contexts where geodiversity is linked to land-use spatial organization and associated ecological processes (Gomes *et al.*, 2019; Scammacca *et al.*, 2022).

The integrated analysis of occupied area, number of patches, and spatial patterns shows that territorial occupation does not occur uniformly. Crops such as soybean and rice present large, continuous areas, characterized by predominantly single-part configurations, in which spatial continuity of land use outweighs compositional diversity. This pattern is consistent with the weak correlations observed between the singlepart metric and abiotic components, as well as with the absence of significant global spatial autocorrelation with geodiversity. From a landscape ecology perspective, such configurations are often associated with territorial matrix simplification and production specialization (Forman; Godron, 1986; Turner, 1989; Turner *et al.*, 2001).

Nevertheless, the spatial distribution of these crops remains linked to characteristics of the physical–natural base. Rice cultivation is predominantly concentrated in the alluvial plains of the Central Depression, favored by water availability, while soybean cultivation is mainly found in the Southern Plateau, where gently undulating relief and deeper soils predominate. These patterns suggest associations between geomorphological, pedological, and hydrographic conditions and land-use specialization, even within highly mechanized production systems (Jačková; Romportl, 2008; Hjort *et al.*, 2015).

In contrast, the Multipart scenarios exhibited more consistent statistical and spatial associations with geodiversity. Areas characterized by higher LULC compositional diversity showed positive correlations with abiotic components and a greater occurrence of High–High clusters in regions of high geomorphological and pedological variability. These results suggest that landscapes with greater physical–natural heterogeneity tend to exhibit more diversified territorial configurations at the local scale. Such behavior is consistent with the concept of a compositionally diverse landscape mosaic (Forman, 1995) and with findings by Tukiainen *et al.* (2017), who identified associations between abiotic heterogeneity and spatial diversity of habitats.

Among natural land cover classes, forest and grassland formations continue to occupy significant portions of the territory, although they display a high degree of spatial compartmentalization. Forest formations are mainly concentrated in steeper areas of the Southern Plateau Escarpment, where geomorphological constraints limit agricultural expansion. Grasslands, in turn, occur predominantly in more accessible areas and are therefore more susceptible to conversion into productive land uses. These results are consistent with patterns observed in other grassland landscapes in southern Brazil (Fernández *et al.*, 2021; De Oliveira Lopes *et al.*, 2024) and suggest that the persistence of natural land covers is associated both with physical–natural conditions and with historical processes of territorial occupation (Gray, 2011; Gray, 2013; Hjort *et al.*, 2015; Chakraborty; Gray, 2020).

The high correlations observed among geology, geomorphology, and pedology, as well as their strong association with the geodiversity index, are consistent with the compositional structure of the index itself and indicate integration among the main components of the physical–natural base (Serrano; Ruiz-Flaño, 2007; Zwoliński *et al.*, 2018). When analyzed together with land use and land cover metrics, these relationships suggest the coexistence of different spatial regimes of territorial organization. While multipart scenarios showed stronger associations with physical–natural heterogeneity, singlepart scenarios were more closely related to spatial continuity of specialized land uses and to landscape matrix simplification (Turner, 1989; McGarigal; Marks, 1995).

Hydrography exhibited behavior distinct from the other analyzed components. Unlike that observed by Datta (2022), its spatial association was primarily linked to specialized and continuous land uses, especially irrigated rice cultivation. This result highlights that different components of geodiversity may relate differently to patterns of territorial occupation, reinforcing the need for analyses that consider both composite indicators and their individual components.

The combined use of Global Moran's I and local spatial association indicators (LISA) enabled the identification of territorial patterns that would not be captured by global statistics alone. Convergence and contrast clusters revealed sectors where high physical–natural heterogeneity coexists with intensified anthropogenic land uses, as well as areas where these relationships are less evident. This approach addresses gaps highlighted by recent studies on geodiversity and spatial analysis, which emphasize the importance of local-scale techniques for understanding intra-regional heterogeneity and complex territorial patterns (Souza *et al.*, 2023; Esmaili, 2024).

In summary, the results indicate that geodiversity exhibits differentiated spatial associations with land use and land cover patterns in the UNESCO Global Geopark Quarta Colônia. The distinction between compositional land-use diversity (Multipart) and spatial continuity of land uses (Singlepart) contributes to understanding different forms of territorial organization and their relationships with physical–natural landscape heterogeneity, expanding the dialogue between geodiversity, landscape ecology, and spatial planning (Wu, 2013).

These findings reinforce the importance of integrated approaches for geodiversity analysis at the landscape scale, as proposed by Gomes, *et al.* (2019), by demonstrating that the physical components of the territory can be interpreted in conjunction with the spatial organization of land use.

FINAL CONSIDERATIONS

The results demonstrated consistent associations between geodiversity and LULC patterns in the Quarta Colônia UNESCO Global Geopark. The integration of geology, geomorphology, pedology, and hydrography allowed the representation of the territory's physical–natural heterogeneity through a synthetic geodiversity index, which served as the basis for the statistical and spatial analyses conducted.

Correlation and spatial autocorrelation patterns indicated that areas with higher geodiversity tend to be associated with multipart scenarios, characterized by greater compositional diversity of land use and land cover, whereas less heterogeneous areas show a higher prevalence of singlepart patterns, related to a simplification of the territorial mosaic. These results are consistent with the hypothesis that abiotic heterogeneity exhibits spatial correspondence with different forms of landscape organization, without implying direct causal relationships.

The combined application of geodiversity metrics, landscape ecology indicators, and spatial autocorrelation analyses proved useful in identifying zones of convergence and contrast between abiotic diversity and land use patterns, highlighting sectors where high physical–natural heterogeneity coexists with intensified anthropogenic transformation.

Thus, this study contributes to advancing the understanding of the relationships between geodiversity and territorial organization at the landscape scale, providing insights to support geopark planning and management. As a limitation, it should be noted that the results reflect spatial associations observed within the study area and based on the adopted metrics. Future research is encouraged to explore different analytical scales, complementary fragmentation indicators, and comparative applications in other geopark territories.

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Martiele Wilhelm: Conceptualization, Investigation, Methodology, Data curation, Formal analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Ariel Felipe Geraldo Zaghetti: Data curation, Formal analysis, Visualization, Writing – Original Draft, Writing – Review & Editing. Raquel Weiss: Supervision, Writing – Review & Editing.

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