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ORIGINAL ARTICLE

Quantitative Assessments of Geodiversity in the Area of the Seridó Geopark Project, Northeast Brazil: Grid and Centroid Analysis

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Abstract
The evaluation of geodiversity is one of the initial and main steps in the development of geoconservation actions. It is fundamental to establish parameters that quantify elements and places of abiotic nature in order to draw attention to those that are richer than the average. In doing so, it is possible to manage areas for the protection of notable geoheritage and to develop sustainable activities such as geotourism. The literature comprises several methodologies for the quantitative assessment of geodiversity, but the use of geoprocessing tools appears to be the least subjective type of analysis. From this standpoint, this work aimed to analyze the geodiversity in an area of geological interest in the northeast of Brazil by using two methodologies. The first is widely used and involved the definition of a grid to overlay the cartographic datasets that are used to define the geodiversity index. The second method is based on a centroid analysis of intersected datasets. These investigations showed that the two methodologies have similar aspects and produce a high geodiversity index for the area. This outcome supports the reliability of these methods when the results converge, with respect to the delimitation of the valuable places where geodiversity should be protected. These methods may be used as basis for the sustainable management of natural resources.

Keywords Geodiversity · Assessment · Methodologies' comparison · Geoprocessing · Grid analysis · Centroid analysis

Introduction

In environmental studies, establishing values for sites or elements of interest is fundamental for the development of preservation or conservation actions. Over time, this has led some specialized authors to propose systems for the valuation of geodiversity. Some of these systems define qualitative values (Gray 2004; Gray 2013; Brilha et al. 2018) but are often considered highly subjective as they depend on the evaluator's interpretation. Other systems define quantitative values that use mathematical models and geotechnology tools (Kozlowski 2004; Reynard et al. 2007; Serrano and Ruiz-Flaño 2007; Ruban 2010; Kot 2014).

The evaluation of geodiversity, especially in a qualitative way, may occasionally have a highly subjective character depending on the researcher's point of view and sometimes also on the level of scientific knowledge of the evaluator. However, subjectivity is detrimental when it comes to research and conservation actions concerning natural capital. Methods of quantitative analysis, employing concrete elements, are therefore essential in the development of studies of the abiotic elements of the environment.

In this perspective, the work of Kozlowski (2004) proposes a methodology for class delimitation in an assessment of geodiversity. The study outlines five classes (very high, high, moderate, low, and very low) for the classification of the abiotic diversity of a site based on the analysis of four parameters: relief, soil, surface water, and landscape structure. Reynard et al. (2007) define criteria for the evaluation of geomorphosites through the analysis of scientific, ecological, esthetic, cultural, and economic values. In that work, the authors seek to reflect in a mathematical way the abiotic diversity of a site via the integrity of its elements, their representativeness and rarity, among other criteria. These authors define

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values from 0 to 1 that correspond to either a non-existent criterion or a very high level of a certain criterion, respectively.

Additionally, Serrano and Ruiz-Flaño (2007) establish an equation to define an index of geodiversity for a region from the analysis of the local geomorphology. The authors propose that this richness is proportional to the number of elements existing in a region and to the roughness index, which represents the local morphological heterogeneity. Furthermore, the index is inversely proportional to the area analyzed. According to this method, the quantitative evaluation of geodiversity is given by the following formula:

$$\mathrm{Gd} = \frac{Eg.R}{\ln S},$$

where *Gd* indicates geodiversity index, *Eg* indicates the number of elements of the analyzed region, *R* is a roughness index, and *S* is the analyzed area. Kot (2014) uses a geodiversity evaluation method based on a points bonification system including the geology, geomorphology, hydrology, pedology, and climate evaluation of the analyzed area. In this method, the author lists classes of values from 0 to 4.

Although statistical methods are more reliable in terms of capturing the natural reality, some of these methods may still present a high subjectivity factor, due to the interaction of the analyzer with the factors of the analysis or the points bonification system. As a method of avoiding this procedure, the literature comprises examples of geodiversity quantification utilizing geoprocessing tools (Jačková and Romportl 2008; Zwolinski 2010; Pereira et al. 2013; Melelli 2014; Forte et al. 2018). One of the first geoprocessing methods is outlined in the work of Jačková and Romportl (2008), who establish cells on a grid over the analyzed area. Each cell represents a small part of the area, and the variety and diversity of elements within its limits corresponds to the richness of the local geodiversity. Zwolinski (2010) establishes a procedure for the analysis of the landform geodiversity, which produces five different classes in a GIS environment with the use of geomorphological data. This method reflects the fact that the higher and more diverse the relief in an area is, the higher the corresponding geodiversity richness index.

Pereira et al. (2013) analyze the geodiversity of an area using a grid application that establishes numerically the quantity of abiotic elements that occur in each cell, and the value obtained represents the wealth of the region. Melelli (2014) uses neighborhood analysis and a focal statistical function to determine the geodiversity index. Forte et al. (2018) propose to establish the geodiversity index of an area from the union of several thematic maps. These overlays generate new polygonal data, the central points of which are the centroids, which can be interpolated by the concentration of occurrences to obtain the index.

The term "geodiversity mapping" encompasses, in addition to spatialization, the statistical analysis and treatment of the abiotic elements of the natural environment. There are three main ways of performing the cartographic analysis of geodiversity: map algebra, grid occurrence counting, and generalized additive modeling. Several variations within these large groups are found in the literature. There is, therefore, a wide range of geodiversity assessment methods that depend essentially on the cartographic base used for the analysis (Rodrigues and Bento 2018).

The evolution of available literature, techniques, and instruments provide different approaches to such studies of the natural environment. In this work, we used two quantitative geodiversity evaluation methodologies applied to an area of northeast Brazil. We first explored the grid overlap method (Pereira et al. 2013), and followed that by an evaluation of the centroid method (Forte et al. 2018). Through this comparison, we aimed to identify the locations with high geodiversity index values within the region of interest and to evaluate the reliability of the methods used.

Study Area

The study area corresponds to the territory of the Seridó Geopark Project, a region of 2800 km^2 in the state of Rio Grande do Norte, in the extreme northeast of Brazil (Fig. 1). The premise of the project proposal is the sustainable use of the natural resources found in this area. Seventeen geosites were inventoried (Silva 2018) and make up the remarkable geoheritage of this territory, comprising six municipalities, from north to south: Cerro Corá, Lagoa Nova, Currais Novos, Acari, Carnaúba dos Dantas, and Parelhas.

The climate of this region is semi-arid, with average rate of 3600 h/year, corresponding to 12 h per day (IDEMA 2009). The vegetation is composed of the caatinga biome, characterized by woody plant formations of low or medium size, typically deciduous and of xerophytic character, with high quantities of thorny plants (IDEMA 2009). The relief in the area has a polygenetic origin, with the occurrence of interplanaltic depressions and semi-arid inter-mountains, covered by different types of caatinga and dotted by inselbergs (Diniz and Oliveira 2015). The hydrography is composed essentially of intermittent rivers, with some cases of perenization by anthropic action.

Geologically, this region comprises units of the Paleoproterozoic to the present day. The basement is composed of high grade metamorphic rocks (Caicó Complex), overlain by neoproterozoic supracrustal rocks (Seridó Group). There is evidence of intrusive and extrusive magmatism in the Ediacaran, Cambrian, Lower Cretaceous, and Paleogene periods. The geological record also comprises sandstones, Neogene conglomerates, and quaternary coverings.

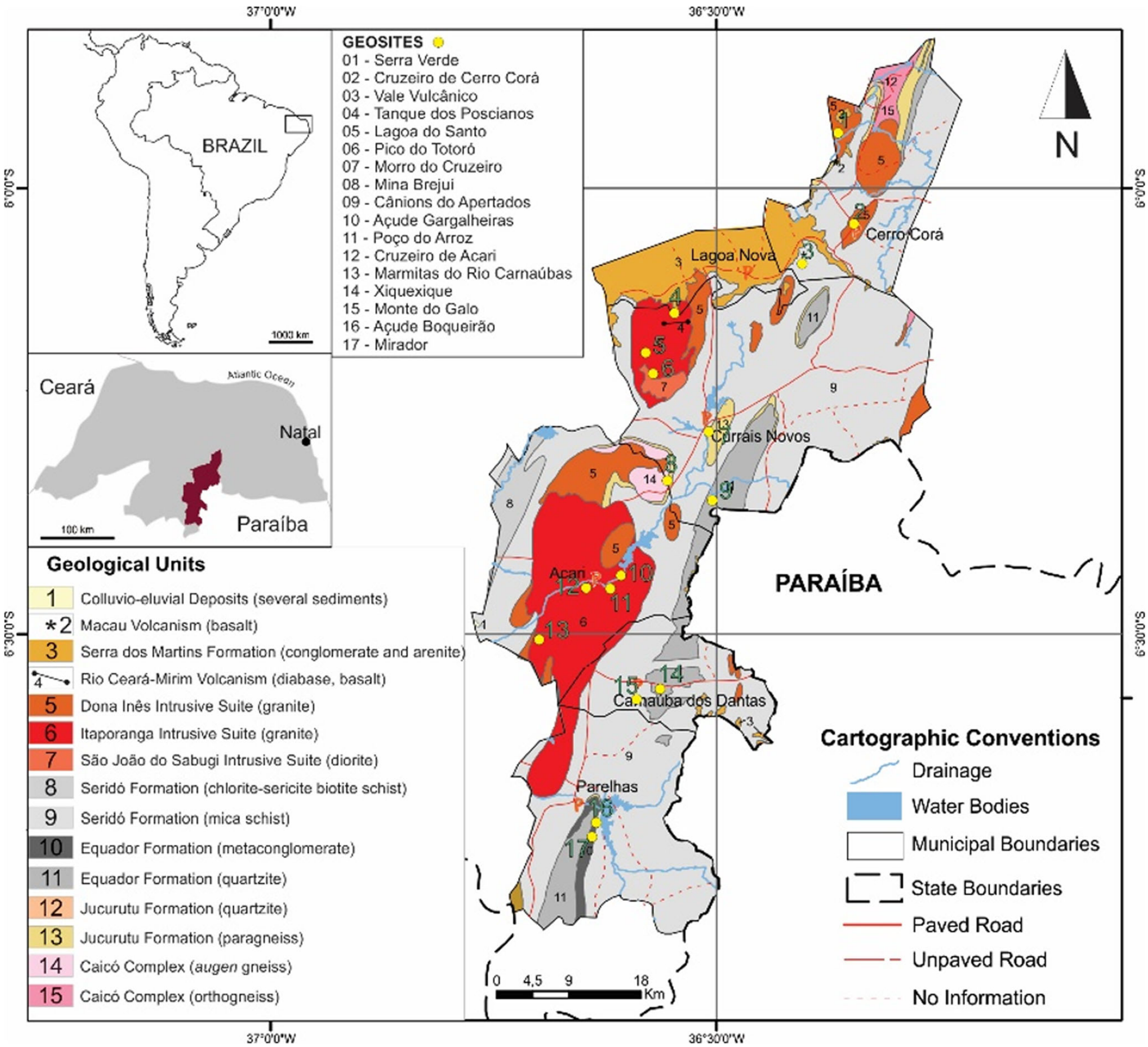


Fig. 1 Geological and location map of the study area

Methods

This work was based on the use of two quantitative geodiversity analysis methodologies in the area of the Seridó Geopark Project. In so doing, the results from the different methodologies were able to be compared to ascertain whether they are consistent and reliable, and the main differences and similarities could be highlighted.

The first method was proposed by Pereira et al. (2013) and was later used in studies in Brazil by Arruda and Barreto (2015), Silva et al. (2015), Araújo and Pereira (2016), and Santos et al. (2017). It is therefore an application that has been appraised in these specialized studies. The method is based on the generation of a regular grid formed by polygons, upon each thematic map used as a cartographic source (Fig. 2). The number of elements within each polygon represents the value, or sub-index. As the total area of this work is 2802 km^2, a mesh with polygons of 2×2 km was created in order to generate 824 polygons to cover the entire region. After the computation of all the data, thus creating the desired sub-indexes, the sum was calculated in order to generate the total index, which was interpreted as the geodiversity index in this methodology. This index can be presented in color scales or textures on a thematic map, by means of classification by simplified or interval categories.

As a way to improve the visual display of the map, it is possible to perform an interpolation. For this, the polygons are converted into central points, which carry in their attributes the corresponding values of the obtained geodiversity index. Finally, a map is generated by the use of kriging or kernel

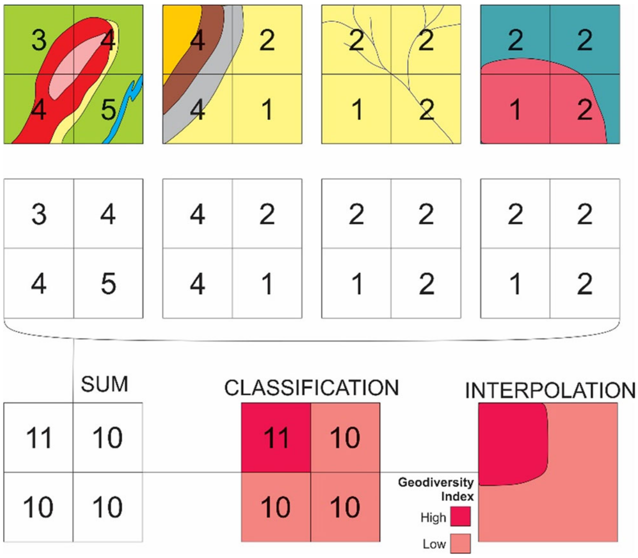


Fig. 2 Schematic representation of quantitative analysis method proposed by Pereira et al. (2013)

density estimation. From its formula, the kernel density is given by the sum of the events. Thus, the closer the points are spatially, the higher the obtained density is, which in the method used in this work represents a greater diversity of abiotic elements and, therefore, a proportionally greater wealth index of geodiversity.

It was assumed that u_1, u_2, u_3, ..., u_i are locations of n occurrence points of events in the analyzed region. The kernel density was calculated by considering the events contained in the radius h around each point u, according to the distance d between the position of u_i and the unmeasured sample and a multiplying factor K, as shown in the equation below,

$$f_h(u) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{d(u_i;u)}{h}\right), d(u_i;u) \leq h$$

where K is the Kernel function, h is the search radius, u is the position of the center of each cell, u_i is the position of the i-th sample, and n is the total number of outbreaks. The cartographic result obtained is a choropleth map, whose units represent, in their areas, different indexes of geodiversity reflecting a greater or lesser concentration of abiotic natural elements. The greater the number of elements in an area is, the greater the density of occurrence of the elements is, and therefore, the greater the wealth index of the region is.

In order to compare the results of this first method with a different methodology, the approach proposed by Forte et al. (2018), initially proposed by Forte (2014), was also applied in this work. This methodology is based on the integration of diverse cartographic sources in a compilation of the abiotic diversity of a region. Unlike other methods existing in the literature, it does not use gridding for the evaluation of the wealth of a region. However, it is also based on the use of geoprocessing resources.

In the first stage of execution of the method proposed by Forte et al. (2018), the diverse sources of information are unified, which graphically represents the abiotic elements of the studied region. Thus, the primary product generated is a map of polygons that correspond to the richness of the local geodiversity. From this map, central points in each of the resulting polygons are generated, providing a map of the point concentration of the wealth of these elements.

Thus, following the procedure of joining the thematic maps and the generation of the centroids of the resulting polygons, a sum operation was performed to unite the mineral occurrences data with the centroids. In this way, the geographic distribution of the centroids of the unified thematic maps and the mineral occurrence data was obtained, representing the union of polygonal and point information for the area. Finally, this map undergoes kernel density processing, resulting in a choropleth map as in the first methodology outlined above. The result of this process was a final choropleth map where the centroid data was interpolated by kernel density estimation to represent the final index of geodiversity for the area (Fig. 3).

In this work, the two methodologies were completed using the Open Source software QGIS 3.0.2, and the data used are indicated in Table 1. The scale of the final map depends directly on the scales of the maps from which the spatial information used in this study was obtained. Thus, the quantitative analysis maps produced in this work are at a scale of

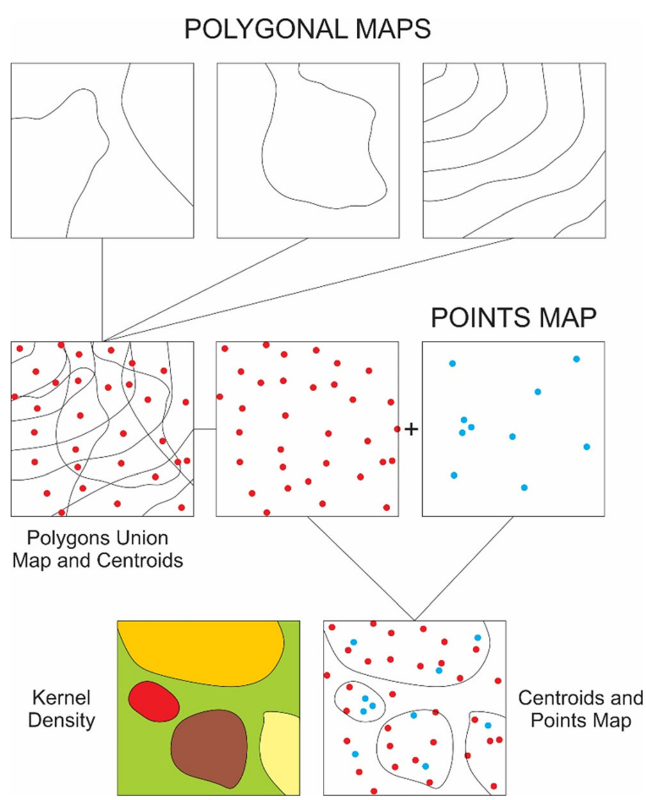


Fig. 3 Schematic representation of centroid analysis method proposed by Forte et al. (2018) and applied in this work

Table 1 Cartographic datasets used

Dataset	Type of data	Scale	Source
Geomorphology	Polygon	1:500.000	Diniz et al. 2017
Hydrography	Polygon	1:500.000	Angelim et al. 2006
Lithology	Polygon	1:500.000	Angelim et al. 2006
Pedology	Polygon	1:250.000	IBGE 2005
Mineral occurences	Point	1:500.000	Angelim et al. 2006

1:500,000, which corresponds to the smallest scale among the thematic input maps.

Results

Methodology of Pereira et al. (2013)

For the determination of the quantitative value of geodiversity in the Seridó Geopark Project using the method of Pereira et al. (2013), a grid with 824 squares of 2 × 2 km was superimposed on each of the information planes used (comprising geomorphology, hydrography, lithology, pedology, and mineral occurrences). For each set of cartographic data, a representative sub-index for the analyzed element was obtained, and the total sum of the sub-indexes indicated the total geodiversity index of the studied area (Fig. 4).

In the analyzed area, the geomorphology sub-index shows minor variations, with obtained values ranging from 0 to 3. Numerically, the highest indexes are found mainly in the scarp of Santana Sierra, to the north of the area, in the margin of the Sertaneja depression with the Borborema plateau in the southern part of the area, and along the margins of the interplanaltic depression of the Acauã in the center. The hydrography sub-index shows the lowest values among the evaluated geodiversity sub-indexes. This is directly due to the incipient hydrography in this region, with the effect that higher values only occur in those places with the few mapped water bodies.

The lithology sub-index in Seridó Geopark Project is representative of the observed lithologies and demonstrates the variation of the mappable lithotypes in the region. The highest values of this specific sub-index occur mainly around the Acari Granite in the center of the region, in the northern portion of the area where the basement rocks, the Seridó Group and various granites occur, and to the south around the Boqueirão dam, around which the metaconglomerates, schists, and quartzites of the Seridó Group occur.

The sub-index of pedology shows higher variability over short spatial scales, as the value is observed to vary by up to four units from one grid square to another. This is not due to the diversity of pedological profiles, but to the way that these types of soils vary on a map. Nevertheless, it constitutes a fundamental component of the region's geodiversity index. The sub-index relating to mineral occurrences shows higher values in the south and center-east portions of the analyzed area, reflecting the diversity of minerals of economic interest in these regions.

From the sum of all the sub-indexes obtained, the geodiversity index of the Seridó Geopark Project according to the method of Pereira et al. (2013) is shown graphically on a map in Fig. 4, with values ranging from 1 to 13.5. In order to better present the final index result, the interpolation of the values was performed by positioning the centroids in each grid square of the analysis mesh used in this work (Fig. 5). The index values obtained were then divided into five classes.

The mean and high values of geodiversity in the Seridó Geopark Project are concentrated in the extreme north and south of the area, in the margins of Santana Sierra, in a small area of the center-east and in a central belt. These results show a good correlation with the Geopark geosites, namely the geosites Morro do Cruzeiro, Mina Brejuí, Açude Gargalheiras, Açude Boqueirão and Mirador, which are located in areas with a very high value (12 to 14) of geodiversity. The geosites Cruzeiro de Cerro Corá, Tanque dos Poscianos, Poço do Arroz, and Cruzeiro de Acari are also in regions with a high index (9–12). The geosites Serra Verde, Vale Vulcânico, Lagoa do Santo, Pico do Totoró, Xiquexique, and Monte do Galo are located in areas of intermediate index values (6–9). Only the geosites Cânions dos Apertados e Marmitas do Rio Carnaúba are found in regions with lower index values (3–6). However, one area with a high geodiversity index value in the region is not currently a designated geosite. This area is located in the center-east portion of the region and hosts a high concentration of mineral occurrences, which is responsible for raising the geodiversity index.

Methodology of Forte et al. (2018)

The second methodology applied in this work is based on the union of cartographic data and the creation of centroids proposed by Forte et al. (2018). The union of the polygonal data and the subsequent creation of its centroids generated 1520 data points, which were added to the data relating to the 485 mineral occurrences, which are also represented by point geometry. The unified map and centroids were subsequently generated (Fig. 6). The cartographic representation of the geodiversity index of the studied area was created through kernel density estimation using the point information from the unified map. The obtained data was subdivided into five index classes (Fig. 7).

The highest values of the geodiversity index in the area of the Geopark obtained from the method of Forte et al. (2018) are found in restricted zones in the northern margin and in the central areas. However, a predominance of high-value areas occurs in the southern area (Fig. 7). In relation to geosites,

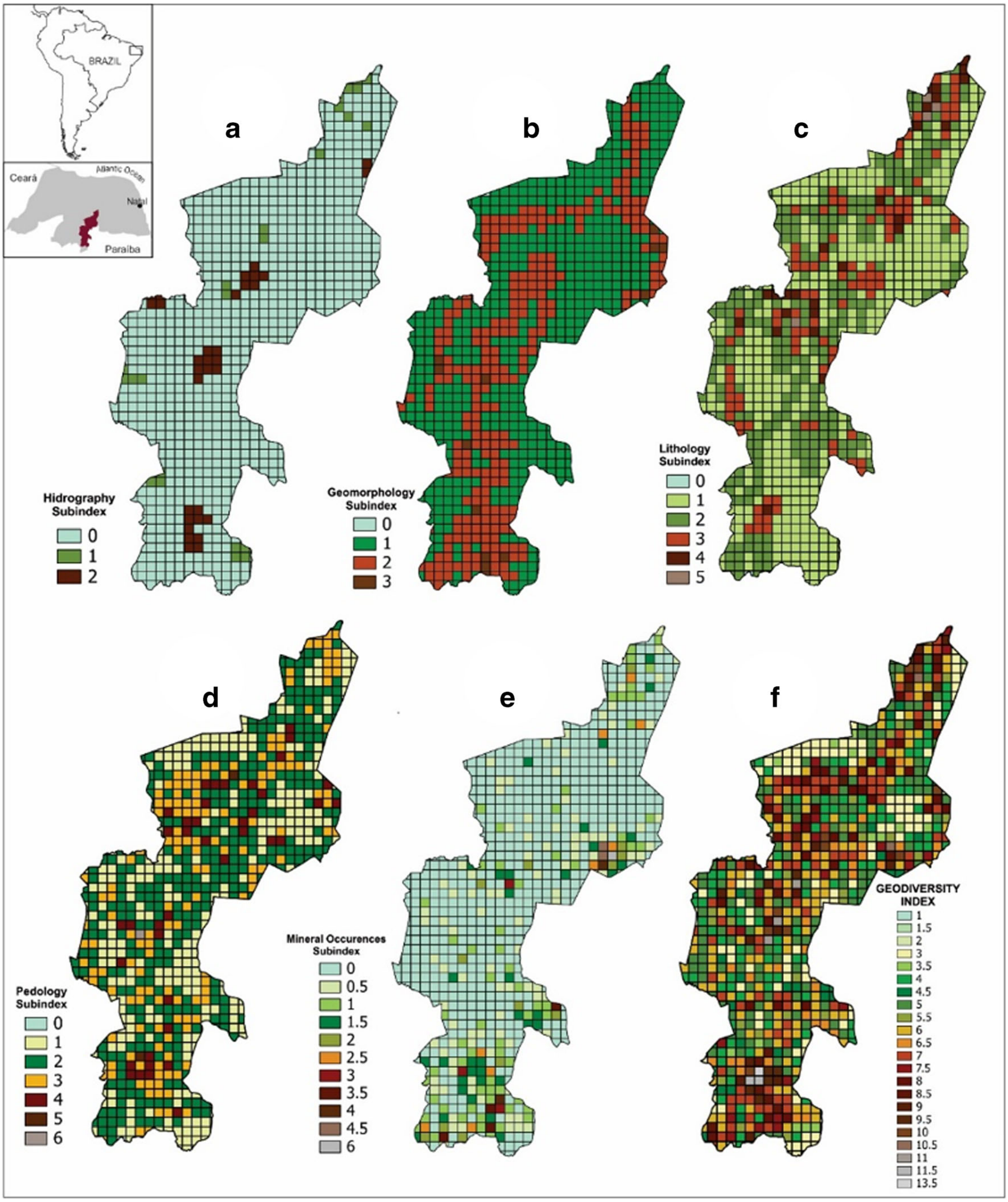


Fig. 4 Maps of subindex and index of geodiversity obtained: **a** hydrography subindex; **b** geomorphology subindex; **c** lithology subindex; **d** pedology subindex; **e** mineral Occurences Subindex; **f**) Geodiversity index

very high values (24–28) of this second geodiversity index are located within the geosites of Morro do Cruzeiro, Açude Gargalheiras, Açude Boqueirão, and Mirador. The geosites Cruzeiro de Cerro Corá, Poço do Arroz, Cruzeiro de Acari, Xiquexique, and Monte do Galo show a good correlation with areas of intermediate to high index values (12–24), whereas the geosites Vale Vulcânico, Pico do Totoró, Mina Brejuí, and Marmitas do Rio Carnaúbas are located in areas of lower geodiversity index (6–12). The geosites Serra Verde, Tanque dos Poscianos, Lagoa do Santo, and Cânions dos Apertados are located in areas of very low geodiversity index (1–6). Five areas with high geodiversity values do not correspond to geosites. These are areas that host a concentration of mineral occurrences or a higher lithological diversity.

The delimitation of higher index areas using the method of Forte et al. (2018) is more restricted and didactic, and these locations are well defined cartographically. This results from the kernel interpolation process and reflects the variation in the

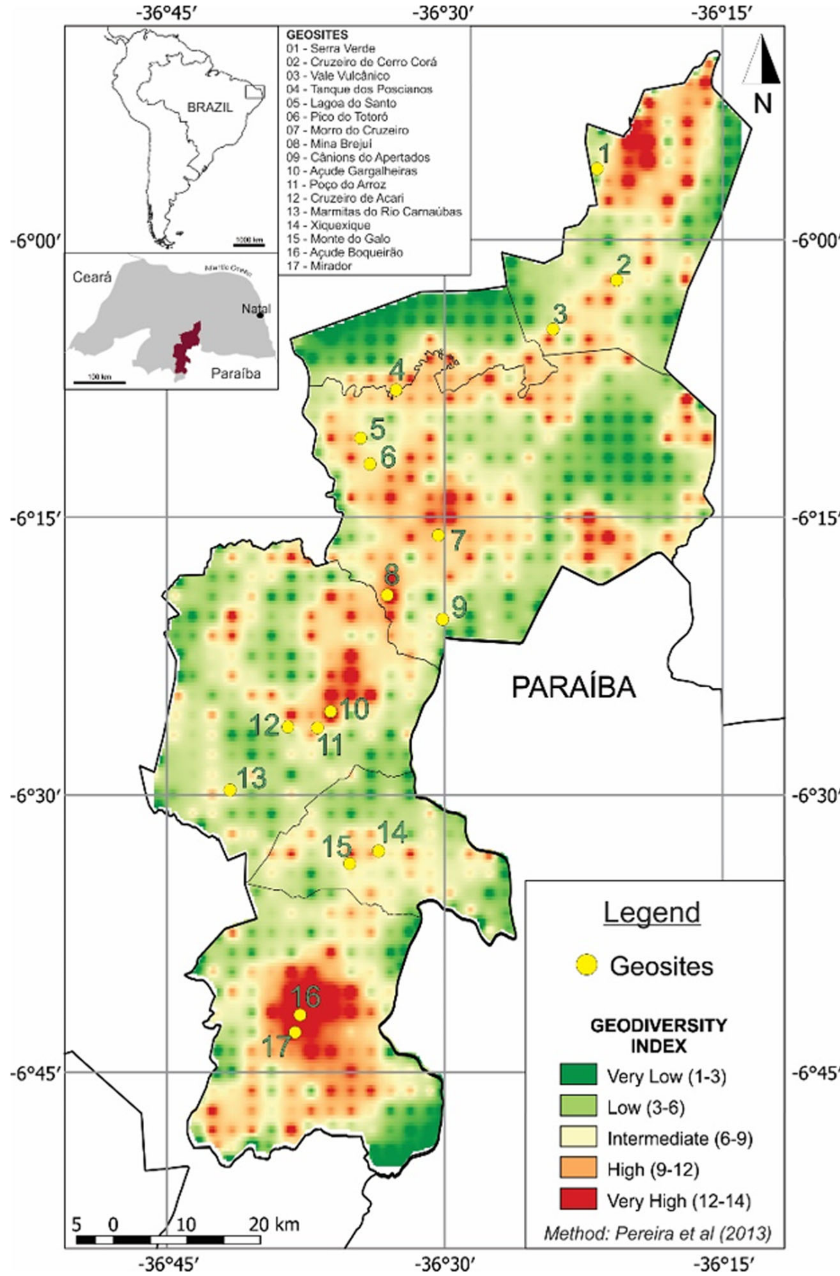


Fig. 5 Geodiversity index map of Seridó Geopark Project according to the method of Pereira et al. (2013)

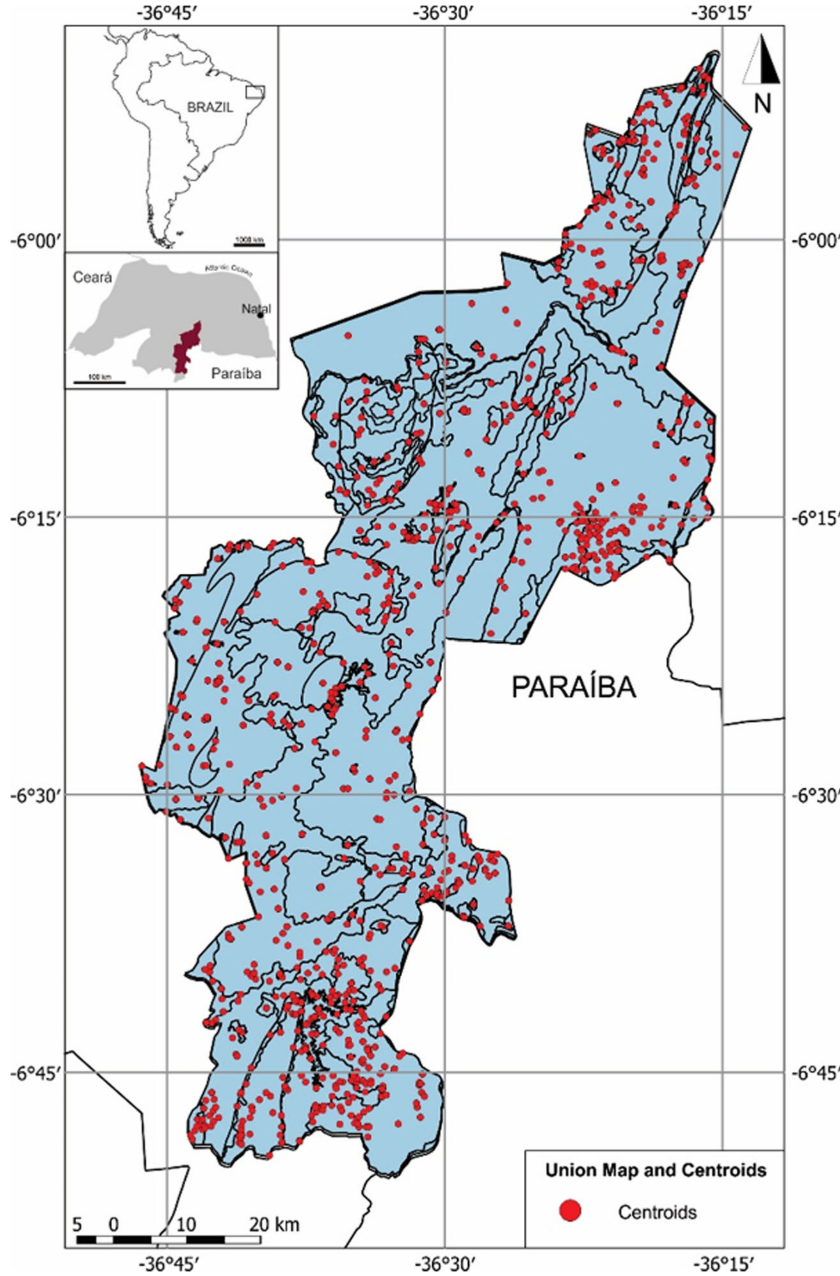
distances between the analyzed samples. This is because, according to the mathematical basis of the interpolator, the positions of the data directly influence the result and the more irregular the mesh, the better defined the areas will be. In contrast, the interpolation is computed with a regular mesh in the method of Pereira et al. (2013), as this method uses points that represent the centers of each grid square.

Discussion and Final Remarks

The two methods of quantitative evaluation used in this research showed good results with respect to the delimitation of regions with higher geodiversity index, compared with the global mean of the area. Both methodologies use geoprocessing tools for geodiversity analysis but are dependent on available cartographic sources. As this area of the Brazilian northeast has a deficit of maps at a sufficiently detailed scale, the results express only the features at the smallest available scale. The elaboration of a more detailed cartographic base will improve the results of both methods and will allow the highest geodiversity index areas to be delineated in an even more satisfactory way. This would better highlight which areas should be prioritized in the geoconservation actions that may be implemented.

In general, higher values of the geodiversity index are mainly influenced by the number of mineral occurrences, by

Fig. 6 Union map of abiotic nature datasets and centroids of polygons



local lithology and geomorphology. A concentration of sites of average to high index values is observed in the escarpment of the Santana Sierra, where there exists a lithological variation and evident relief, which both translate into the high quantitative geodiversity value of the area. The interplanaltic depression of Acauã, located at the center of the region, also represents an area of high geodiversity index, as well as the regions to the south and center-east of the region, where there are many mapped mineral occurrences.

The results of the quantitative evaluations reveal an area of high geodiversity index where no location of geological interest is currently identified in the inventory of the Seridó Geopark Project. Therefore, it has indicated a necessity of new analysis, with acquisition of more data to verify the existence of a new geosite in this region that would become the eighteenth to be located within the Geopark. Only the geodiversity index does not guarantee the existence of a new geosite in the region, which must be confirmed in the field stage. New fieldwork should aim to acquire more detailed data on other areas of the Geopark.

When compared, the two methodologies showed a strong similarity. As the approach involving the use of polygonal meshes on cartographic data is already widely used in the literature, its results can be utilized as parameters for the validation of other quantitative methods, such as the second methodology tested in this work. The delimitation of high

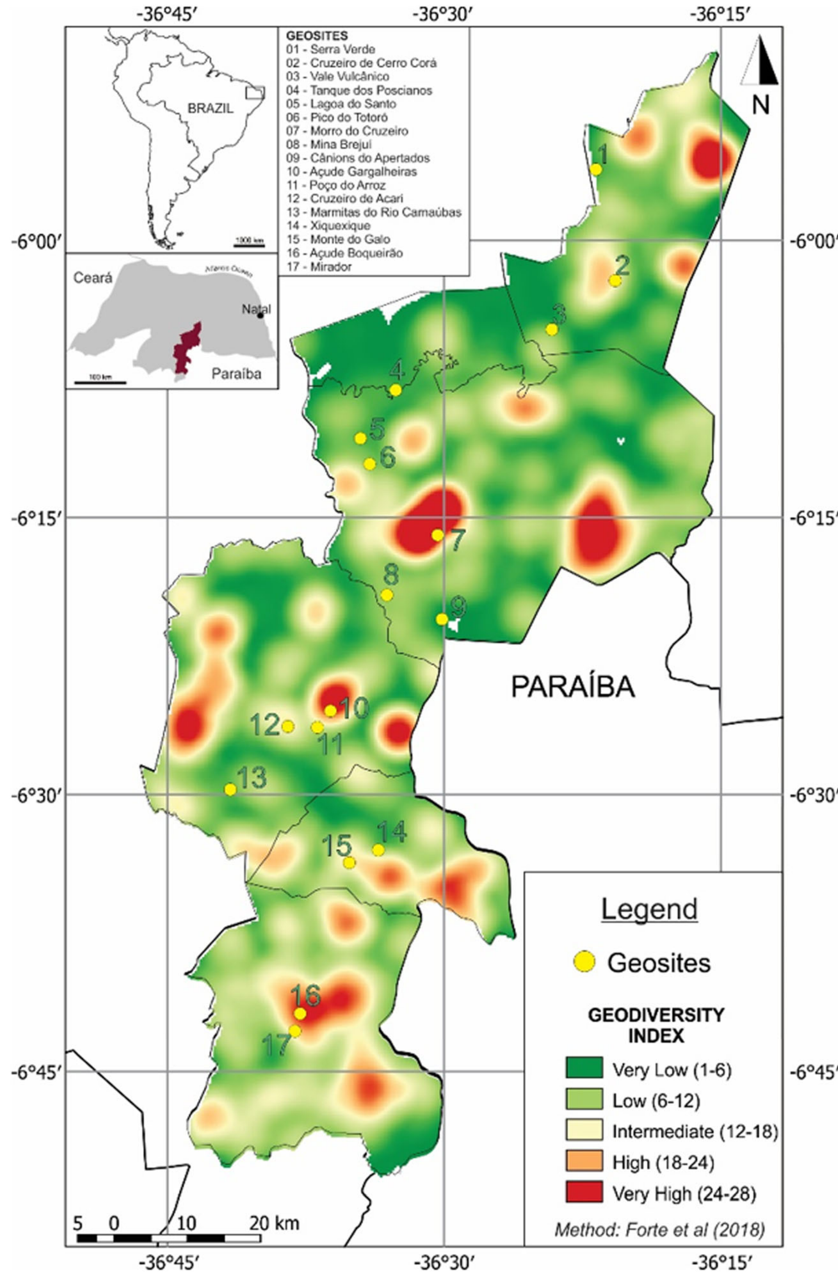


Fig. 7 Geodiversity index map of Seridó Geopark Project according to the method of Forte et al. (2018)

geodiversity index areas is similar in both methods, and these areas were mainly observed in the south, north, center, and center-east regions of the territory. The areas corresponding to the mean value of the index areas are more spaced out, especially in the method of Pereira et al. (2013). It is, therefore, not possible to establish a clear similarity between the two methods used in the definition of mean values. However, lower index values identified by the two methodologies show a good correlation.

The main difference between the methods used in this study is the visual presentation of the results, as there is a strong similarity in the definition of the areas of higher geodiversity index value. For the interpolation in the method of Pereira et al. (2013), the center points of each grid are used, which generates a more regular mesh, leading the interpolation to a more quadratic form, with a less continuous visual aspect, however correct it may be. The method of Forte et al. (2018) demonstrates a more realistic-looking interpolation. This occurs because the interpolated data are irregularly scattered as they represent the centroids of the unified polygons of the mapped information. It is therefore possible to affirm that both methods have a very high applicability with regard to the quantitative evaluation of the geodiversity of an area in the form of an index. This is mainly because these methodologies are not very subjective, do not involve the direct intervention of the evaluator, and are only dependent on the representation of the elements to be computed for scoring purposes.

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