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PROFILE

Geodiversity Assessment of Paraná State (Brazil): An Innovative Approach

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Abstract Geodiversity is considered as the natural range of geological, geomorphological, and soil features, including their assemblages, relationships, properties, interpretations, and systems. A method developed for the quantitative assessment of geodiversity was applied to Paraná, a Brazilian state with an area of about 200,000 km^2. The method is based on the overlay of a grid over different maps at scales ranging from 1/500,000 to 1/650,000, with the final *Geodiversity Index* the sum of five partial indexes calculated on a 25 × 25 km grid. The partial indexes represent the main components of geodiversity, including geology (stratigraphy and lithology), geomorphology, paleontology, and soils. The fifth partial index covers mineral occurrences of geodiversity, such precious stones and metals, energy and industrial minerals, mineral waters, and springs. The *Geodiversity Index* takes the form of an isoline map that can be used as a tool in land-use planning, particularly in identifying priority areas for conservation, management, and use of natural resources at the state level.

Keywords Geodiversity · Assessment · Indices · Mapping · Nature conservation · Paraná State (Brazil)

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Introduction

The concept of geodiversity is in fact a fairly recent one. According to Gray (2004, 2005), the word geodiversity was used, most probably for the first time, during the 1993 Malvern Conference on Geological and Landscape Conservation, as well as in articles from Australia in the mid-1990s. In spite of being a rather new notion, most experts, mainly from Europe and Australia, define geodiversity as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, processes), and soil features. It includes their assemblages, relationships, properties, interpretations, and systems" (Gray 2004). This author also characterizes geodiversity using an enlarged set of values, including scientific, educational, cultural, esthetic, economic, and functional, together with a group of common threats.

Complementary for some other authors, geodiversity should include not only the natural materials and processes described above, but also the systems produced by man-made processes (e.g., Serrano and Ruiz-Flaño 2007). However, for the majority of researchers, the results of man-made processes should be excluded from the definition of geodiversity, arguing that their inclusion dilutes geodiversity to a wide-ranging concept with no practical application for the resolution of common problems. Therefore, for the purpose of the present paper, man-made systems are not included.

The geodiversity concept has already been used for a variety of purposes. For instance, the Brazilian Geological Survey (from Portuguese Companhia de Pesquisa de Recursos Minerais [CPRM]) has recently published the Geodiversity Map of Brazil (at 1:2,500,000 scale; CPRM 2006), a synthesis of the major geosystems which constitute the national territory, as well as their limitations and potential uses (Silva 2008). However, this CPRM geodiversity map was based only on lithostratigraphy and mineral resources databases, not taking into account other geodiversity elements as landforms, soils, and hydrography that are also important to support decision-making and land-use management.

In the UK, following the experience of applying Local Geodiversity Action Plans to several regions (Burek and Potter 2006), a national Geodiversity Action Plan was produced in order "to provide an environment in which the rich geodiversity of the UK can be understood, valued, and conserved. Making geodiversity relevant to the way we work and live, providing a sense of place and contributing to the decisions we make about a sustainable future for our environment, for both people and nature" (Geoconservation Commission 2008).

Nevertheless, the concept of geodiversity is not as widely accepted and used as that of biodiversity. Geodiversity is frequently referred to as just a theoretical approach with no particular relevance or application. In the literature, geodiversity often appears linked with issues associated with geological heritage and geoconservation (e.g., Gray 2004, 2008a, b; Alexandrowicz and Kozlowski 1999; Carcavilla and others 2008; Gordon and others 2012), but these concepts should not be misinterpreted as being one and the same. Whereas geodiversity refers to all the abiotic variety of nature, geological heritage is simply the set of the most relevant geodiversity elements with particular importance for science, education, or tourism. Geoconservation is a general term encompassing all the steps required to ensure the identification, evaluation, conservation, and promotion of geological heritage (Henriques and others 2011).

In order to be accepted as a useful tool, geodiversity must be assessed according to an accepted methodology. Only then can it be fully used for nature conservation and land-use planning, as biodiversity currently is. Common geological and/or geomorphological maps play an important role in qualitative, but not quantitative, geodiversity assessment. In addition, as technical documents, they are difficult to read for non-geologists, thus limiting their use in routine planning.

But how can geodiversity be assessed? The creation and calculation of geodiversity indices involving all geodiversity elements are not yet well established or widely implemented, with only a few attempts made so far (Kozlowski 2004; Carcavilla Urqui and others 2007; Serrano and Ruiz-Flaño 2007; Jačková and Romportl 2008; Benito-Calvo and others 2009; Zwoliňski 2009; Hjort and Luoto 2010, 2012; Ruban 2010, 2011; Knight 2011; Pellitero and others 2011). These recent studies provide a first set of proposals for an assessment method. However, these proposals are difficult to apply practically because they tend not to consider the whole concept of geodiversity. Several major key-points remain unsolved, including: Which criteria should be used to assess geodiversity? How should the scale-factor be dealt with, i.e., how does the size of the area under analysis influence the type of criteria and indicators? How should the results of a given methodology be presented (e.g., map, table…)?

The development of a proper methodology for geodiversity assessment is a key subject, from both a theoretical and applied point of view. Just as biologists have had many years' experience dealing with biodiversity assessment, so the use of geodiversity indices will hopefully constitute a similarly important tool with which to support land-use planning and nature conservation initiatives (Beer and Higgins 2000; Benson and Roe 2000).

This work aims to define and test a methodology for geodiversity assessment adapted to both national and regional scales. This method is intended to assess all geodiversity components and to avoid overrating any particular component, such as lithology or relief, a common weakness of many other methods. A second aim is the production of a *Geodiversity Index map* based on the calculation of a *Geodiversity Index*. This kind of map represents a proper planning tool, allowing easy interpretation by those with no or little geological background. The state of Paraná (Southern Brazil) was used as an example with which to test the proposed methodology considering the availability of different cartographic data.

State of the Art

As mentioned in the previous section, the assessment of geodiversity is a relatively new subject, and one that has involved research following two distinct trends. Some authors referring to geodiversity assessment have in fact conducted studies on the identification and characterization of geological heritage, which is but a small part of the whole concept of geodiversity (e.g., Engering and Barron 2007). In contrast, other authors have taken a more holistic approach and consider "*geodiversity assessment*" as the quantification of the entire range of natural geological diversity (e.g., Carcavilla Urqui and others 2007; Serrano and Ruiz-Flaño 2007). This second tendency forms the basis for the present proposal, attempting as it does to combine all elements of geodiversity occurring in nature.

Burnett and others (1998) and Nichols and others (1998) were probably the first authors to try to assess geodiversity employing a methodology based on the Shannon–Weaver diversity index (Shannon and Weaver 1963), the latter being used by biologists in the assessment of biodiversity. Initially intending to calculate the relationship between the biodiversity and geodiversity indices, these early studies showed that, taking into account variation in terrain and soil properties, areas of high geomorphological heterogeneity were also characterized by high values of the biodiversity index. Similar conclusions were reached by Silva (2004) and Jačková and Romportl (2008), in spite of the later investigations also admitting having some limitations in terms of their geodiversity assessment method.

Existing approaches to geodiversity assessment essentially focus on geomorphology. For instance, Serrano and Ruiz-Flaño (2007) and Serrano and others (2009) proposed the calculation of a *Geodiversity Index* based on the relationship between a variety of physical elements (geological, geomorphological, hydrological, soils) and the roughness and surface of geomorphological units.

The result for each geomorphological unit is a semi-quantitative scale involving five geodiversity values, from very low to very high. However, such an approach clearly seems to bias the concept of geodiversity toward that of the geomorphological unit. In addition, the determination of roughness coefficients involved is not compatible with the geodiversity assessment of large areas (hundreds or thousands of square kilometers). The methodology proposed by Kozlowski (2004) also places a strong emphasis on geomorphology. Here five classes based on four main elements (relief, soils, surface water, and landscape structure) were defined in order to assess the geodiversity of Poland, again ranging from very low to very high.

Benito-Calvo and others (2009) recently presented another geodiversity assessment exercise for a large area, based on morphometric, morphoclimatic, and geological properties, as well as, indirectly, soil properties. Using their developed methodology, the authors concluded that the highest diversity values of the Iberian Peninsula were related to Alpine collisional orogens and reactivated chains of the Precambrian–Paleozoic massif. In contrast, regions associated with intraplate orogens accompanied by sedimentary cover and characterized by extensive planation surfaces had lower values. The lowest geodiversity values were associated with Mesozoic areas with no significant tectonic deformation, as well as Cenozoic basins.

A partial exercise in geodiversity assessment based on the method used for biodiversity assessment was developed by Costantini and L'Abate (2009), with the aim of evaluating and grouping Italian pedosites.

Finally, Hjort and Luoto (2010) used features of geology, geomorphology, and hydrology to assess geodiversity across a 285 km^2 area in northern Finland. Employing a grid-based system, the authors concluded that their method was suitable for both mapping and quantifying geodiversity, arguing that it could be used to understand geodiversity–environment and geodiversity–biodiversity relationships.

Geological Setting of Paraná State

The state of Paraná is located in southern Brazil (Fig. 1a) and is bordered by São Paulo State to the north, the Atlantic Ocean to the east, Santa Catarina State to the south, the Republic of Argentina and the Republic of Paraguay to the southwest and west, respectively, and the state of Mato Grosso do Sul to the northwest. Paraná State occupies an area of 199,570 km^2 (Santos and others 2009).

Two main geological and morphostructural domains have been defined as present within Paraná State (Fig. 1b): the *Atlantic Orogenic Belt* and the *Paraná Sedimentary Basin*. Areas of a third domain, *Cenozoic Sedimentary Basins and Tectonic Depressions,* are less extensive (Mineropar 2006a).

Located in the east of the state, the *Atlantic Orogenic Belt* is polyorogenic in nature, associated with various geotectonic cycles expressed by sedimentation, metamorphism, faulting, folding, and igneous activity. The evolutionary stages of the Atlantic Orogenic Belt are still poorly understood. Rocks are grouped into a metamorphic core with structures representing three major Proterozoic cycles linked to: the Atlantic Paleoproterozoic supercontinent, the Rodinia supercontinent of Mesoproterozoic/Neoproterozoic age, and the western Gondwana supercontinent dating to the end of the Neoproterozoic (Almeida and Carneiro 1998). The long geological evolution of the Atlantic Orogenic Belt ended with the cratonization of an extensive area, known as the South American Platform, during the early Paleozoic.

From a geomorphological point of view, the Atlantic Orogenic Belt morphostructural unit consists of two morphosculptural units: Serra do Mar and Paraná First Plateau (Maak 2002). The *Serra do Mar* unit is a chain of mountains with peaks up to 1,800 m in altitude and straight slopes exceeding 47 %. These mountains are composed of high-grade metamorphic rocks such as migmatites, gneisses, schists, and quartzites, often in association with intrusive rocks. Characterized by mountainous relief ranging between 400 and 1,200 m in altitude, and straight slopes of between 30 and 47 %, the northern sector of the *Paraná First Plateau* is shaped on low-grade metamorphic rocks, metavolcanic rocks, granitic intrusions and diabase dikes. The southern sector is relatively uniform, with average heights of between 850 and 950 m, slopes less than 6 % and open valleys. This smooth landscape is carved on crystalline rocks, such as migmatites, shales, and gneisses, crosscut by pegmatite and diabase dikes (Maak 2002).

In South America, the *Paraná Sedimentary Basin* covers a large area of about 1,600,000 km^2, representing a significant proportion of the Paraná State. Marine and continental deposits dating from the Silurian to the Upper Cretaceous fill the basin. This morphostructural unit comprises two morphosculptural units: Paraná Second Plateau

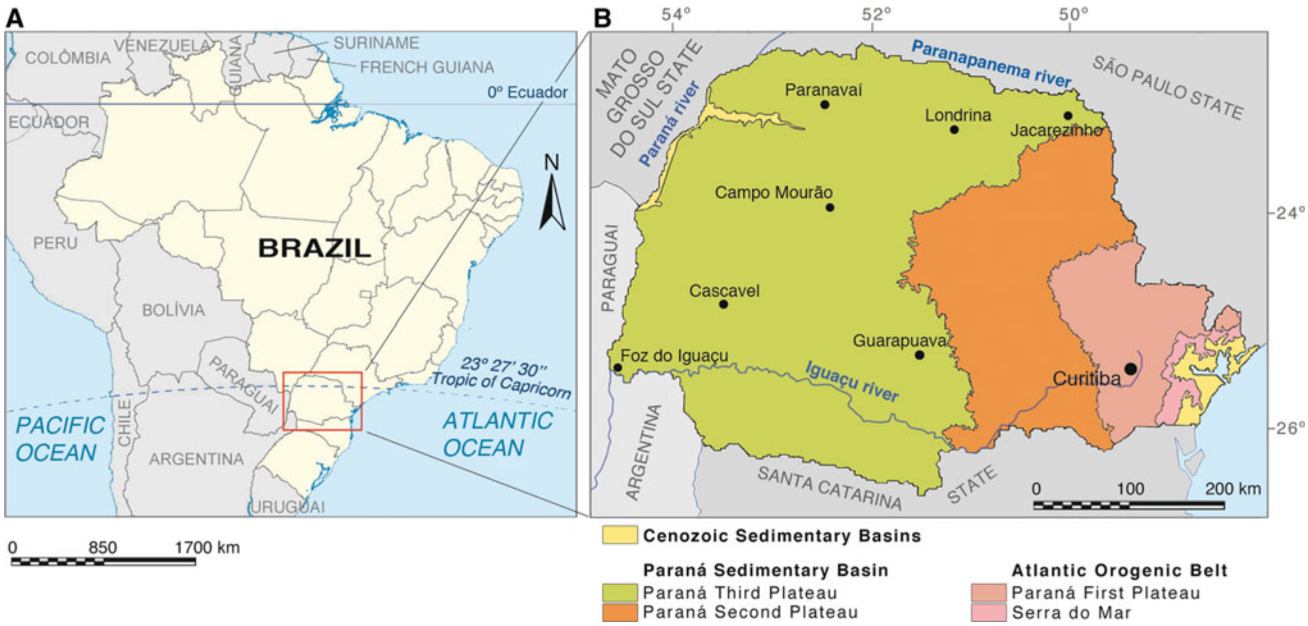

Fig. 1 **a** Location of Paraná State (adapted from IBGE 2005); **b** geological and morphostructural domains of Paraná State (adapted from Mineropar 2006a)

and Paraná Third Plateau (Maak 2002). The *Paraná Second Plateau* is modeled in monocline structures of Paleozoic sedimentary rocks. Its eastern border is characterized by altitudes of around 1,150 m, while the western border ranges between 350 and 1,200 m. The *Paraná Third Plateau* developed on the Mesozoic basalt flows and Cretaceous sandstones of the northwest. The topography of the plateau, which generally slopes to the west-northwest, ranges from a high of 1,250 m to a low of 220 m at the Paraná River.

The *Cenozoic Sedimentary Basins and Tectonic Depressions* morphostructural unit represents the discontinuous unconsolidated Cenozoic sediments deposited over the Atlantic Orogenic Belt and Paraná Basin. The majority of these sediments occur in the Paraná River valley, the Curitiba Plateau and the eastern coastal plain (Angulo 1992).

Geodiversity Assessment Methodology

The following methodology is based on the definition of partial numerical indices calculated over different maps representing the highest number of geodiversity elements. The *Geodiversity Index* is obtained from the sum of these partial indices, with the latter resulting from the sum of units and occurrences in areas defined by a grid.

Scale

Scale selection is of great significance since it reflects the detail level of available data. Previous studies concerned with the quantitative assessment of geodiversity (e.g., Benito-Calvo and others 2009; Serrano and others 2009; Hjort and Luoto 2010) have made use of a variety of differently scaled maps, the scale varying with the level of detail required.

Small-scale maps are not suitable for detailed local studies, while the detail of large-scale maps is not appropriate for use in national or regional studies, since the latter would demand a large number of maps, resulting in an overly exhaustive legend.

Due to the large area of Paraná State, small-scale maps with scales ranging from 1/500,000 to 1/650,000 were used. These maps represent an adequate source of information to support this geodiversity assessment procedure. However, given this range of scales, it is necessary to balance the detail of information, using the different legend levels of each map. For instance, the geological map contains a stratigraphic legend that includes different levels of information such as period, epoch, stage, group, and formation. Therefore, the most suitable level of information that can be used from this legend should be selected in order to maintain a balance with the levels of information of other maps.

Grid

The overlay of a grid onto a map is considered a basic tool for the geodiversity assessment of any territory. The grid provides squares in which units and occurrences can be counted and the discrimination of results achieved. Several authors have discussed the accuracy and suitability of different grid resolutions (e.g., Hengl 2006 and references therein). In the present study, various grids were tested following consideration of the literature. Taking into account the area of Paraná State and the various map scales, a grid size of 25 × 25 km, resulting in 371 squares, was considered to enable the most accurate differentiation of results (Fig. 2). Differentiation means the maximum range between the highest and lowest *Geodiversity Index* values. The selected 25 × 25 km grid size has provided a 1–11 range, when applied to the geological and geomorphological maps. A smaller grid size would provide lower maximum values, while a larger grid size would lead to higher minimum values. Both cases result in less differentiation.

Geodiversity Index

This method utilizes all the elements of geodiversity represented in the chosen geological (Mineropar 2006a), geomorphological (Mineropar 2006b; Santos and others 2009), paleontological (Mineropar 2006a), and soils maps (Bhering and Santos 2008). Besides these, various maps providing information regarding occurrences of outstanding geodiversity were also considered (Mineropar 2006a). These outstanding elements are as follows: sources of precious stones and metals, industrial metals and minerals, geological energy sources such as coal, oil, gas, and uranium, and sources of mineral waters and springs.

The aim of the *Geodiversity Index* is therefore to express, in the most balanced way possible, all of these aspects without emphasizing any particular geodiversity element, as was noted to occur in previous studies (Carcavilla Urqui and others 2007; Serrano and Ruiz-Flaño 2007; Benito-Calvo and others 2009; Hjort and Luoto 2010). The *Geodiversity Index* results from the sum of the following five partial indices: (1) geological;

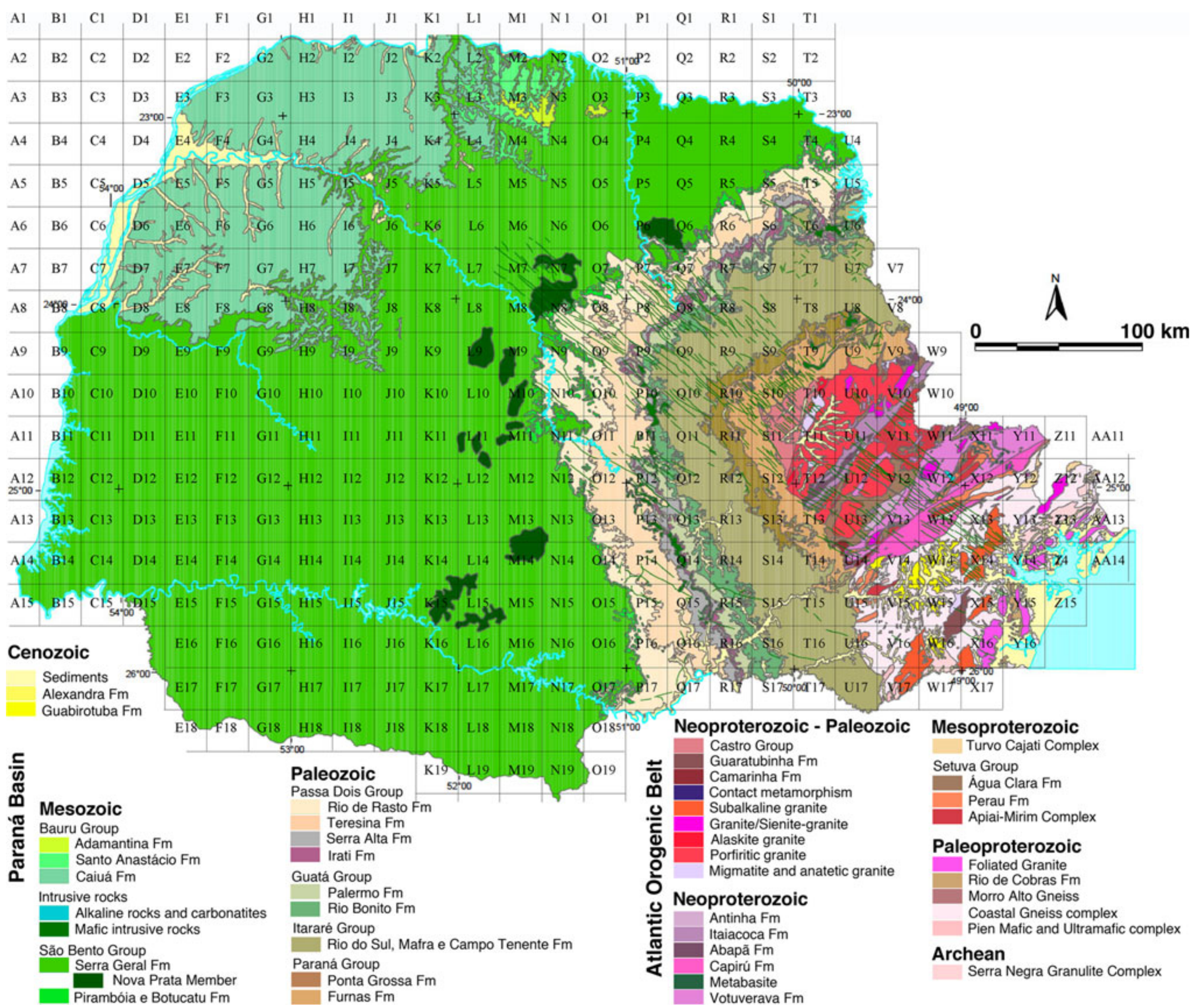

Fig. 2 Geological map of Paraná State (1/500,000 scale; adapted from Mineropar 2006a) overlaid by a 25 × 25 km grid

(2) geomorphological; (3) paleontological; (4) pedological; (5) mineral occurrences. The above-mentioned partial indices are further explained in forthcoming subtopics.

Geological Index

The *Geological Index* was calculated using the geological map available in the 1/500,000 scale Geological Atlas of Paraná State (Mineropar 2006a) (Fig. 2), a map containing 45 stratigraphical (formations and groups) and lithological (basalts, granites…) units. The *Geological Index* was calculated by counting the units occurring in each grid square (Fig. 3). For instance, in Fig. 3a eight geological units in square W12 are represented, whereas Fig. 3b shows only two geological units in each square.

Geomorphological Index

The *Geomorphological Index* is the sum of two subindices: *Relief* and *Hydrographic*. The *Relief Sub-index* is based on the 1/650,000 scale geomorphological units map (Mineropar 2006b; Santos and others 2009).

The *Relief Sub-index map* provides information regarding the main geomorphological features of the state, using units divided into three hierarchical levels: morphostructural units, morphosculptural units, and morphosculptural subunits (Fig. 4).

Paraná State contains three morphostructural units: the Atlantic Orogenic Belt, the Paraná Sedimentary Basin, and the Cenozoic Sedimentary Basins (Fig. 1). Mid-level morphosculptural units include the Serra do Mar mountain range, the three Paraná Plateaus, and plains. Fifty morphosculptural subunits comprise the lowest level (Fig. 4). These subunits were initially established based on landform attributes such as dissection, summit morphology, slopes, valleys, and altitudinal gradients.

Calculation of the *Relief Sub-index* is carried out by counting one point for each morphosculptural subunit, plus one for each boundary between morphostructural and

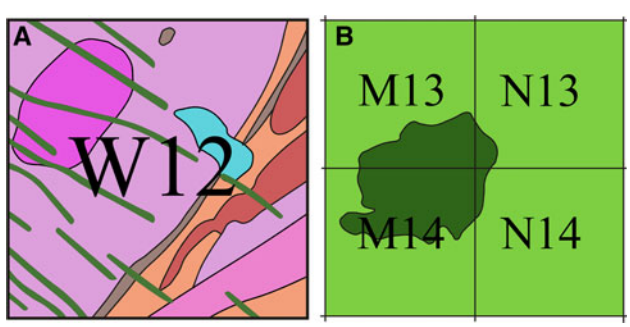

Fig. 3 Example of geological index assessment in a 25 × 25 km grid size. Each *color* represents different stratigraphic and lithological units. **a** *Square* W12 containing eight geological units; **b** *squares* M13, M14, N13, and N14 with two geological units each

morphosculptural units (Fig. 5). The latter points are considered in the assessment due to the importance of morphological changes, which result from the contact of these main units.

The *Hydrographic Sub-index* takes into account the influence of hydrological features on geomorphology. The *Hydrographic Sub-index* is based on the assessment of the 1/650,000 scale geomorphological units map (Mineropar 2006b) using Strahler's system of stream ordering (Strahler 1952, 1957).

According to this system, the lowest hierarchy level is assigned to minor rivers represented on the map, while the highest value of 5 is conferred on major rivers, such as the Paraná River on the Brazil–Paraguay border, as well as lakes and coastal areas. Large tributaries like the Paranapanema and Iguaçu rivers are assigned intermediate values (Fig. 1b).

The value of the *Hydrographic Sub-index* is calculated as half of the maximum hierarchical level of the rivers occurring in each square, rounded up to the nearest unit (Fig. 6). Accordingly, a score of 3 ($5/2 = 2.5 \cong 3$) is given to squares containing major rivers, lakes, and coastal areas, a score of 2 ($4/2 = 2$; $3/2 = 1.5 \cong 2$) to squares containing midsized rivers, and a score of 1 ($2/2 = 1$; $½ = 0.5 \cong 1$) to squares with minor rivers. A score of 0 is assigned to squares, in which no hydrological elements are represented.

Paleontological Index

Calculation of the *Paleontological Index* essentially follows the procedure described for the assessment of the geological and geomorphological indices, using the 1/500,000 scale *Map of Paleontological formations and main paleontological sites of Paraná* included in the geological atlas of Paraná (Mineropar 2006a). *Paleontological Index* values correspond to the number of different fossiliferous formations counted within each square.

Pedological Index

The *Pedological Index* is calculated via the counting of soil orders represented in the 1/600,000 scale *Map of Soils of Paraná State* (Bhering and Santos 2008), which contains information regarding the distribution of 9 orders, integrating 38 supergroups of soils, classified according to the Brazilian table of soil classification (EMBRAPA 2006). Considering the close relationship between soils, geomorphology, and lithology, the assessment of the *Pedological Index* is based on the number of different soil orders represented in each square (Fig. 7). If soil supergroups were considered, the *Pedological Index* would be overestimated in relation with the geological and geomorphological indices.

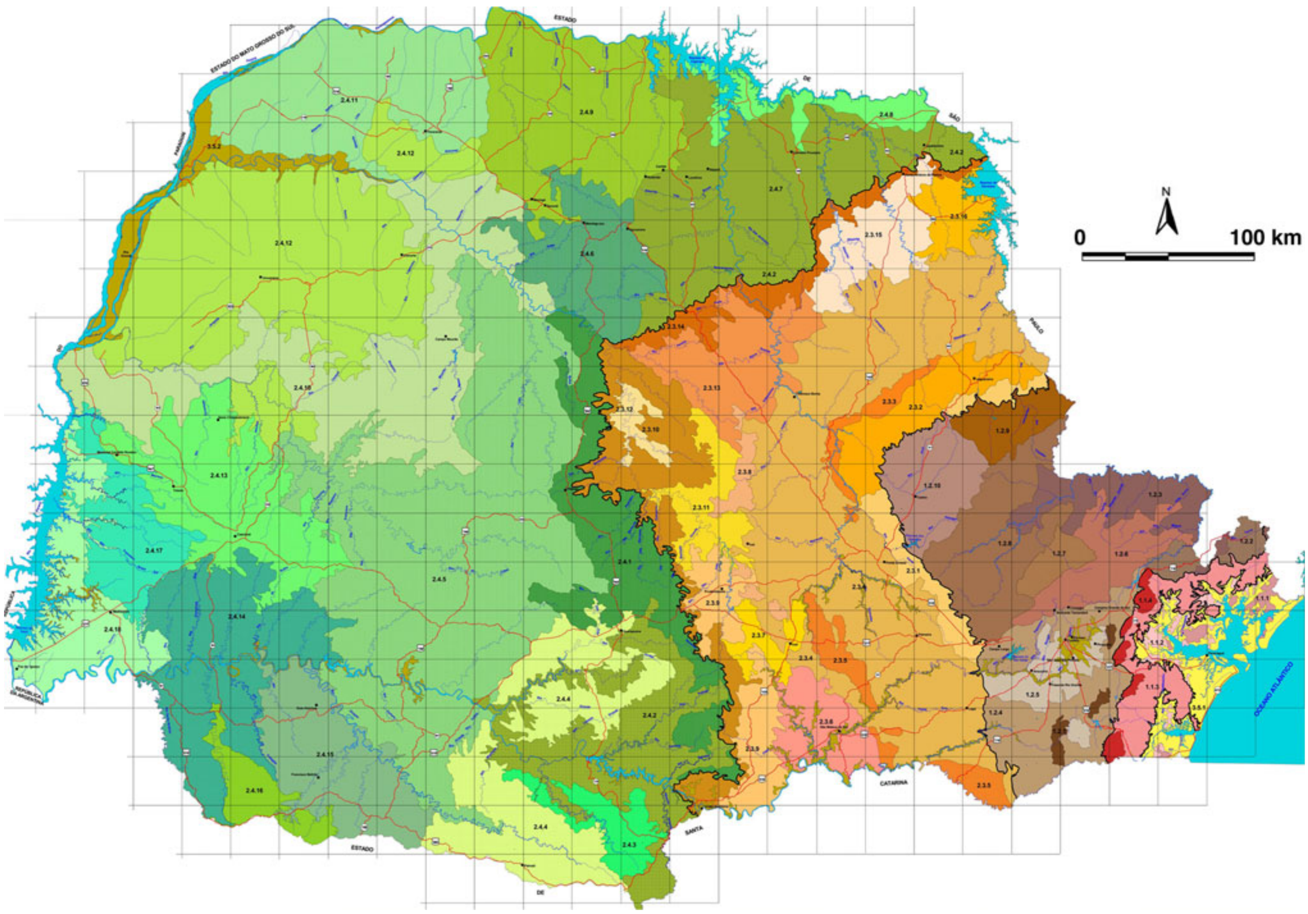

Fig. 4 Geomorphological units map (adapted from Mineropar 2006b) overlaid by the same grid as Fig. 2. The *bold lines* divide morphostructural from morphosculptural units. The different *colors* represent morphosculptural subunits

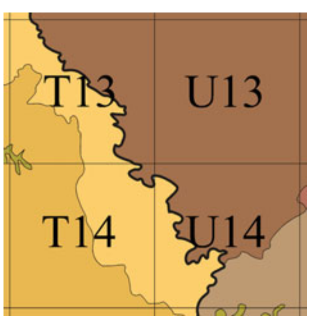

Fig. 5 Example of Relief Sub-index assessment in a 25 × 25 km grid size. The different *colors* represent morphosculptural subunits. *Squares* U13 = 1; T13 = 5; T14 = 5; U14 = 7. The *bold line* marks the boundary between the Atlantic Orogenic Belt (*right*) and Paraná Basin (*left*) morphostructural units (adapted from Mineropar 2006b)

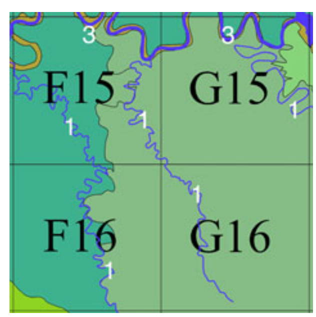

Fig. 6 Example of Hydrographic Sub-index assessment in a 25 × 25 km grid size overlaid on the geomorphological units map (adapted from Mineropar 2006b). River hierarchy in Paraná state: squares F15 and G15 score 2 points; F16 and G16 score 1 point (see text for further information)

Mineral Occurrences Index

The *Mineral Occurrences Index* deals with other geodiversity features not covered in the previous indices, such as minerals, energy sources, mineral waters, and springs. This index is calculated according to a set of 1/500,000 scale maps available in the geological atlas of Paraná (Mineropar 2006a), which provide the following data:

1. Precious stones and metals—agate, amethyst, diamond, gold, silver;
2. Metallic minerals—lead, copper, tin, manganese, molybdenum, nickel, titanium, zinc, rare earth;

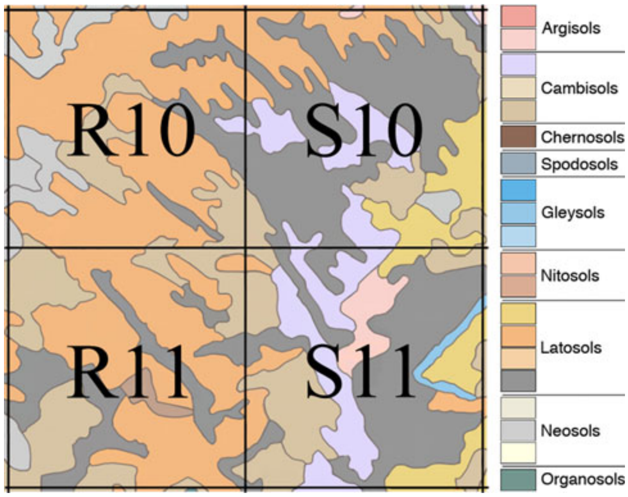

Fig. 7 Example of pedological index assessment in a 25 × 25 km grid size overlaid on the map of soils of Paraná State (adapted from Bhering and Santos 2008). The legend represents the 9 soil orders considered in the map of soils of Paraná State (adapted from Bhering and Santos 2008). *Squares* R10 = 3 orders; S10 = 3 orders; R11 = 4 orders; S11 = 5 orders

3. Industrial minerals—quartz sand, refractory clay, barite, calcite, kaolin, feldspar, fluorite, gypsum, limonite, muscovite, pegmatite, pyrite, quartzite, quartz, sericitic shale, talc, talc schist, vermiculite;
4. Geological energy sources—anthracite, bituminous coal, lignite, peat, oil shale, natural gas, uranium (Fig. 8);
5. Mineral waters and springs.

Each map occurrence of any of the above items scores one point for the corresponding grid square. Repeated occurrences of the same element in the same square are not considered.

Geodiversity Index Map

The *Geodiversity Index* score of each grid square is the sum of all the previously outlined partial indices. A *Geodiversity Index map* can therefore be produced, using isolines to join squares sharing the same geodiversity values (Fig. 9). Five classes of geodiversity were considered for Paraná

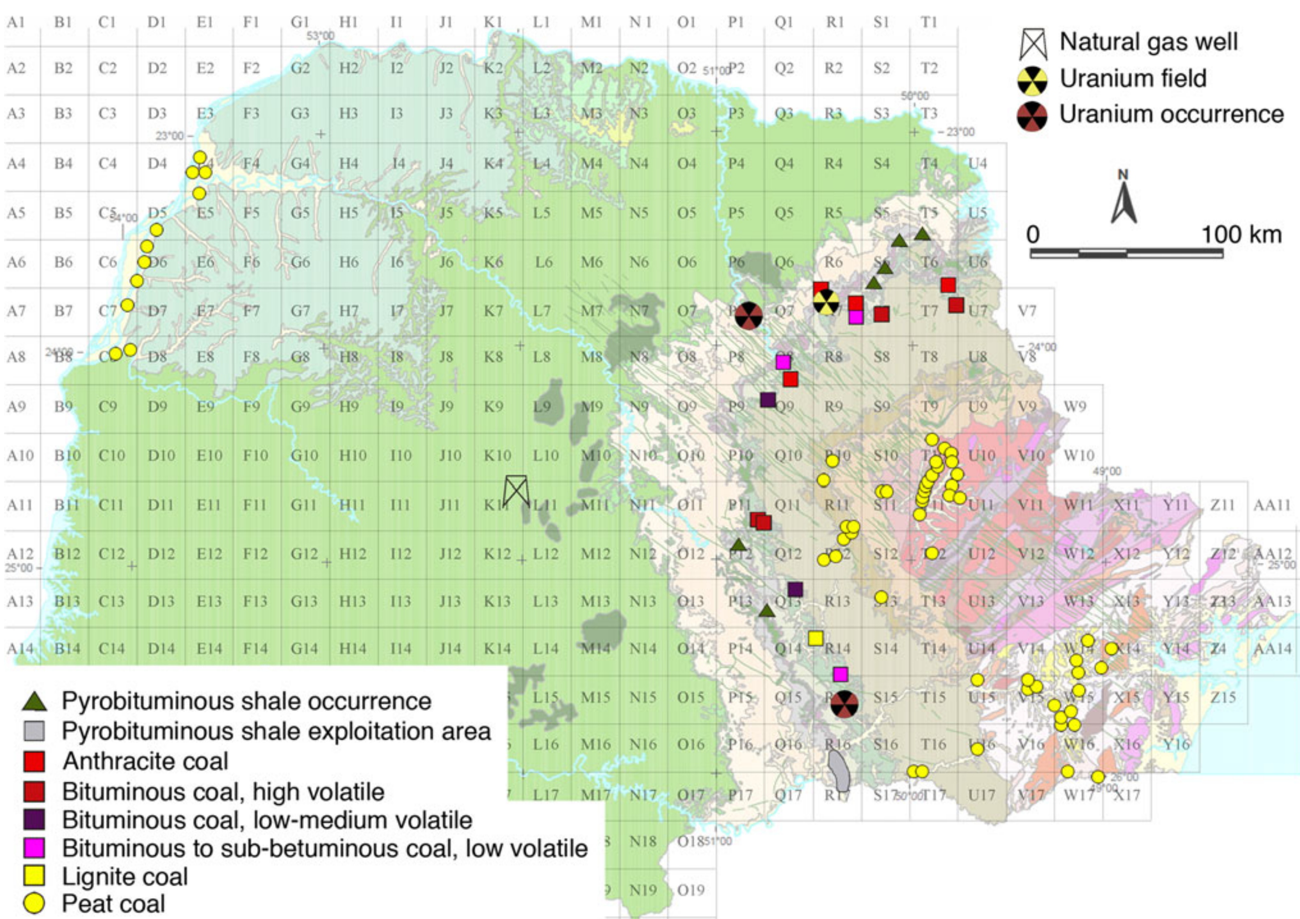

Fig. 8 Geological Energy Sources of Paraná Map (adapted from 1/500,000 scale Mineropar 2006a) overlaid by a 25 × 25 km grid, used for the assessment of the mineral occurrences index

State, taking into account the minimum (5) and maximum (33) values obtained: very low (< 11), low (11–15), medium (16–20), high (21–25), and very high (> 25).

Results and Discussion

Based on the outlined assessment methodology, the results obtained for the partial and final geodiversity indices are now presented and discussed.

Geological Index scores range between 1 and 11 points. Due to the high lithological and stratigraphical diversity associated with the Atlantic Orogenic Belt and the Paleozoic sedimentary cover of the Paraná Sedimentary Basin, the highest values are located in the eastern sector of the state (Fig. 2, e.g., U14). On the other hand, the homogeneity of the basaltic flows in central and southwestern areas justifies their low *Geological Index* levels (Fig. 2, e.g., H13).

Geomorphological Index scores also vary between 1 and 11 points, with the highest relief and hydrographic subindex scores being 8 and 3 points, respectively. The highest values of the *Relief Sub-index* (6–8 points) are associated with the strong morphological contrast between the coastal plain and the vigorous relief of the Atlantic Orogenic Belt in the east (Fig. 4). High values (5–7 points) are also observed in areas characterized by a strong morphological contrast between morphostructural or morphosculptural units. The high values of the *Hydrographic Sub-index* (3 points) in the west of the state are due to the presence of major rivers in the region, such as the Paraná river.

Paleontological Index scores range between 0 and 8 points. The highest values are associated with Paleozoic fossiliferous units of the Paraná Sedimentary Basin (Fig. 2). Igneous and other non-fossiliferous rocks are not assigned any points in this index.

Values obtained for the *Pedological Index* vary between 2 and 6 points. The Paraná Basin is characterized by regions with varying levels of soil diversity. Accordingly, the large area of basaltic flows has *Pedological Index* values of around 3 points, while the Paleozoic stratigraphic

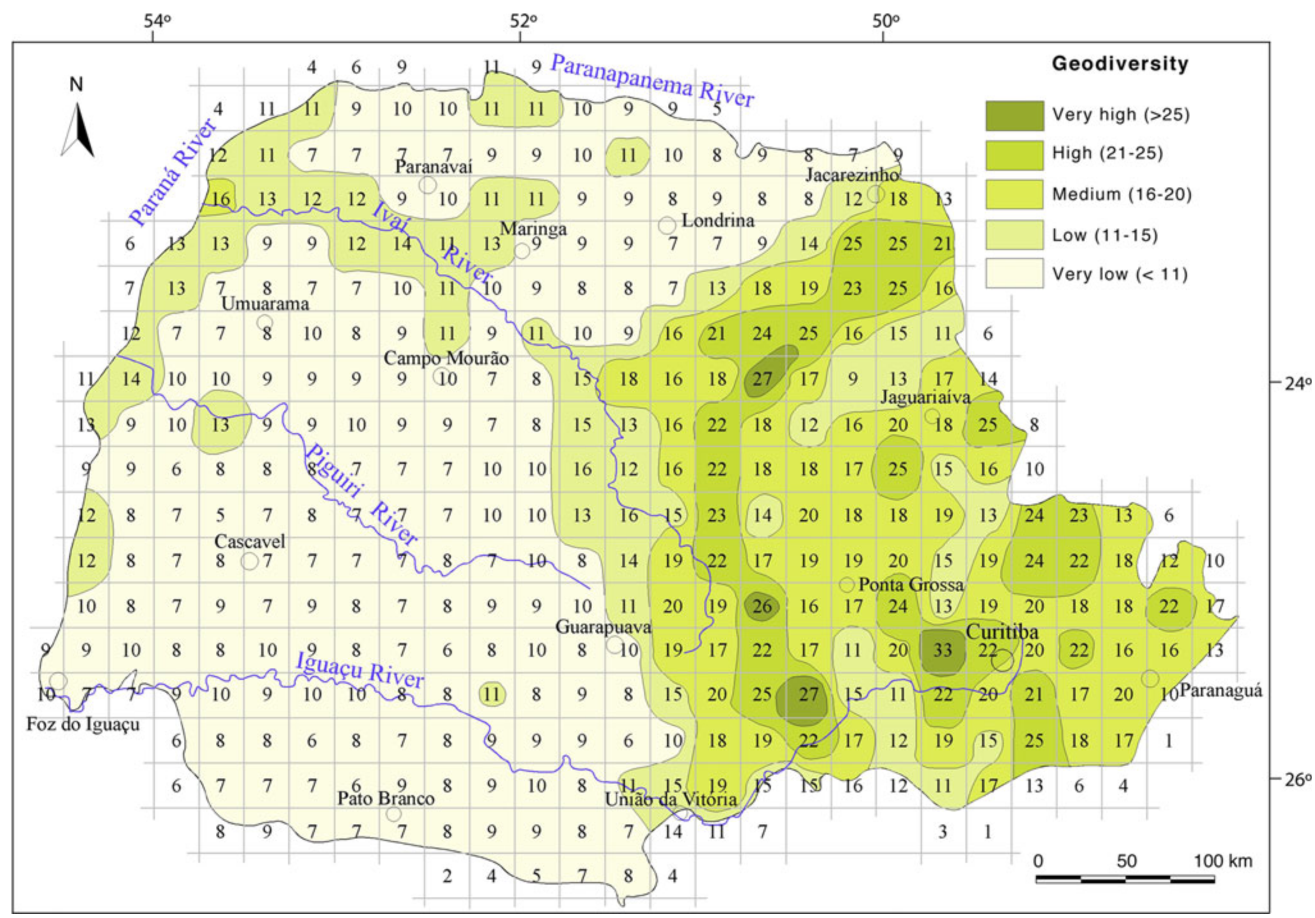

Fig. 9 Geodiversity index map of Paraná State; values are assigned to each of the 371 *squares* of the 25 × 25 km grid

units, with their diverse range of soils, have higher index values. However, despite these differences, the *Pedological Index* discriminates less between regions and thus has less influence on the overall variation in the *Geodiversity Index*.

The *Mineral Occurrences Index* introduces strong discrimination between "hot spots"—i.e., sites with high concentrations of special minerals, geological energy sources, or hydrogeological features—and areas without such occurrences. The highest values (7–10 points) are concentrated on the Atlantic Orogenic Belt and have a significant influence on the overall *Geodiversity Index*.

Finally, values of the *Geodiversity Index* in Paraná State range between 5 and 33 (Fig. 9). *Very low geodiversity* scores (< 11) are observed in regions characterized by smooth relief, related to the presence of basaltic flows outcropping in central and western areas of the state. These low values are also associated with an absence of both fossils and mineral occurrences, as well as low soil diversity. The increase in *Geodiversity index* scores in the westernmost region of Paraná State (11–16 points) is due to the presence of high *Hydrological Sub-index* values related to the Paraná River and its main tributaries. Values of *high geodiversity* (21–25) and some hot spots of *very high geodiversity* (> 25) characterize the east of Paraná State, a region home to a large variety of geomorphological and stratigraphical units (Figs. 2, 4). Within the Paraná Basin, such high *Geodiversity Index* values are also the result of the variety of Paleozoic paleontological formations present in the area, as well as many instances of industrial minerals (kaolin and pegmatite), metallic minerals, and springs. The highest score (i.e., 33 points) was observed at Campo Largo region. Around 40 km west of Curitiba, the region is characterized by strong geomorphological contrasts thanks to the presence of a boundary between Atlantic Orogenic Belt and Paraná Sedimentary Basin morphostructural units.

Conclusions

This methodology for assessing geodiversity was developed with the aim of quantifying the maximum possible number of geodiversity elements. The method was tested across an area of about 200,000 km^2, although one may consider its adaptation to other areas regardless of the main geological setting.

This methodology is based on cartographic data concerning geology, geomorphology, paleontology, pedology, and mineral, water, and energy sources occurrences. Scale selection, legend level, grid size, and weighting of each of the geodiversity elements were important aspects considered in this proposal.

The cartographic scales, legend levels, and grid size chosen for the assessment of the geodiversity of Paraná State have been revealed to be appropriate, providing a clear distinction of values for the various indices.

Taking into account the different geodiversity elements assessed, the following considerations can be pointed out:

(1) Geology is a mandatory component that was expressed by lithological and stratigraphical units that can be easily assessed using common geological maps;
(2) The most suitable maps for the quantitative assessment of geomorphology are those with geomorphological features represented by areas, rather than by linear structures. The morphostructural map of Paraná State revealed itself to be the most adequate for this purpose. Hydrographical features are relevant components of the landscape whose properties may not be fully expressed during relief evaluation. Rivers were therefore considered separately and assessed according to their hierarchy, enhancing the geomorphological index.

The *Paleontological Index* was developed based on the counting of fossiliferous units. An alternative method could involve the counting of taxonomic levels within fossiliferous formations, although this would generate large scores and potentially lead to the overestimation of paleontological assets in geodiversity assessment. This latter approach may be more suitable for the assessment of smaller areas.

In order to avoid the overrating of the pedological index, its evaluation was based on the counting of soil orders and not lower levels of information, such as soil supergroups.

Finally, *Mineral occurrences of geodiversity* reflect important features not expressed by the previous indices, such as special mineral deposits, geological energy sources, thermal waters, and springs. This index is highly dependent on the state of knowledge and existence of maps containing such information. Nevertheless, data may be obtained from other types of document including papers, reports, and inventory lists.

The cartographic representation of the *Geodiversity Index* has the potential to be an extremely efficient tool for management purposes. The *Geodiversity Index map* presented here brings together information usually scattered across multiple sources and can be easily understood by non-earth science specialists. Due to their importance in land-use planning, special attention should be given to areas with high geodiversity. The analysis of these data may be useful for the definition of priority areas for conservation. Areas with high geodiversity have a higher potential to be used for educational and tourism purposes. The *Geodiversity Index* map may have a particular relevance for land-use planning, as it is a graphical representation of different physical elements that characterize the territory. Together with other methods dedicated to natural elements, this methodology may be useful for the definition of ecological structures, protected areas, geoparks, etc. The *Geodiversity Index* should therefore be considered as a tool for natural resource management, nature conservation, or nature tourism strategies.

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