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Geodiversity Hotspots: Concept, Method and Cartographic Application for Geoconservation Purposes at a Regional Scale

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Abstract

As a parallel to the "biodiversity hotspot" concept used in conservation biology, "geodiversity hotspots" can be defined as geographic areas that harbor very high levels of geodiversity while being threatened by human activities. Identifying geodiversity hotspots may offer a powerful way to set geoconservation priorities, but numerical methods integrating both geodiversity values and threats are still lacking. Here we propose for the first time an integrated approach using GIS and geoprocessing to map geodiversity hotspots at a regional scale, with a cartographic application to the Ceará State (Northeastern Brazil). The method is based on the quantification and mapping of two numerical indices: a geodiversity index (GI) and a threat index (TI). On one hand, the GI is calculated as the sum of four sub-indexes representing the main components of geodiversity, i.e., geological diversity (rocks, minerals, fossils), geomorphodiversity (topography and landforms), pedodiversity (soils and palaeosoils) and hydrodiversity (surface and underground waters). On the other hand, the TI is calculated as the sum of three sub-indexes including the level of environmental protection, the degree of land degradation and the type of land use. Mapping and delineation of geodiversity hotspots are automatically obtained from a combination of GI and TI, i.e., in areas where higher geodiversity indexes coincide with higher threat indexes. In the study area, results show the spatial delimitation of five geodiversity hotspots, including the Araripe basin (to the South), partly recognized as a UNESCO Global Geopark since 2006, and the Fortaleza metropolitan region (to the North), both faced with severe threats to geodiversity. In addition to a tool for geoconservation, geodiversity hotspots could also provide useful support for biodiversity research and action programs, given the structural and functional links between geodiversity and biodiversity.

Keywords Geodiversity · Hotspots · Geoconservation · Quantitative assessment · Brazil

Introduction

In recent years, geodiversity – i.e., the abiotic equivalent of biodiversity – has gained international recognition in the scientific and political decision-making spheres (Gray 2008; Gordon et al. 2012; Erikstad 2013; Comer et al. 2015). A commonly used definition proposes to consider it as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features", including "their assemblages, structures, systems and contributions to landscapes" (Gray 2013). Despite some initial skepticism about the validity of parallels with biodiversity, notably because they occupy very different space and time scales, the term "geodiversity" has shown its usefulness to environmental conservation for a couple of decades (see the precursory works of the Tasmanian/Australian forest managers: Sharples 1993, 1995), with reaffirmation of its importance in the current context of climate change (Prosser et al. 2010; Brazier et al. 2012; Brown et al. 2012). As an integral part of nature focusing on the variability of non-living features, the concept of geodiversity is today widely recognized both for its own scientific and societal values (cultural, aesthetic, economic, functional or educational;

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Gray 2013), as well as its role in supporting biodiversity in more integrated approaches to nature management (Gordon and Leys 2001; Gray et al. 2013; Peña et al. 2017; Brilha et al. 2018). Because geodiversity provides the substrates, landform mosaics, and physical processes for species habitat and diversification, it has a crucial influence on biodiversity across a wide range of scales, from micro-environments to continent-scale biomes (Hjort et al. 2015).

In the same way as for biodiversity, however, geodiversity has been threatened by a large variety of human activities and pressures for at least a century (e.g., Gordon and MacFadyen 2001; Gray 2013). In this context and given the numerous values and ecosystem services related to abiotic nature (Gray 2011; Gordon and Barron 2013), geodiversity may be viewed either as a type of heritage or as a resource whose conservation is mainly justified in terms of protected and/or managed geosites (Brilha 2002; Prosser et al. 2010; Fuertes-Gutiérrez and Fernández-Martínez 2012). From this concern is born a new field of research and experimentation techniques, grouped under the term "geoconservation", whose foundations and principles were stated in the mid-1990s by Sharples (1993, 1995). Geoconservation is primarily concerned with protecting geodiversity features that are considered worthy of conservation for their geoheritage value (i.e., mainly for their geological and geomorphological values), together with cultural, aesthetic and/or ecological values (Reynard and Brilha 2018). Geoconservation may also include conservation management of geodiversity for its functional value in delivering ecosystem services and/or in supporting biodiversity, but not conservation of geodiversity *per se* (e.g., Gordon and Barron 2013; Gray et al. 2013; Crofts and Gordon 2015). In the field, geoconservation refers to a set of practices aimed at maintaining geosites and geodiversity sites facing natural or human threats (Brocx and Semeniuk 2007; Prosser et al. 2013; Crofts and Gordon 2015), both in situ (e.g., protection of geosites by legislation tools and/or physical intervention) and *ex situ* (e.g., rescue excavations, museum collections). However, a major difficulty arises in how geoconservation priorities can objectively be identified at larger scales (e.g., state or region levels).

To achieve this goal, numerous quantitative methods for geodiversity assessment have been proposed in the last ten years (see Zwoliński et al. 2018, for a review). Many have given too much importance to geomorphology and morphometric parameters (e.g., Serrano and Ruiz-Flaño 2007; Benito-Calvo et al. 2009; Hjort and Luoto 2010), creating an imbalance with the other physical components (geological, pedological, hydrological) in geodiversity assessment. Other methods have tried to achieve better balance between the different components of geodiversity (Perreira et al. 2013; Silva et al. 2013) but they do not integrate the threats in the global assessment. A tentative quantification of both geodiversity and its loss has been proposed by Ruban (2010), but the methodological proposal is based on a very controversial definition of the geodiversity concept, viewed as "a diversity of geological heritage sites". Such an approach, which does not account for the abiotic diversity in a spatially continuous way, has been strongly criticized by Knight (2011). Recently, Santos et al. (2017) have contributed to this issue by integrating an urban growth map in order to quantify the impacted areas on geodiversity in a municipality of the Rio de Janeiro State (Brazil). However, geodiversity is far from being only threatened by urbanization, in a current context of global change along with territorial specificities on a local scale (e.g., local economy and agricultural practices, national legislation and patterns of protected areas).

Given the gaps identified in the existing studies, we propose here an alternative approach by theorizing and applying the concept of "geodiversity hotspot" for the identification of geoconservation priorities at large (regional or national) scales. The aims of this paper are threefold: (1) to set the foundations of the "geodiversity hotspot" concept with reference to benchmark studies in the field of conservation biology; (2) to propose an efficient method of quantification and mapping of "geodiversity hotspots" using a simple GIS procedure; (3) to present an example of cartographic application of the method at a regional scale (Ceará State, Brazil), where "geodiversity hotspots" have been mapped and interpreted in the light of field-based empirical studies.

The "Geodiversity Hotspot" concept

The "hotspot" concept was first developed in the field of conservation biology. It was introduced by Myers (1988) to identify those areas of the planet where significant levels of biodiversity are particularly threatened with destruction. After a major revision of the hotspot-map (Mittermeier et al. 1999), the concept was popularized owing to a famous paper published in the journal *Nature* (Myers et al. 2000) and to its rapid institutional adoption by the powerful American organization *Conservation International*. According to the Myers' team, a biodiversity hotspot must meet two strict criteria: (i) it must have at least 1500 vascular plants as endemics (i.e., it must be biologically rich and irreplaceable), and (2) it must have 30% or less of its primary vegetation, i.e., it must be seriously threatened. Today around the world, 36 areas qualify as biodiversity hotspots, most of which occur in tropical forests. The hotspot approach has been successful with conservation organizations because of the concreteness of the concept, but it has also proved relevant to politicians and general public by focusing its definition on ideas of *threats* and *vulnerability*

(Van Dyke 2014), so highlighting the urgency to proceed with conservation actions in the most endangered places of the Earth. In 2017, ~2.7 million square kilometers (i.e., 10.9% of the total area) of biodiversity hotpots were officially protected (Hrdina and Romportl 2017), with varied degrees of environmental protection and inequal distribution (e.g., hotspots located in the most developed countries have a higher proportion of protected areas in IUCN categories I-IV). Despite some criticism (e.g., Kareiva and Marvier 2003; Marchese 2015), the "hotspot" concept has become an effective tool to set conservation priorities worldwide, playing an indubitable role in decision-making for cost-effective strategies to protect terrestrial biodiversity.

In the field of geoconservation, the first mention of the term "geodiversity hotspot" is credited to Gray (2008) who focused on parts of the world characterized by significantly higher visible geodiversity, classifying them into the following four categories: (i) areas of the continents with long and complex geological history; (ii) plate margins, particularly convergent margins where active development of new rocks and landforms is favored by intense exogenic (erosion) and endogenic (tectonics, volcanism) processes; (iii) areas of higher relief (e.g., mountains areas, major canyons), where a diversity of rocks is exposed; and (iv) coasts, partly because of the high degree of rock exposure and partly due to the range of processes, sediments and landforms produced in the various zones of the coastal environments. Since then, the term "geodiversity hotspot" has been used by other authors (e.g., Ruban 2010; Silva et al. 2013; Stepišnik and Trenchovska 2018) in the same restrictive acceptance, considering hotspots as areas of higher geodiversity without taking into account the potential threats to them.

Because the term "hotspot" is imbued with a strong semantics in environmental conservation, we propose here an original definition of the concept applied to the field of geoconservation that takes into account the two criteria essential to the identification of hotspots. In our conception, geodiversity hotspots must be defined as geographic areas that harbour very high levels of geodiversity while being threatened by human activities (Bétard 2016; Fig. 1). In the present-day globalization context, the main threats to geodiversity are urban growth and soil impermeabilization (Santos et al. 2017), land degradation (desertification, deforestation, intensive agriculture practices, industrial expansion: Crofts and Gordon 2015) and higher external vulnerability due to the absence of legal protection tools in many countries. Locally, threatening projects such as dam construction or mining projects may also have a negative impact on exposed or invisible geodiversity elements (Gray 2013).

In summary, geodiversity hotspots should be considered as both the richest – or "geodiverse" – and most endangered areas of a given territory or geographical zone at a chosen scale (regional, national, continental or global). This conceptual framework serves as a strong basis to define a methodological approach to identify and map geodiversity hotspots for geoconservation purposes.

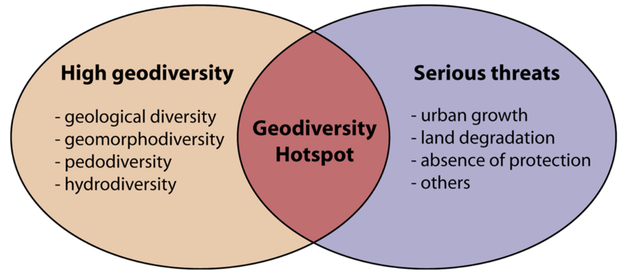

Fig. 1 The "geodiversity hotspot" concept: a connection between high geodiversity areas and major threats

Method and Data

In this section we propose an innovative methodology based on a three-step analytic procedure to map geodiversity hotspots using GIS technology: (i) the calculation and mapping of a Geodiversity Index (GI); (ii) the calculation and mapping of a Threat Index (TI); and (iii) the combination of GI and TI to calculate a Sensitivity Index and to delineate "geodiversity hotspots" (Fig. 2).

Geodiversity index

In the first step, the methodology used to calculate the Geodiversity Index (GI) is largely based on the quantitative assessment method proposed by Pereira et al. (2013) and further upgraded by Araujo and Pereira (2018) with application to the Ceará State. It consists of overlaying a grid onto different thematic maps (geological, geomorphological, soil and hydrographic maps) in order to obtain a final Geodiversity Index calculated from partial thematic indexes. The extraction method for each grid cell is based on the notion of "georichness" which may be defined as an abiotic equivalent of "specific richness" used in biodiversity assessment. Each geoinformational layer was previously homogenized, in order to eliminate duplication of polygons of the same type within each cell while counting them as "georichness" value. In the GIS, the counting of occurrences inside each cell was automatically performed using the *Spatial Join* tool of ArcGIS®.

A first methodological adaptation was to consider four partial indexes with the same weight corresponding to the four main components of geodiversity (i.e., geological diversity, geomorphodiversity, pedodiversity and hydrodiversity) (Fig. 3). Each component or partial index was itself subdivided into several sub-indexes calculated along a

Table 1 Input data retained for quantitative assessment of geodiversity

Index	Sub-index	Data/layers	Scale/ resolution	Source	Acquisition method
Geological diversity	Lithology	Lithologic layer (polygons)	1:500,000	CPRM 2003	Classification of rock types
	Mineralogy	Mineral occurrence layer (points)	1:500,000	CPRM 2003	Classification of mineral occurrences
	Paleontology	Lithologic layer (polygons)	1:500,000	CPRM 2003	Extraction and ranking of fossiliferous formations
Geomorpho-diversity	Local relief	SRTM DEM v4 (raster)	90 m	U.S. Geological Survey	Raster calculator = max elevation – min elevation
	Landform taxa	Morphostructural map of Ceará	1:500,000	Peulvast and Claudino Sales 2003	Interpretation of morphostructural map + field survey
Pedodiversity	Soil taxa	Soil map of Ceará State	1:500,000	IPECE 2007	Digitalization of soil units
	Palaeosoils	Paleosoil layer (polygons)	1:500,000	Specially created for the study	Geoprocessing of satellite images + field survey
Hydrodiversity	Hydrography	Rivers (lines) and lakes (polygons)	1:500,000	CPRM 2003	Strahler classification of river network
	Hydrogeology	Hydrogeological map of Brazil	1:5,000,000	CPRM 2014	Conversion to 1:500,000 scale using the lithologic layer of CPRM 2003

normalized scale (values ranging from 0 to 5), which allows the comparison of the geodiversity variables with the same weight. The discretization method used for translating the "georichness" values into a 5-scale diversity index was based on an equal interval classification (0 = null; 1 = very low; 2 = low; 3 = medium; 4 = high; 5 = very high). Another adjustment was to use a grid size of 10 × 10 km which was considered as the most accurate given the dataset and the scale/resolution of the maps (Table 1). In the area where the method was tested, the dataset was composed of a digital elevation model (SRTM DEM 90 m) and of various thematic maps with homogenous scale, including the geological digital atlas of Ceará at 1:500,000 (CPRM 2003) and the morphostructural map published therein (Peulvast and Claudino Sales 2003), a soil map of the Ceará State at 1:500,000 (IPECE 2007) and, finally, the hydrogeological map of Brazil at 1:5,000,000 (CPRM 2014) converted into at 1:500,000 scale by using the digital layers of the geological atlas of Ceará (CPRM 2003). For the calculation of the four partial indexes, the following geoprocessing steps were applied (see also the supplementary materials given in Online Resources 1 to 4):

1. The "geological diversity" index was calculated as the sum of the *lithological* (rock types), *mineralogical* (mineral occurrences) and *paleontological* (fossiliferous formations) *sub-indexes* (Online Resource 1). The lithological and mineralogical sub-indexes were computed following the method proposed by Pereira et al. (2013). For the paleontological sub-index, the method used here considers the fossiliferous potential of geological formations based on the data available in the scientific literature (Table 2). The calculated values correspond to the number of different fossiliferous formations counted within each square, combined with the coefficient value attributed to each formation depending on their fossil content.
2. The "geomorphodiversity" index was evaluated both topographically (*local relief sub-index*) and morphologically (*landform taxa sub-index*) (Online Resource 2). The local relief sub-index was generated from the SRTM DEM using the function "Range" in the *Zonal Statistics* tool of ArcGIS®, in order to calculate the difference between maximum elevation and minimum elevation inside each cell. The landform taxa sub-index was obtained after digitalization of the landform units from the morphostructural map of Ceará at 1:500,000 (Peulvast and Claudino Sales 2003); the calculation of individual values was carried out by counting the number of landform taxa in each grid cell.
3. The "pedodiversity" index was performed by taking into account a palaeopedological sub-component (*paleosoils sub-index*) in addition to the variety of soil units (*soil taxa sub-index*) (Online resource 3). The paleosoils sub-index was only based on the presence/absence of paleosoils in a binary way (0 = absence; 1 = presence), from original data produced by geoprocessing of Landsat ETM + imagery in combination with extensive field surveys and available pedolological data (mapping of lateritic legacies). The

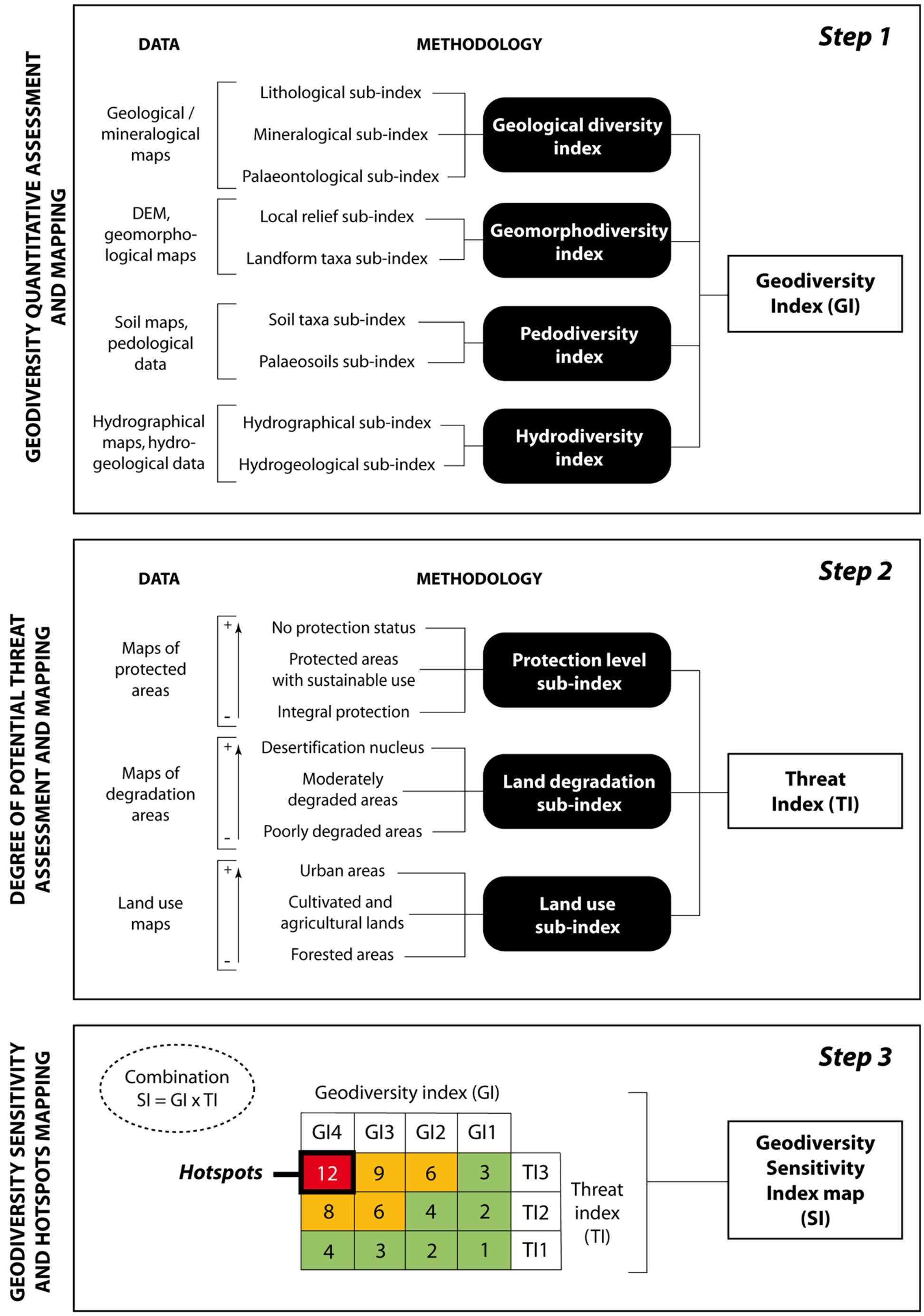

Fig. 2 Spatial analysis methodology to map geodiversity hotspots using a three-step analytical procedure

paleosoils sub-index was added to a soil taxa sub-index which was calculated after digitalization of the soil map of Ceará State at 1:500,000 (IPECE 2007) and was based on the counting of soil sub-orders in each cell.

4. The "hydrodiversity" index was evaluated by taking into consideration both surface waters (rivers, lakes and sea = *hydrographical sub-index*) and underground waters (aquifer productivity = *hydrogeological sub-index*) (Online Resource 4). The hydrographical sub-index was based on the method proposed by Pereira et al. (2013), i.e., on the assessment of river network (extracted from the digital atlas of Ceará at 1:500,000; CPRM 2003) using Strahler's system of stream ordering (Strahler 1957). A score of 0 was assigned to squares in which no hydrological element is represented, while a maximal value of 5 was attributed to rivers of highest hierarchy value (e.g., Jaguaribe River) as well as lakes and coastal areas. The hydrogeological sub-index was based on the values of aquifer

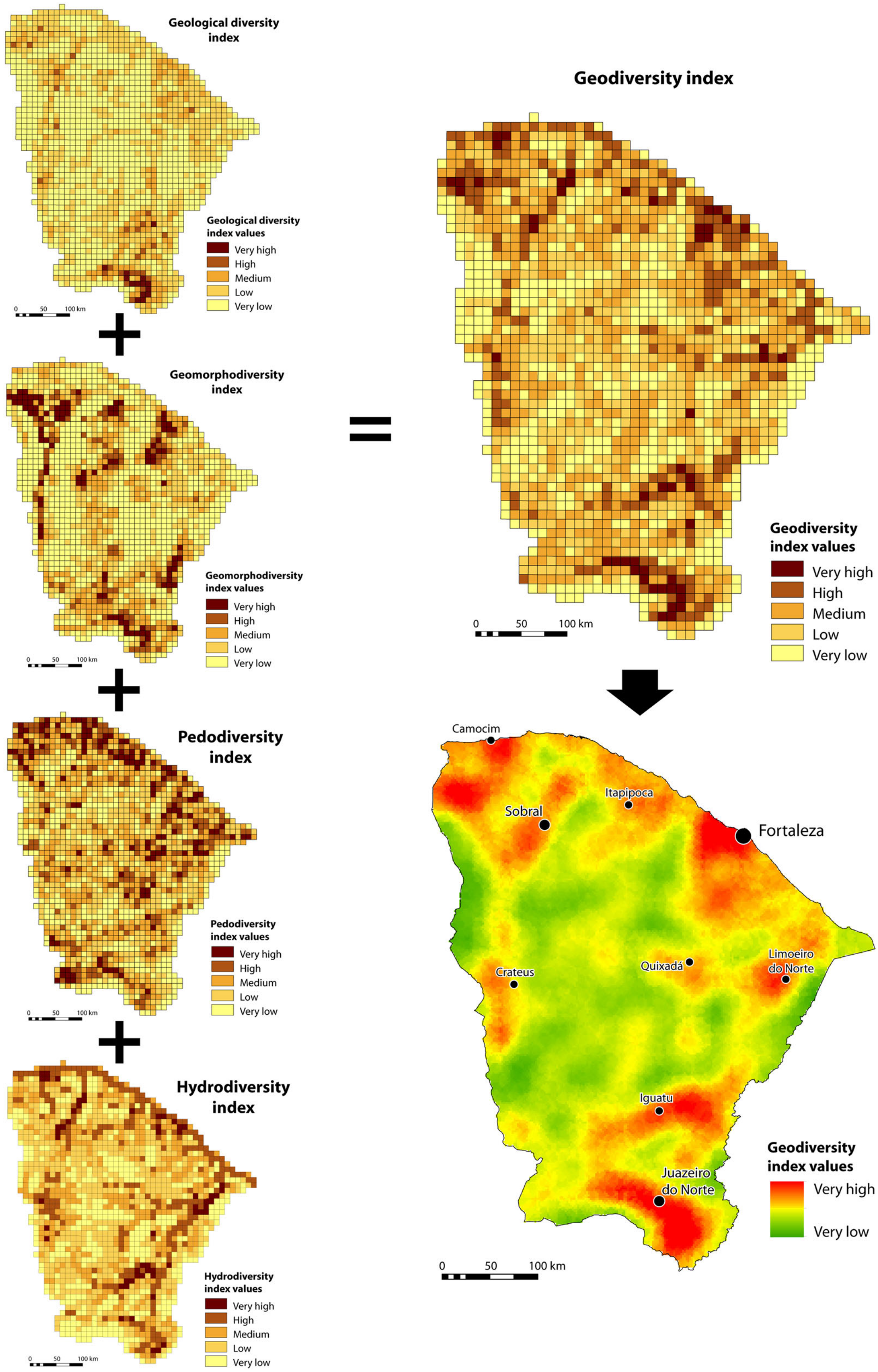

Fig. 3 Calculation of a geodiversity index applied to the Ceará State (Brazil) as the sum of four partial indexes: *geological diversity, geomorphodiversity, pedodiversity* and *hydrodiversity*. Note that the highest geodiversity index values are found in southern Ceará, where the Araripe Basin concentrates high values of geological, geomorphological, soil and hydrological diversities

Table 2 Fossiliferous formations of the Ceará State and related coefficient values for the calculation of the Paleontological sub-index

Symbol	Formation	Lithology	Fossil content	Coef. value
Jsls	Serrote do Limoeiro	Sandstones, siltites and argilites	Rare ichnofossils	1
Sm	Mauriti	Sandstones and conglomerates	Rare ichnofossils	1
εOjp	Pacujá	Sandstones, shales and siltites	Ediacaran fossil fauna	1
K2ae	Exu	Sandstones and conglomerates	Pterosaur remains, plant trace fossils	1
ENb	Barreiras	Clayey sandstones and conglomerates	Rare ichnofossils (bioturbation), some marine microfossils	1
K2apa	Açu	Sandstones and conglomerates	Locally fossiliferous, including some bivalves, plants and fishes	1
K1arb	Rio Batateiras	Sandstones, siltites and shales	Fossil faun of ostracods, fishes, plant trace fossils and other ichnofossils	2
K1va	Abaiara	Sandstones, siltites and shales	Fossil ostracod fauna	2
K1arb	Rio Batateiras	Sandstones, siltites and shales	Fossil faun of ostracods, fishes, plant trace fossils and other ichnofossils	2
K1aa	Arajara	Sandstones and siltites	Numerous invertebrate ichnofossils	2
Ssg	Serra Grande	Conglomerates and sandstones	Locally fossiliferous, numerous ichnofossils	2
J3vb	Brejo Santo	Shales, siltites and sandstones	Fossil fauna of ostracods, conchostracans and some vertebrates	2
K1im	Marlhada Vermelha	Siltites, shales and sandstones	Numerous fossil vertebrates	3
K2apj	Jandaíra	Limestones, shales and siltites	Numerous fossils of marine vertebrates, bivalves, echinoids and ostracods	3
K1ic	Icó	Sandstones, shales and marls	Numerous fossils and ichnofossils	3
K1rpa	Antenor Navarro	Sandstones and conglomerates	Dinosaur footprints, numerous ichnofossils	3
Jsli	Missão Velha	Sandstones	Silicified trunks ("petrified forest"), numerous fossil vertebrates	4
K1as	Santana	Marls, shales and gypsum	Fossil Konservat Lagerstätte: various and numerous plant and animal fossils	5

productivity extracted from the hydrogeological map of Brazil at 1:5,000,000 (CPRM 2014) after re-scaling at 1:500,000 based on the contours of geological units of the digital atlas of Ceará (CPRM 2003). The calculated values correspond to the number of different aquifer reservoirs counted within each square, combined with the coefficient value attributed to each aquifer based on groundwater flow (very low productivity = 1; low productivity = 2; moderate productivity = 3; high productivity = 4; very high productivity = 5).

Threat index

The second step of our methodology is the calculation of a Threat Index (TI) based on the integration of three sub-indexes: (i) the *level of environmental protection* (from integral protection to the absence of legal protection); (ii) the *degree of land degradation* (from poorly degraded lands to "desertification nucleus", i.e., extreme degradation areas); (iii) the *type of land use* (from forested lands to urban areas) (Fig. 4). Each sub-index was calculated on a normalized scale ranging from 1 (low threat) to 3 (high threat) and then added into a final Threat Index. The steps for the preparation of each sub-index are presented as follows:

1. The "protection level" sub-index was based on the mapped contours of "conservation units" ("unidades de conservação") of the Ceará State at 1:100,000 (MMA 2012). Here we assume that the level of legal protection is a factor of external vulnerability inversely proportional to the degree of potential threat (DPT), i.e., from high DPT in areas without any protection status to low DPT in areas with high protection level (e.g., national parks, nature reserves) (Bétard 2016). The correspondence between the classification of "conservation units" and the associated sub-index values is provided in Table 3.
2. The "land degradation" sub-index was evaluated from the atlas of areas susceptible to desertification in Brazil at 1:5,000,000 (MMA 2007). The correspondence between the classification of degradation areas and the associated sub-index values was defined as follows: (i) value 1 (low threat) was affected to poorly degraded areas, i.e., areas that are not susceptible to desertification processes; (ii) value 2 (medium threat)

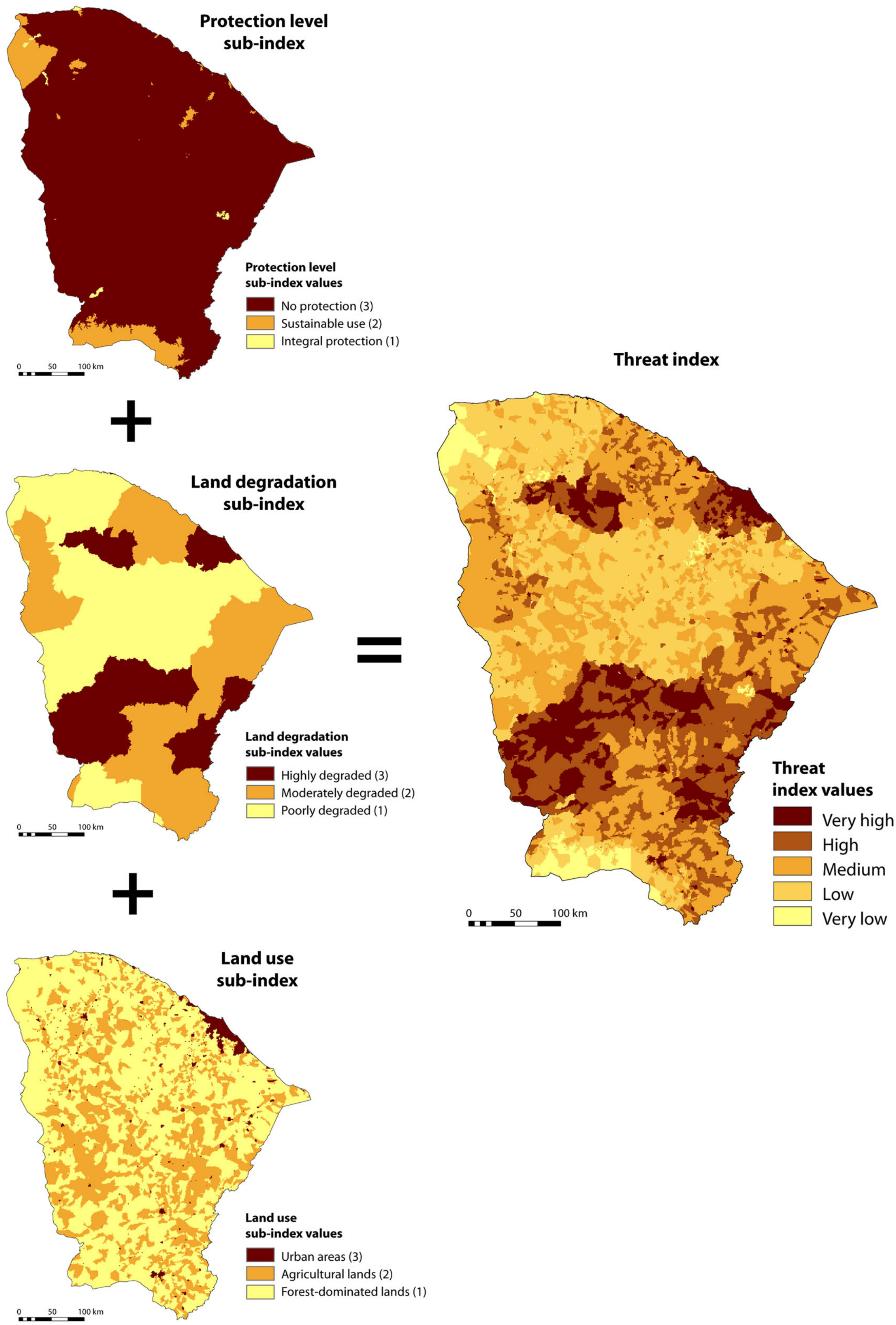

Fig. 4 Calculation of a threat index applied to the Ceará State (Brazil) as the sum of three sub-indexes: the level of environmental protection, the degree of land degradation and the type of land use. Note that a major part of central and northern Ceará is exposed to severe threats because of the absence of legal protection and of the rapid degradation of lands under the influence of urban growth and agricultural development around cities

Table 3 Values of the "Protection level" sub-index based on the type of legal protection

Type of legal protection	Type of conservation unit (Brazilian UCs)	Sub-index value
Integral protection	Estação Ecológica	1 (low threat)
	Reserva Biológica	1 (low threat)
	Parque Nacional/Estadual/Natural Municipal	1 (low threat)
	Monumento Natural	1 (low threat)
	Refúgio de Vida Silvestre	1 (low threat)
Sustainable use	Área de Proteção Ambiental	2 (medium threat)
	Área de Relevante Interesse Ecológico	2 (medium threat)
	Floresta Nacional/Estadual /Municipal	2 (medium threat)
	Reserva Extrativista	2 (medium threat)
	Reserva de Fauna	2 (medium threat)
	Reserva de Desenvolvimento Sustentável	2 (medium threat)
	Reserva Particular do Patrimônio Natural	2 (medium threat)
No legal protection	No protection status	3 (high threat)

was attributed to moderately degraded areas, regrouping the classes "moderada" and "grave" (MMA 2007); value 3 (high threat) was correlated to highly degraded areas ("muito grave") including "desertification nucleus" ("núcleos de desertificação").

3. The "land use" sub-index was based on the land use map of Brazil at 1:1,000,000 (IBGE 2014). A low threat value (1) was established for land use classes dominated by forest and woodlands (>50% of the total area), that correspond to areas poorly affected by human disturbances; a medium value (2) was applied to land use classes dominated by agricultural lands (pastures, cultivated lands), given the potential threats related to intensive agricultural practices (e.g., overgrazing, soil and water pollution). Finally, a high threat value (3) was exclusively determined for urban areas, due to the heavy threats related to urbanization and impermeabilization processes on geodiversity features.

Sensitivity index

The third step of the methodology is the calculation of a Sensitivity Index (SI) which is automatically obtained from a combination of the two previous indices using the following formula:

$$\text{SI} = \text{Geodiversity Index (GI)} \times \text{Threat Index (TI)}.$$

In order to optimize the calculation between the two sets of data using the *Raster Calculator* tool provided by *Spatial Analyst* in ArcGIS®, the grid of the Geodiversity Index map was previously converted into spatially continuous raster values by interpolation (kriging method). Finally, the mapping and delineation of geodiversity hotspots on the final Sensitivity Map correspond to areas (in red colors) where higher geodiversity indexes meet with higher threat indexes (Fig. 2).

Results

Application to the Ceará State (Brazil)

The methodology presented here was tested and applied to the Ceará State (Northeastern Brazil) where we accumulated numerous field and qualitative data (geological, geomorphological, pedological and hydrological) in the past years (for an overview, see Peulvast and Bétard 2015), allowing us to draw an expert opinion on the results obtained by an independent quantitative (geostatistical) method.

The geodiversity index map (Fig. 3) shows that the areas of higher geodiversity are located to the South (Araripe Basin), to the North (Baturité-Fortaleza region) and to the Northwest (Sobral-Ibiapaba region), already known as areas with high geodiversity values (Peulvast and Bétard 2015; Araujo and Pereira 2018; Bétard et al. 2018). Other areas with high or moderate geodiversity may be detected on the map: the Iguatu Basin and the high scarp of the Pereiro massif (Gurgel et al. 2013), the lower Jaguaribe valley and its Cretaceous paleolandforms around Limoeiro do Norte (Peulvast and Claudino Sales 2004), the Quixadá region and its impressive landscape of granitic inselbergs (Maia et al. 2015). By contrast, the lower geodiversity areas correspond to the low plains of the semi-arid interior (Sertão), the monotonous sandstone dip slope of the Serra da Ibiapaba (West) and the vast substructural surfaces of the "Chapadas" of Araripe (South) and Apodi (Northeast).

Combining the Geodiversity Index and the Threat Index provides a new light on geoconservation issues at a regional scale (Fig. 5). Results show the spatial delimitation of five geodiversity hotspots, including the Araripe Basin (to the South) and the Fortaleza metropolitan region (to the North), both facing severe threats to geodiversity (e.g., land degradation, rapid urban growth). The case of the Araripe Basin is particularly interesting. Partly recognized as a UNESCO Global Geopark since 2006, this region of southern Ceará is confronted with strong geoconservation issues, both in terms of geoheritage value of sites and objects (qualitative assessment) and the richness/variety of geodiversity attributes (quantitative assessment), in a context of growing threats combined with the absence of legal protection in the major part of the area (Bétard et al. 2018). Despite the existence of the UNESCO Geopark whose perimeter covers a large part of the Araripe Basin in the State of Ceará, its territorial inscription has no protection value, being only a labeling tool. In such a context, the responsibility for the management and protection of geodiversity only depends on the national jurisdiction and the political will to put in place the measures of protection and regulations that are needed. Apart from the integral protection of specific geosites introduced in 2006 ("natural monument" designation applied to four sensitive geosites), there is no adequate tool of protection over most of the territory, which is prone to numerous threats and human disturbances affecting all the components of abiotic nature (urbanization, deforestation, intensive agriculture, mineral extraction, water and soil pollution; Bétard et al. 2018). The fact that the Araripe Basin appears as a hotspot on the Sensitivity Map is not surprising and confirms that: (i) it is an area of high intrinsic geodiversity; and (ii) this region is subject to serious threats that would necessitate taking urgent conservation measures.

Discussion

The spatial delineation of the other hotspots (red areas) was less intuitive and shows the value of an indirect approach, based on simple geostatistics and independent criteria at a larger scale. These results not only help to set geoconservation strategies at a regional scale (to be eventually completed by further investigations and geoheritage

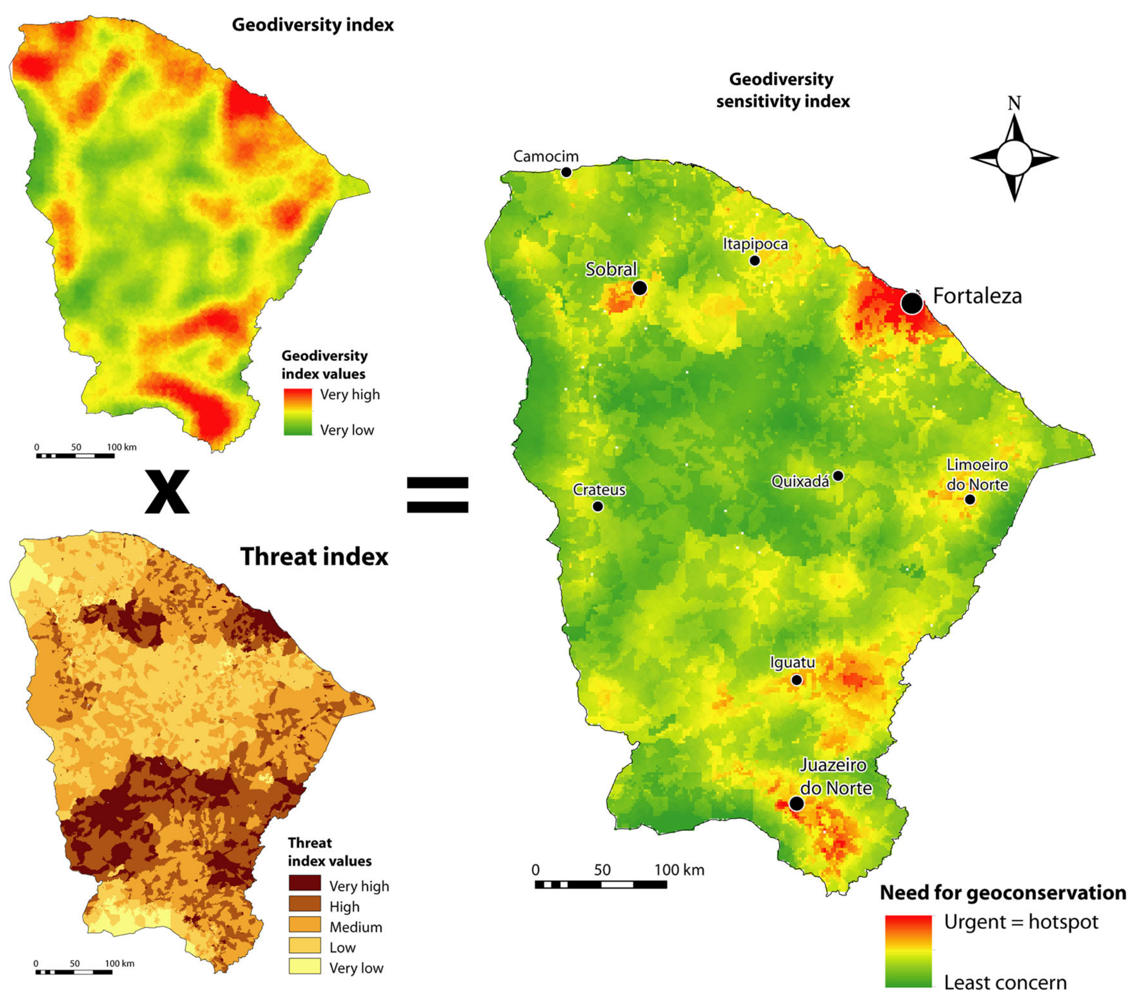

Fig. 5 Calculation of a geodiversity sensitivity index applied to the Ceará State (Brazil). Note that the main hotspots (areas in red color) are located around the principal urban centres of the Ceará State, i.e., Fortaleza (>2.6 million inhab.), Juazeiro do Norte (>250,000 inhab.) and Sobral (>200,000 inhab.)

inventories on a local scale) but can also serve as a useful support for defining more integrated management strategies to conserve both geodiversity and biodiversity. Because geodiversity has a strong influence on biodiversity (e.g., Brazier et al. 2012; Gray 2013; Hjort et al. 2015), a greater geological, geomorphological, pedological and/or hydrological heterogeneity is likely to underpin higher levels of biodiversity. This is the case of the Araripe Basin, where high geodiversity values coincide with areas of high biodiversity hosting exceptional concentrations of endemic species (Araripe national forest: Ribeiro-Silva et al. 2012; Gaiotti et al. 2017). This is an emblematic case where a geodiversity hotspot spatially corresponds to a biodiversity hotspot – the Atlantic Forest being one of the 36 hotspots recognized on the planet after Myers et al. (2000).

The method and results presented in this study may also be discussed in the light of the lessons and criticisms addressed to the hotspot concept in the field of conservation biology (e.g., Kareiva and Marvier 2003; Marchese 2015). The main criticism of such methods is the reliance only on a quantitative assessment of geodiversity (i.e., georichness) that involved here an expert qualitative control and field-based (empirical) evaluation of the results. Like other prioritization methods and tools used in the field of nature conservation, the choice to focus attention on "hotspots" may have the effect of neglecting "geodiversity coldspots", i.e., portions of ordinary abiotic nature or lower geodiversity where conservation issues may be different without necessarily being less important (geoheritage values, provision of ecosystem services). A large part of the semi-arid interior of Ceará (or Sertão) appears as a huge geodiversity coldspot, giving the false impression that conservation issues should be absent in this vast region (Fig. 5). However, some major geosites such as the Quixadá inselberg field are drowned in the coldspot, along with many isolated bornhardts and inselbergs across the pediplain, which often concentrate unquantifiable heritage values (cultural, aesthetic and/or archaeological values). Intrinsically, geoheritage value is not necessarily related to geodiversity. Individual geosites may harbor high geoheritage value but very limited diversity. In many cases, geodiversity hotspots may have important geoheritage values (like in the Araripe Basin hotspot: Bétard et al. 2018) but this needs to be assessed in terms of the above values. This decorrelation between geodiversity and geoheritage is fundamental, in the same way as a distinction exists between biodiversity and biological species of high heritage value. Where geodiversity is important is in providing the foundation for biodiversity through structural and functional links with habitats and plant or animal species, and in maintaining natural capital and ecosystem services (Gray 2011; Gordon and Barron 2013; Gray et al. 2013). Therefore, identifying geodiversity hotspots may be highly relevant and valuable for developing more integrated approaches to environmental management.

A last point of discussion concerns the scale effects, as already pointed with the case of the inselbergs and bedrock landforms with small dimension, synonymous of high geo (morpho)diversity on a local scale. This raises the question of the spatial scale or resolution used in the mapping method: our results do not allow the detection of hotspots of minor scale and also explains that the coastal strip – highly threatened by urbanization and the development of mass tourism – was poorly detected in the Sensitivity Map at this scale (Fig. 5). Another important point is that geodiversity occurs at all scales, from the elemental to the global. Using a 10 × 10 km grid only provides information on geodiversity at a medium (landscape) scale. Keeping all these elements in mind, the hotspot-based approach presented here appears as a new, alternative way for defining geoconservation priorities at a regional or national scale.

Conclusion

Inspired by experiences in biological conservation, the "geodiversity hotspot" concept developed in this paper has shown its effectiveness to set geoconservation priorities at a regional or national scale. The method was tested and applied to a vast area of ~150,000 km² (Ceará State, Brazil), but is possibly reproductible at any geographical scale, depending on the dataset and the objectives of the work. The main innovations in the methodological proposal were as follows: (i) to achieve a better balance between all abiotic components in the calculation of the Geodiversity Index; (ii) to take into account the threats to geodiversity by integrating the level of environmental protection, the degree of land degradation and the type of land use; and (iii) with the help of GIS, to combine both geodiversity values and threats to propose a Sensitivity Map where geodiversity hotspots are easily detectable. In addition to a tool for geoconservation, geodiversity hotspots could also support biodiversity research and action programs in a more integrated approach to environmental management, given the structural and functional links between geodiversity and biodiversity.

Further research and methodological improvements will require the development of more sophisticated metrics (Brown and Williams 2016; Santini et al. 2017) that may help to provide new information about the mechanisms that underlie the current patterns of geodiversity. Among the interesting avenues to explore, alternative methods of spatial interpolation of input data may be tested against multivariate analysis, in addition to statistical tests that may help to control the independencies and respective weights of abiotic variables.

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Compliance with ethical standards

Conflict of Interest The authors declare that they have no conflict of interest.

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