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ORIGINAL ARTICLE

Kernel Density Applied to the Quantitative Assessment of Geodiversity

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Abstract

The development of research involving the geodiversity concept has been growing in the last two decades. The quantification of spatial patterns of geodiversity seems to be one of the most promising lines of research related with natural diversity, since it explores the relations between abiotic elements. This last aspect can be crucial, not only for territorial management, but also for conservation initiatives associated with biodiversity. The main aim of this study was to develop a new GIS procedure, based on centroid analysis, to calculate a geodiversity index, using kernel density, and to test its application in two municipalities with different area surfaces and geological setting. The proposed method is an upgrade of those previously published based on a spatial grid system at a landscape scale. The results of this method show that it is possible to obtain a spatial geodiversity standard that reflects the spatial variation of natural abiotic elements on both territories and that lithology and geomorphology are the key drivers that control the geodiversity index. In addition, the testing procedures have demonstrated that this method can be applied to areas with any geological and geomorphological setting and at different scales and also to be a useful tool for land use planning.

Keywords Geodiversity · Assessment · Spatial scale · GIS · Centroid analysis · Kernel density

Introduction

The geodiversity concept was proposed in the beginning of the 1990s in Australia (Gray 2004; Zwolinski 2004; Serrano and Flaño 2007), emerging as a new topic in earth sciences (Hjort and Luoto 2010). This concept, considered the abiotic equivalent of biodiversity (Crofts 2014), was mainly addressed to those who worked with territorial management (Johansson et al. 1999). Despite being considered the foundation of the ecosystem (Santucci 2005) and a valuable environment asset (Stace and Larwood 2006), geodiversity has not achieved the same level of development and reconnaissance that biodiversity did (Xuelei et al. 2003).

There are several definitions for geodiversity (e.g., Sharples 1995; Eberhard 1997; Johansson 2000; Stanley 2001; Nieto 2001; Australian Heritage Commission 2002; Gray 2004; Kozlowski 2004; Serrano and Flaño 2007), in which geological, geomorphological, and soil features are considered the most important elements of it. However, there is no agreement on a definition that could be used in an international convention on geodiversity, as suggested by Crofts (2014). Without this agreement, crucial measures concerning a global strategy for geodiversity are much more difficult to implement, even if geodiversity has now a strong theoretical and conceptual status (Gray 2008). Nevertheless, the use of this concept, even by earth scientists, can lead sometimes to different interpretations (Carcavilla et al. 2008) like "soil geodiversity" (Van den Ancker 2006), "geothermal geodiversity" (Cody 2007), "climatic geodiversity" (Kot 2005), and "landform geodiversity" (Zwolinski 2009).

The characterization of geodiversity patterns is a major asset for territorial management (Hjort and Luoto 2010), and from a scientific and social point of view, there is an increasing need for the knowledge, promotion, and protection of geodiversity (Nieto et al. 2006). Also, the current use of the biodiversity concept in public policies and territorial management lead to the recognizance of the importance of abiotic elements in territorial management and nature conservation (Serrano and Flaño 2007). In 1996 (updated in 2002), the Australian Natural Heritage Charter considers equal weigh to biodiversity and geodiversity regarding nature conservation, elevating the status and the acceptance of geodiversity at all levels (Gray 2008).

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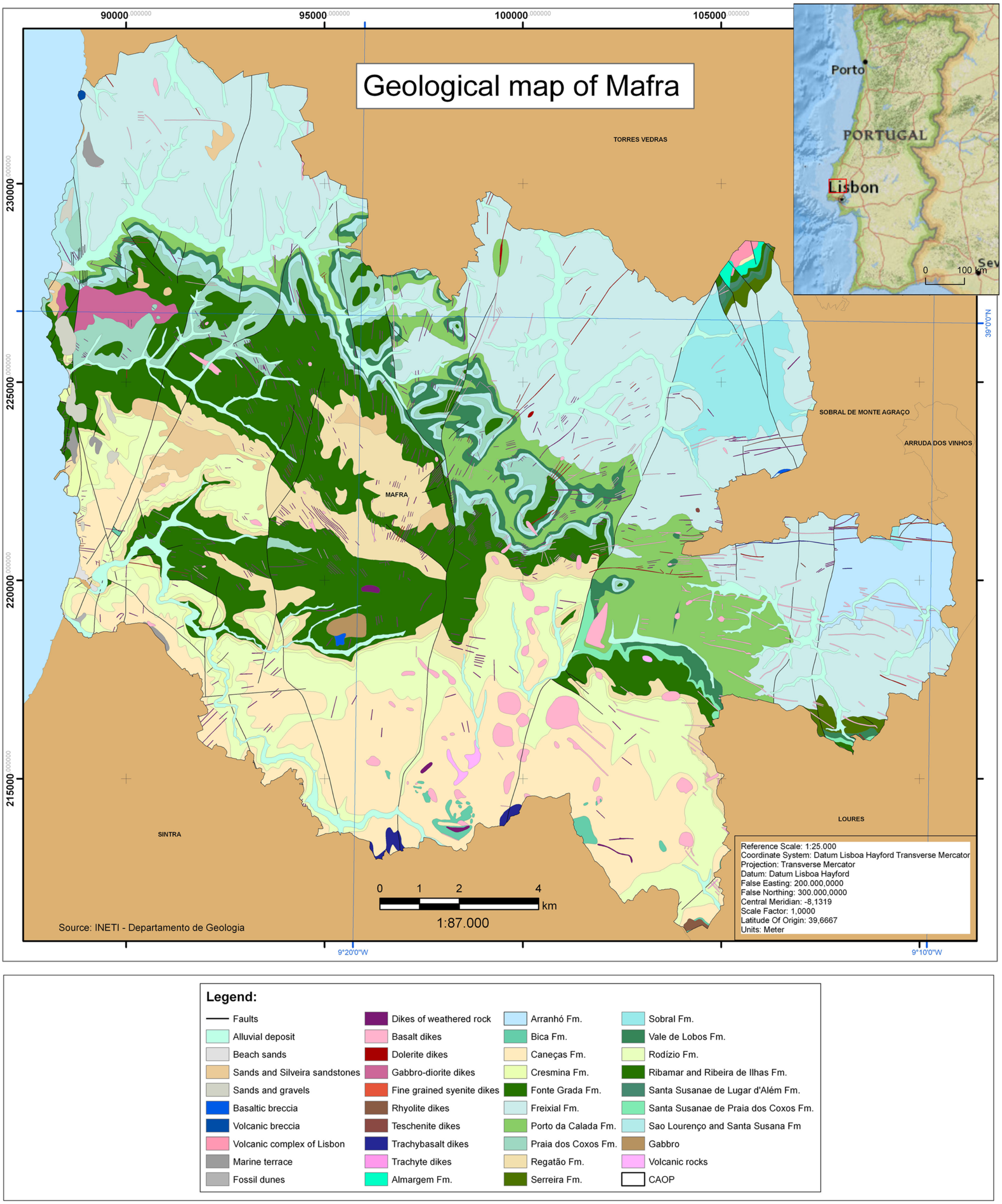

Fig. 1 Location and geological map of the municipality of Mafra, Portugal

The assessment of geodiversity is a recent issue concerning the evaluation of natural diversity. While the first attempts to quantify geodiversity were mainly limited to topographical/relief features (Xavier-da-Silva et al. 2001; Serrano and Flaño 2007; Benito-Calvo et al. 2009; Zwolinski 2009; Hjort and Luoto 2010; Muller 2011; Manosso 2012; Pellitero 2012), other approaches tried to considerer all types of geodiversity elements (Carcavilla et al. 2007; Pereira et al. 2013; Forte 2014; Silva et al. 2015). More recently, other authors made new approaches to geodiversity assessment (Argyriou et al. 2016; Manosso and Nóbrega 2016; Najwer et al. 2016; Kaskela and Kotilainen 2017; Stepisnik and Trenchovska 2017).

This wider perspective may allow the inclusion of geodiversity as a specific and objective measure in territorial management plans, as tested by Ilic et al. (2016) and Santos et al. (2017). It can also contribute decisively to support sustainable development policies (Stace and Larwood 2006) and landscape planning (Muller 2011). Mapping a geodiversity index is clearly an open issue, as referred by Melelli (2014) and still today, it is not clear if all the abiotic elements could be analyzed together (Gray 2004).

Recent progresses in geographical information systems (GISs) with the development of new tools for spatial analysis allowed new approaches in the quantitative analysis of abiotic diversity (Xavier-da-Silva et al. 2001; Gspurning and Sulzer 2007; Jacková and Romportl 2008; Zwolinski 2009; Silva et al. 2013; Forte 2014).

This paper reports a new procedure (Forte 2014) to estimate the geodiversity through the calculation of a geodiversity index, based on GIS techniques and not supported on a spatial grid system which was a solution adopted in many previous studies. This new approach based on centroid analysis and kernel density (Forte 2014) allows a more precise understanding of the number, frequency, and the distribution of the variables, than spatial grid system does. One of the main limitations of the spatial grid system that this approach tries to overcome is related with the scale problem, more specifically the modifiable areal unit problem (MAUP), referred by Marceau (1999).

Study Areas

In order to test the procedure, the method was applied to two municipalities with different surfaces and geological contexts, aiming not only to compare different regions at different scales but also to increase the scientific knowledge on this topic, using a new approach on spatial analysis, the kernel density.

The municipality of Mafra (Fig. 1) is located in central Portugal, between latitudes 38° and 39° north and longitude 9° west. Its surface is about 291 km^2 and is mainly constituted by upper Jurassic and Cretaceous sedimentary formations and some volcanic rocks of the same age.

The municipality of Morro do Chapéu (Fig. 2) is located in Northeastern Brazil (state of Bahia), about 392 km west of Salvador da Bahia, between latitudes 10° and 12° south and longitudes 40° and 41° west. Its surface of about 5742 km^2 is mainly constituted by Meso-proterozoic and Neo-proterozoic sedimentary formations.

Method

The main aim of this work was to develop a new method to calculate a geodiversity index that can be represented in a map, as it is done already with biodiversity indexes. This method focuses territorial management at municipal scale, despite being suitable for other scales. How to measure the variety of minerals, fossils, rocks, landforms, and soils, in a certain area is the key question. As stated above, there are already several proposals to calculate a geodiversity index, mainly centered on a grid system that allows to count in each cell the occurrence of different geodiversity elements.

This paper presents a different general approach, not based on a grid system (Forte 2014). Using the ArcGIS.10© software package, the method is based on an overlay operation, with different datasets (i.e., geology, geomorphology, hydrography, soils), that combines the characteristics of all datasets into one single polygon dataset. The new polygons are then transformed into point features, followed by a kernel analysis. A raster file is then created and reclassification of data is made. A final map is generated with a numerical expression of the geodiversity index (Fig. 3).

It should be noted that it is not possible to assess all abiotic elements at the same scale, as Marceau (1999) has already mentioned. In addition, every method can only deal with part of the big picture in what concerns the assessment of the diversity of abiotic nature. Previous works about geodiversity assessment have proposed to use several types of geodiversity elements. In this work, geology, geomorphology, hydrography, and soil elements were chosen as the most important ones, since they are decisive for territorial management. The geology dataset comprises the information available on geological maps, namely the different geological units, faults, and dikes. The geomorphology dataset used the information from geomorphological unit maps, based on the classification proposed by Ross (1992) and later adapted by Pereira et al. (2013) to assessment purposes. The hydrography dataset represents the river network that was categorized using the Strahler method (Strahler and Strahler 2002). The rivers' hierarchy is related with the width of the river channels and depends on the scale analysis. Finally, the soil dataset comprises the information available on the soils map.

Concerning the vector cartography for the municipality of Mafra, scales of 1:25,000 and 1:50,000 were chosen because they are the most common maps used in territorial management in Portugal. For the municipality of Morro do Chapéu, scales of 1:100,000 and 1:200,000 were selected, but only the later was used for the numerical assessment because this is the most common map scale in the Bahia state.

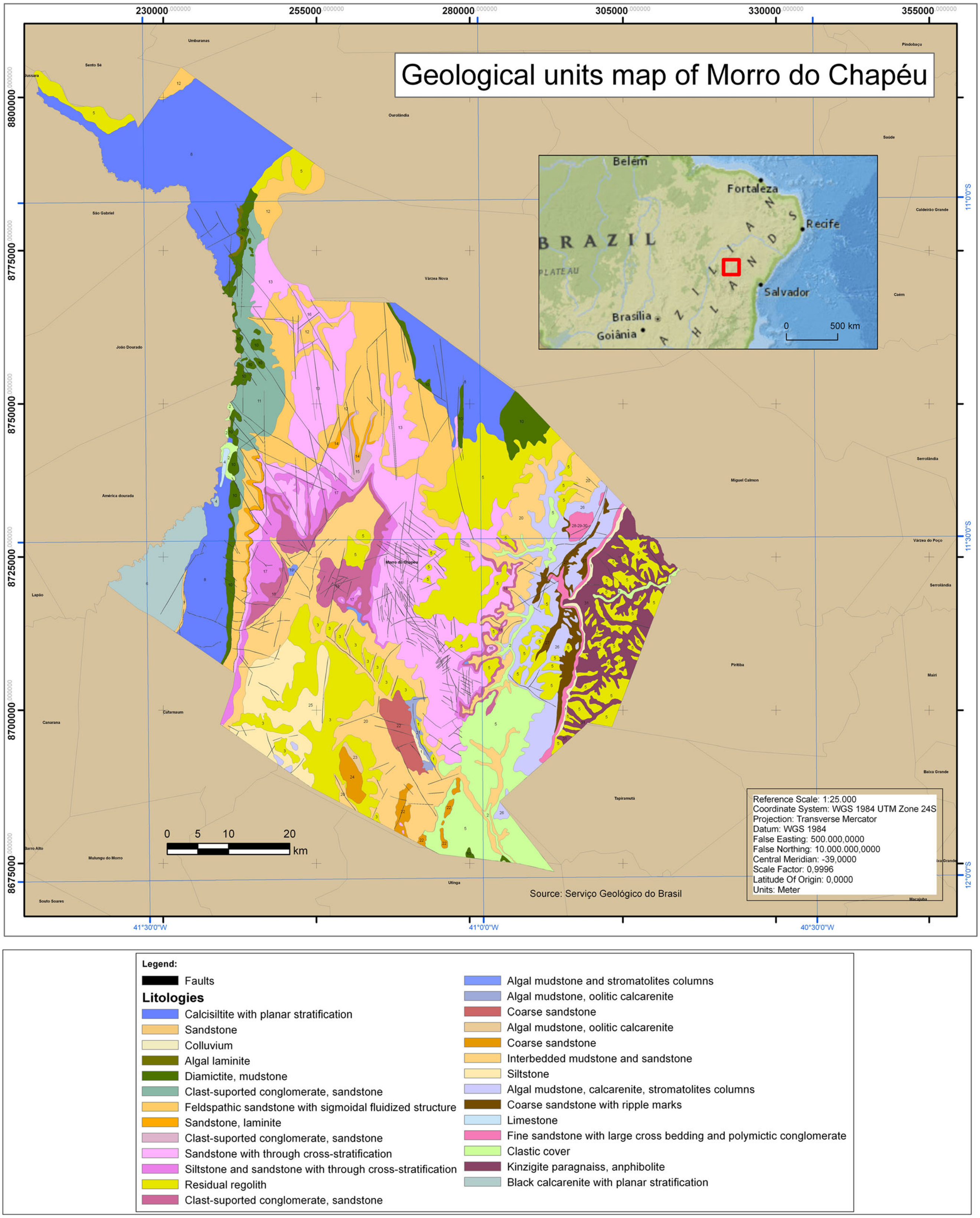

Fig. 2 Location and geological map of the municipality of Morro do Chapéu, Bahia, Brazil

Excluding the geomorphological units map of Mafra, manually created trough GIS, all the cartography used in this work was published by national organizations (namely the geological survey) and was validated in order to

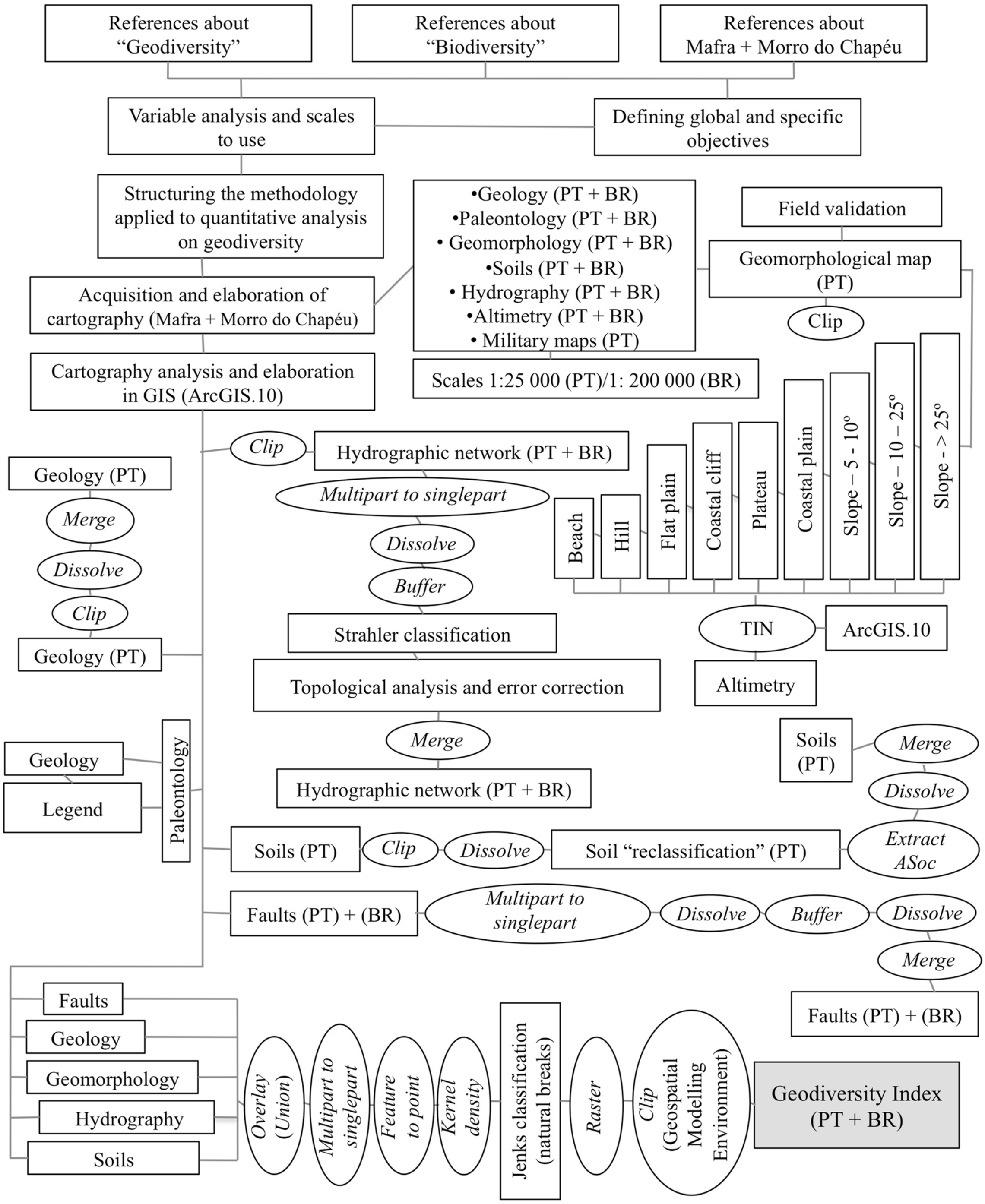

Fig. 3 Methodological procedure used to quantify geodiversity in the municipalities of Mafra, Portugal, and Morro do Chapéu, in Brazil (Forte 2014)

eliminate errors (e.g., topology, attributes) and to guarantee its integrity to avoid faults in the subsequent steps.

To start the assessment procedure, all the vector cartography has to be in polygon format. This requisite obliged to perform some preliminary operations for some of the datasets. Having all four datasets ready (geology, geomorphology, hydrography, and soils), it is necessary to apply an overlay operation to merge all datasets in one single dataset. With these new feature classes, it is now possible to transform them into point features (centroids), which are generated from the representative locations of input features. With this new dataset, a kernel analysis was made for point features (Fig. 4) and a raster file was generated.

This raster file has a 5-m cell size in Mafra and 40 m for Morro do Chapéu. In this analysis, the chosen unit area was

Fig. 4 Illustrative procedure for geodiversity quantification, using spatial operations of overlay, point attribution for all the new polygons, and kernel analysis

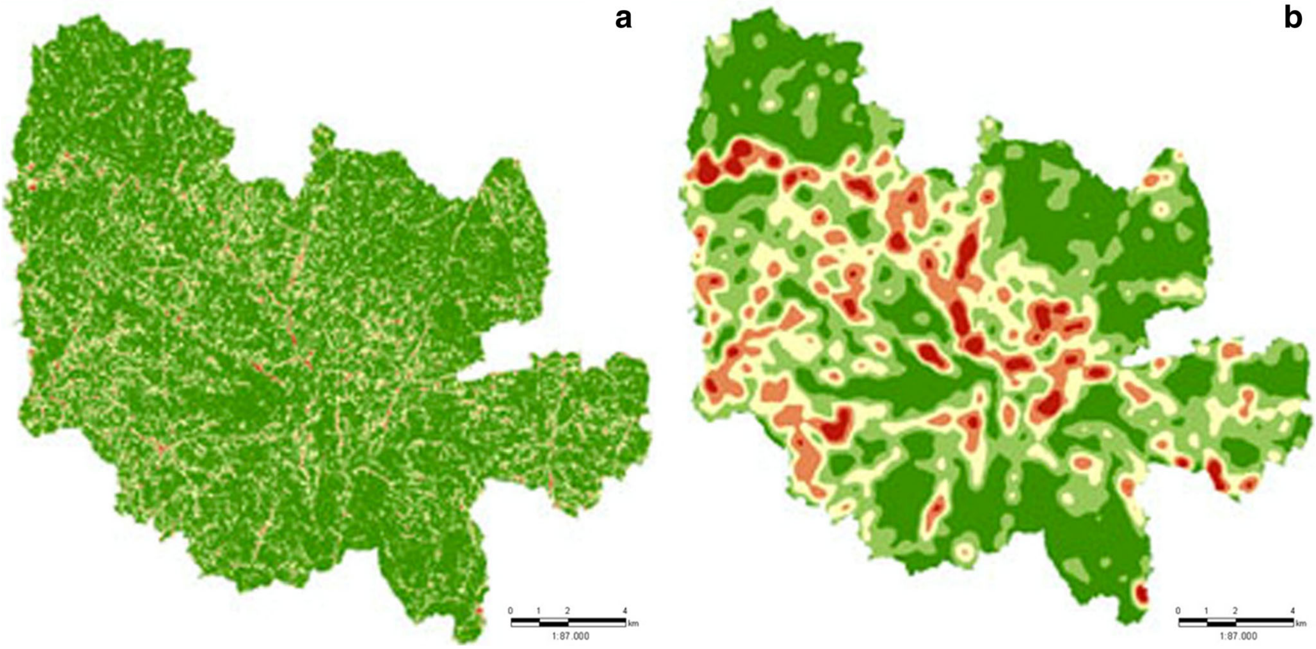

Fig. 5 Maps when used different distances for the search radius in Mafra (**a** 50 m, **b** 500 m)

km^2, i.e., points per square km. Since one of the aims of this method was to compare areas at different scales, in Morro do Chapéu, the density points was also calculated by 64 km^2, which corresponds to an equivalent unity at a scale eight times lower. It should be noted that point density can only be calculated if the coordinate system is in the metric system.

In order to get a reference value for the search radius to be used in the kernel analysis, several tests were made (Fig. 5). Based on these tests, the optimum value in Mafra was 250 m for 1:25,000 scale, and in Morro do Chapéu, the search radius was 2000 m for 1:200,000 scale. The surface value is higher at the location of each

Table 1 Dataset groups used to test all the variables for the procedure of geodiversity quantification in the municipalities of Mafra (M) and Morro do Chapéu (MC)

Mafra		Morro do Chapéu	
M1	Hydrographic network, lagoons, geology (without dikes), geomorphology, soils	MC1	Hydrographic network, lagoons, dolines, geology, geomorphology (subdivision of level 3), soils
M2	Geology (without dikes), geomorphology, soils	MC2	Lagoons, geomorphology (subdivision of level 3), geology, soils, dolines
M3	Hydrographic network, lagoons, faults, geology (with dikes), geomorphology, soils	MC3	Hydrographic network, lagoons, faults, dolines, geology, geomorphology (subdivision of level 3)
M4	Hydrographic network, lagoons, geology (without dikes), faults, geomorphology, soils	MC4	Geology, geomorphology (subdivision of level 3), soils
M5	Geology (with dikes), geomorphology, soils	MC5	Lagoons, hydrographic network, faults, dolines, geology, geomorphology (level 3)
M6	Hydrographic network, lagoons, geology (with dikes), faults, geomorphology	MC6	Lagoons, hydrographic network, dolines, geology, geomorphology (level 3)
M7	Hydrographic network, lagoons, geology (without dikes), geomorphology		

point, or centroid, and diminishes till zero at the end of the search radius limit. In the end, the kernel density corresponds to the geodiversity index. Aiming a better visual representation of data, a reclassification is made using natural break classification, as it allows to maximize the differences between classes and to obtain a final numerical expression of the geodiversity index.

Once all datasets are properly prepared to be processed by the software, it is now possible to use different combinations of datasets to check their behavior in the calculation of the geodiversity index (Table 1). It should be noted that in order to compare the geodiversity index in two different regions (like Mafra and Morro do Chapéu), it is necessary that each dataset for both regions uses the same classification system. For instance, as it was not possible to make a reclassification of the Mafra soil map according to the World Reference Base for Soil Resources (WRB) used in the Morro do Chapéu soils map, this dataset was not used in a comparative analysis between both testing areas.

For the geology dataset of Mafra, and also in order to understand if the high concentration of dikes in this region could bias the final result, two datasets were used: one with all geological elements and another without the dikes.

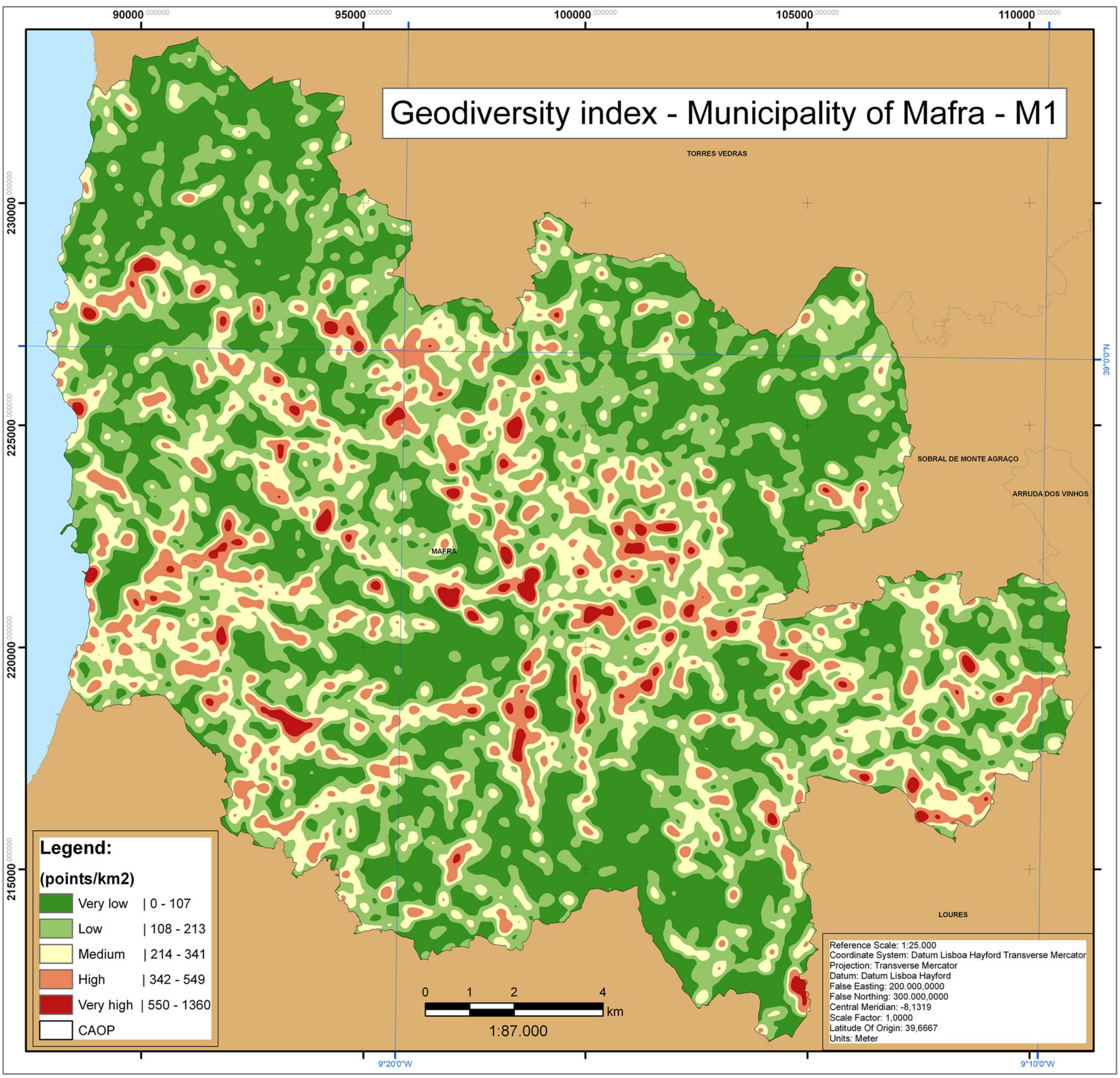

Fig. 6 Geodiversity index of the municipality of Mafra using M1 data (Table 1)

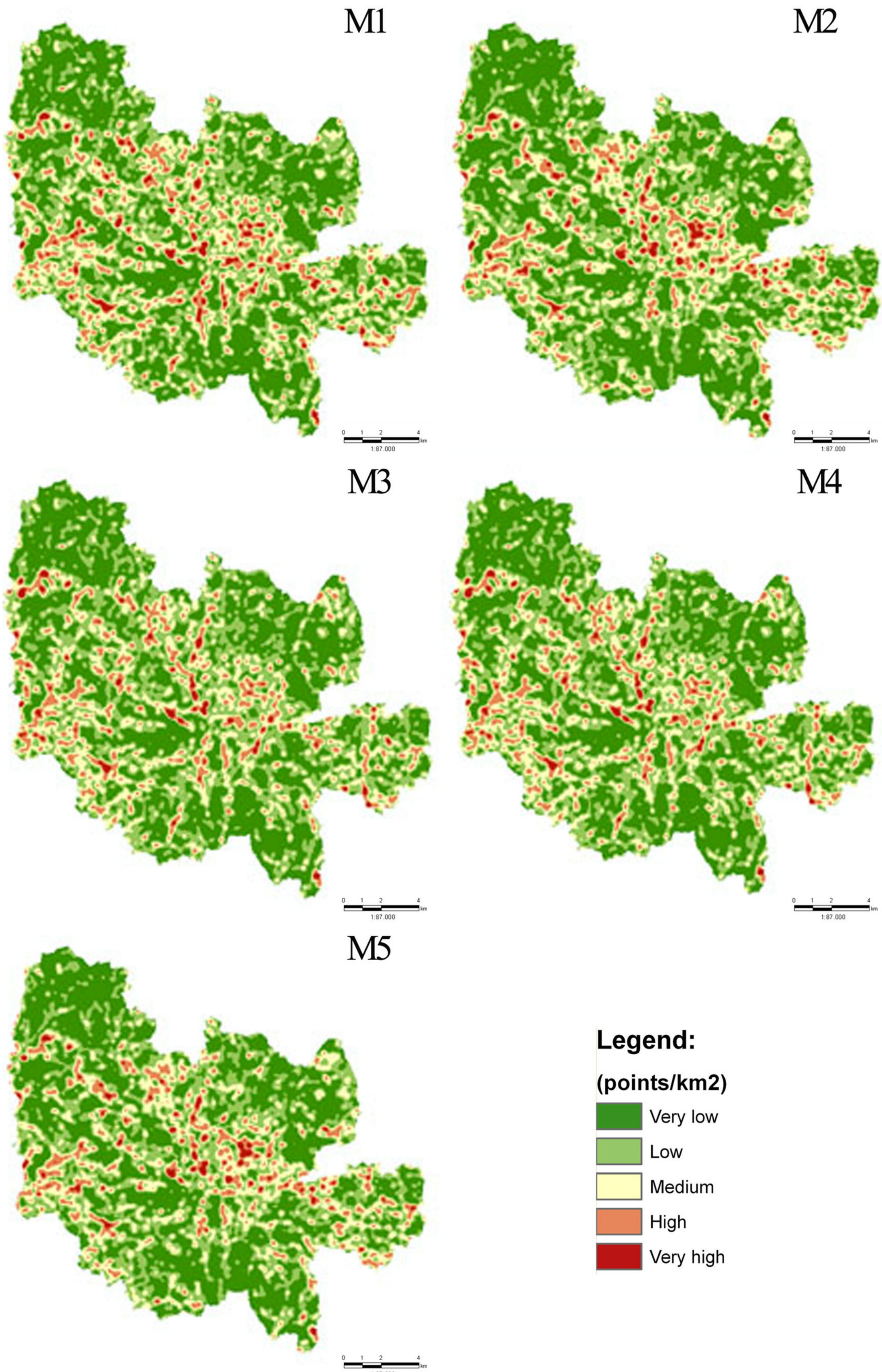

Fig. 7 Geodiversity maps of Mafra considering all variables, using M1 to M5 data (Table 1)

In a first attempt, paleontological data (number of species in each geological formation) was also included in the procedure, but in the end, it was excluded because it became clear that this dataset was originating biased results.

Results

The application of the method described in this work in two regions with contrasted geodiversity and surface allowed the determination of geodiversity indexes for both areas and its visual representation on maps (Figs. 6 and 9). The geodiversity index varies from very low to very high in a five-level scale. The higher the centroid density (points by square km), the higher is the geodiversity index.

A general observation of all geodiversity maps produced for Mafra and Morro do Chapéu areas shows that highest diversity values are associated with dissected areas, medium-high slopes, and a higher lithological diversity.

A more detailed observation of all Mafra maps reveals that despite obvious small variations between maps, the general pattern of the geodiversity index is the same. This means that although the use of different combinations of variables (e.g., with or without soils, with or without hydrographic network) and different number of centroids in each dataset (e.g., from 27,473 to 57,323), there is a significant similarity between maps and a good detail in all maps (Figs. 7 and 8), which supports the idea that geology and geomorphology are the most important variables to define a geodiversity index.

It is also important to stress that the method was only applied to the area of each municipality, with no contiguous areas. When this occurs due to missing data or by option, it means that there is a small distortion in these adjacent areas. Since the analysis is based in centroids through a search radius, this means that distortions can occur if the datasets do not include adjacent datasets. For the Mafra example, centroids that are located precisely at the municipality limits have a distortion of 50%, lowering till 0% as it goes 250 m inside the limit of the search radius. For the Morro do Chapéu example, this value is 2000 m.

Concerning Morro do Chapéu, there are some important differences to remark (Fig. 9). In the dataset that included all the variables, three of the four maps present similarities between them (Fig. 10). On the contrary, in the dataset that used a different geomorphological classification (level 3, instead of subdivision of level 3) and excluded soils (Fig. 11), there are substantial differences between them and the first dataset of four maps. Also, there is less detail on all maps with a lower number of centroids (e.g., from 1671 to 6385), which means that point density is less precise at 1:200,000 scale and not enough to validate the analysis with a geomorphological classification larger than the one used with the subdivision of level 3 (Table 1).

Having produced different maps of the geodiversity index using different combinations of datasets for both areas, a new question arose about the represented patterns: what if they were just random patterns? In order to solve this question, the high/low clustering tool (Getis-Ord General G) was applied to all maps. This tool measures the degree of concentration of the z-score, or standard deviation, both for high or low values. The result of this test showed that for all Mafra maps, patterns were not random (Figs. 7 and 8). In Morro do Chapéu, maps patterns were not random in the first dataset group (Fig. 10)

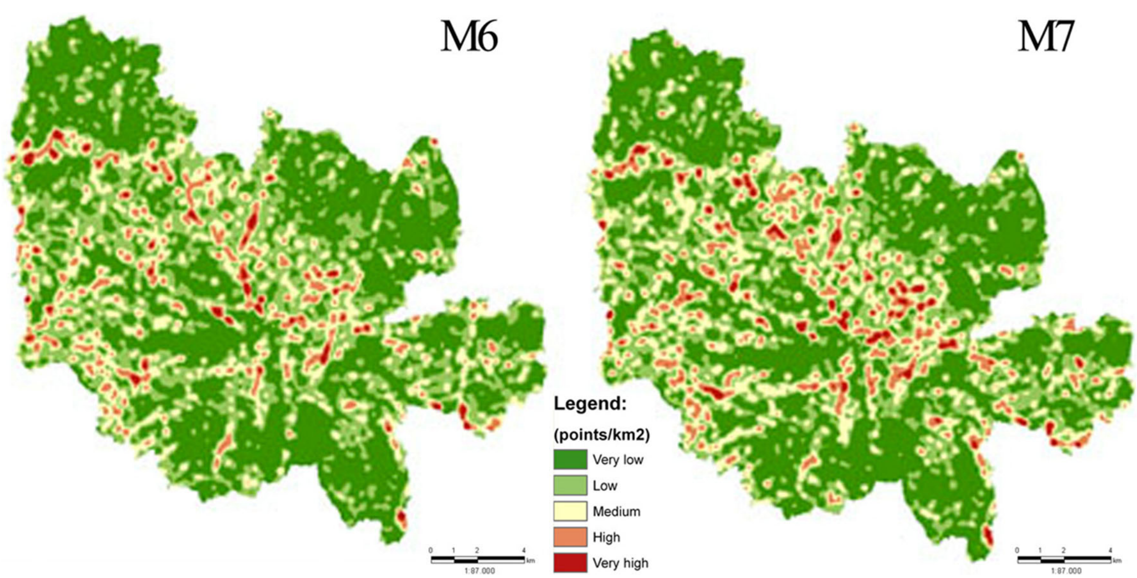

Fig. 8 Geodiversity maps of Mafra excluding soils, using M6 and M7 data (Table 1)

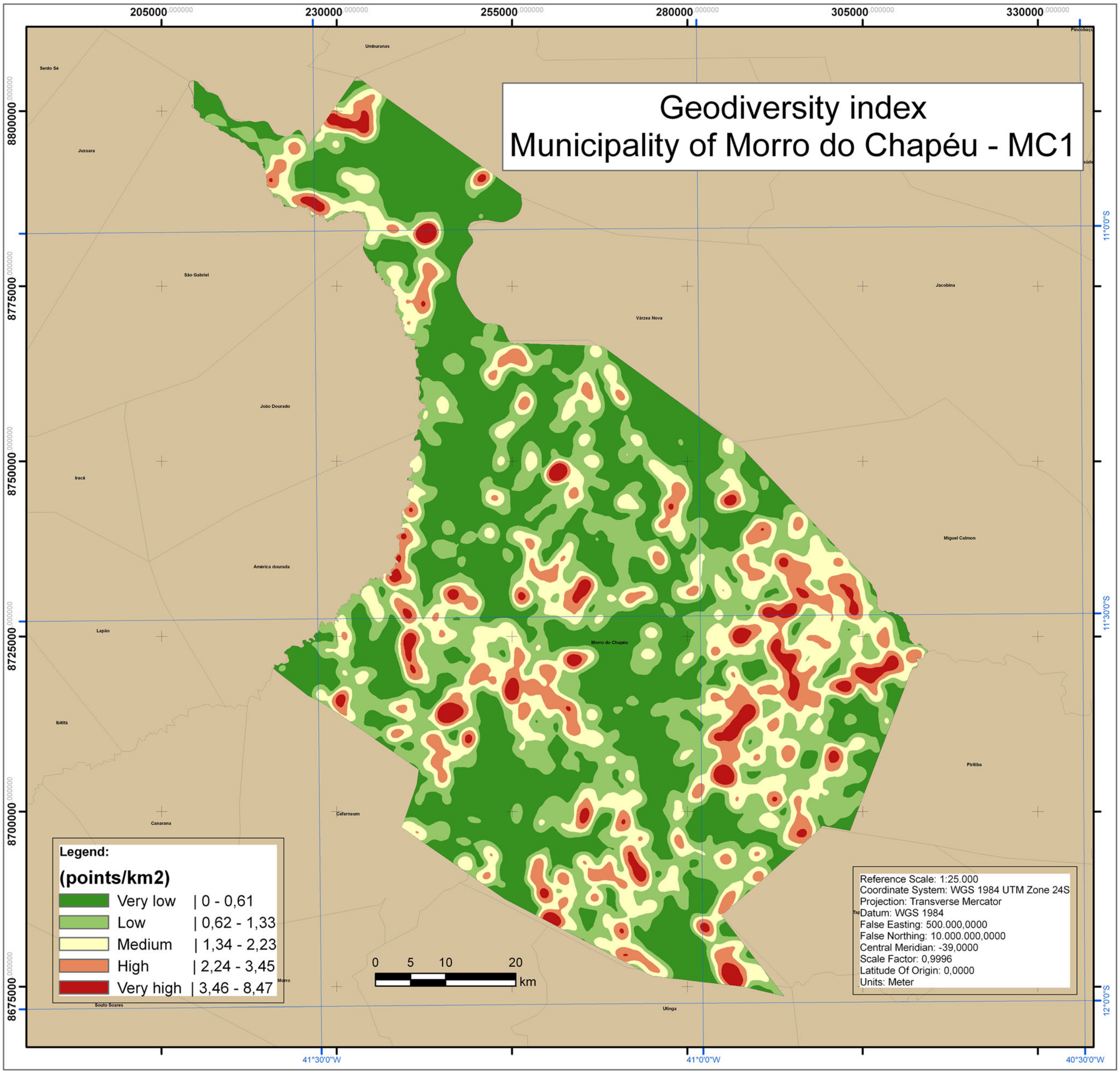

Fig. 9 Geodiversity index of the municipality of Morro do Chapéu using MC1 data (Table 1)

but were classified as random in the second dataset group (MC5, MC6), on which soils were excluded and level 3 classification for geomorphology was used (Fig. 11). This demonstrates that only subdivision of level 3 is suitable to validate the analysis.

Discussion and Final Remarks

The results obtained with the application of this procedure for the calculation of a geodiversity index show unequivocally that geology and geomorphology are the key drivers that control geodiversity patterns. Other variables (e.g., soils, hydrographic network, faults) are not determinant to influence the geodiversity index, although they can contribute to obtain a better detail in maps with bigger scales (e.g., 1:25,000, 1:10,000).

The methods that are based in a spatial grid system do not allow to understand in detail the number, frequency, and distribution of variables, like this method do. As Marceau (1999) refers and this method has confirmed, point data analysis allows a better understanding at bigger scales. For 1:25,000 scale, this method is precise concerning territorial management plans and allows to understand very well the geodiversity index patterns. In addition, the use of a single variable with high density,

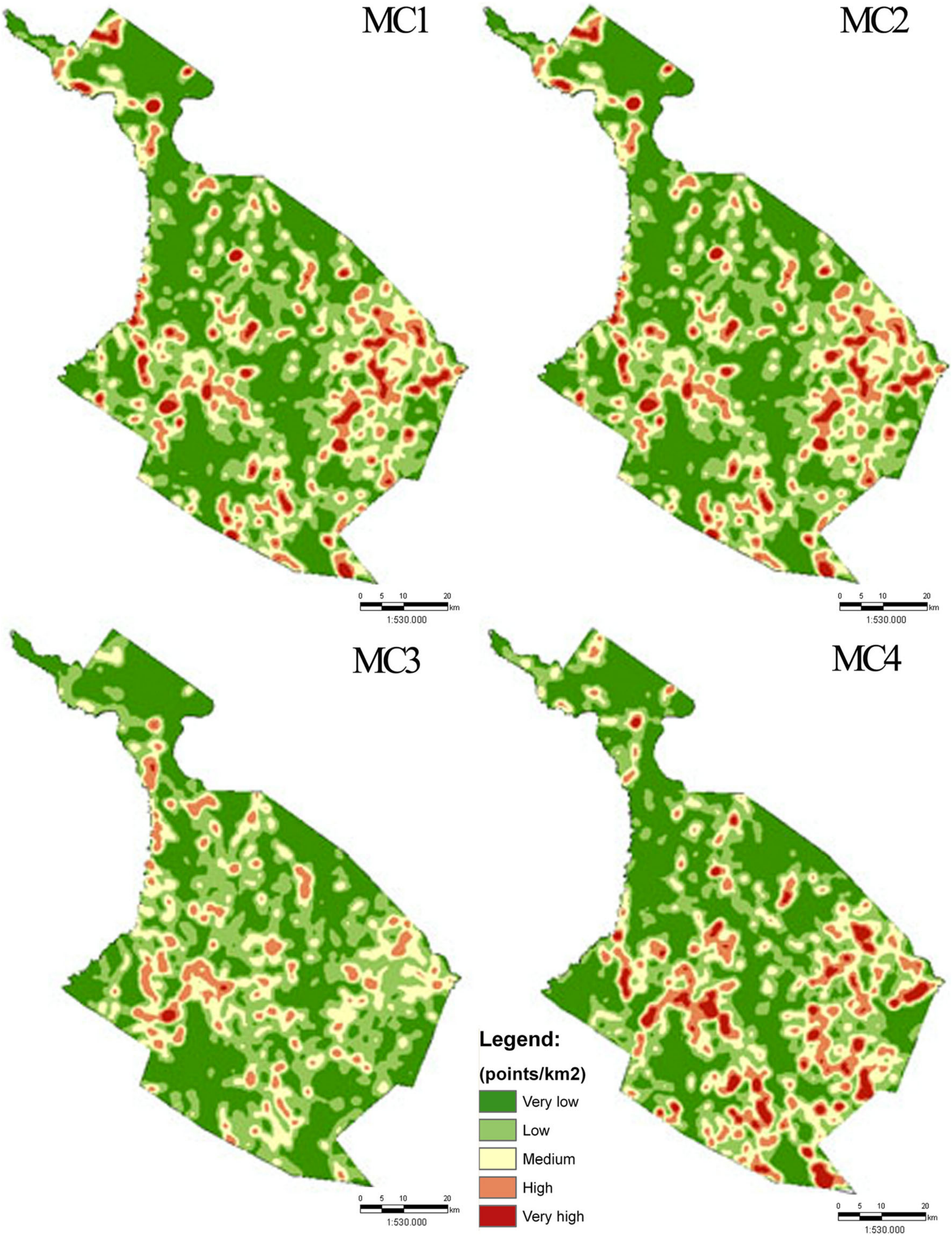

Fig. 10 Geodiversity maps of Morro do Chapéu that included all variables, using MC1 to MC4 data (Table 1)

like faults and dikes, has no relevant effect in the final pattern at this scale.

At 1:200,000 scale, this method is less precise but even so, it allows to characterize solid patterns using key drivers. Concerning geomorphological units, the subdivision of level 3 should be the highest to be used because otherwise the spatial analysis could not be valid, as point density is not enough to validate the analysis. With other variables, like faults or dolines, results were biased when included in the spatial analysis, which means that at 1:200,000 scale, faults and dolines must be excluded if there is a high density of occurrences.

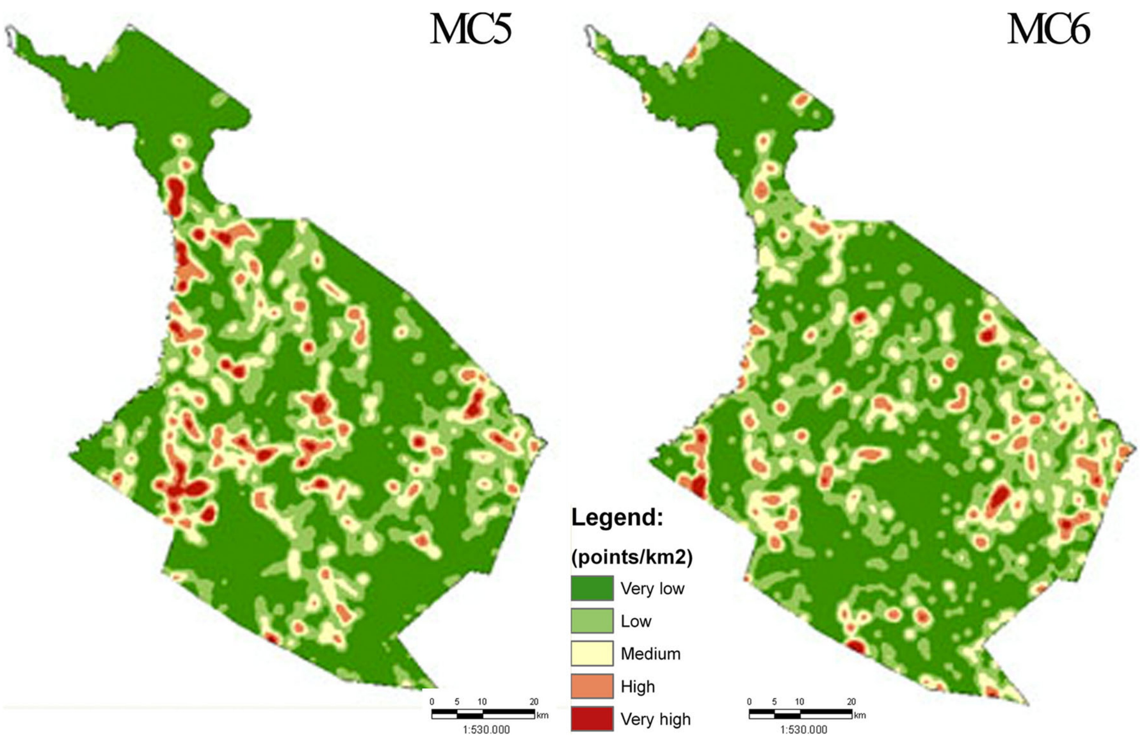

Fig. 11 Geodiversity maps of Morro do Chapéu that excluded soils, using MC5 and MC6 data (Table 1)

Results have shown that it was not possible to directly compare both territories at different scales, even if scale is transpose from 1:200,000 to 1:25,000. Two facts were crucial for this: firstly, it was not possible to transpose soil classification to the World Reference Base for Soil Resources in Mafra and also in Morro do Chapéu, the exclusion of soils does not allow a comparison only with geology and geomorphology at 1:200,000 scale.

As Gray (2004) argued, it is not possible to analyze all the abiotic elements together at the same time, as the paleontological analysis revealed in this method. The trials done in the scope of this work showed that a high number of species occurring in a certain geological unit originates an artificial increase in the geodiversity index where that unit crops out.

The method here presented has the potential to be used for comparative analyses when using the same scale, assuming that standard classification systems are used for all variables. Geology and geomorphology must always be included in the geodiversity assessment because they are the key drivers. Other variables may be discarded, but for evaluations using the 1:25,000 scale, a higher detail on the geodiversity pattern can only be achieved if all variables are used in the calculation of the geodiversity index. The results obtained in two test areas have shown that this assessment method can be applicable in regions with different geological settings and different scales.

Territorial management actions should take into account the cartographic expression of geodiversity indexes. The procedure for the determination and mapping of geodiversity index here presented has demonstrated that municipal management may benefit from it, particularly for working scales around 1:25,000.

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