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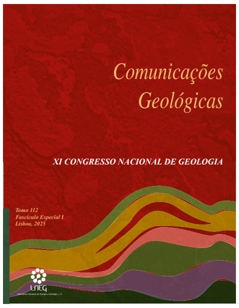
Assessment of geomorphological diversity indices of Portugal mainland

Avaliação da diversidade geomorfológica de Portugal Continental



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Abstract: The results from the assessment of diversity, evenness, and richness indices of geomorphology of mainland Portugal are presented, based on four hierarchical levels of geomorphological units. These indices were calculated on a hexagonal analytical grid, testing eight cell dimensions (1 km, 2 km, 5 km, 10 km, 15 km, 20 km, 25 km and 30 km). The 10 km dimension provided a clearer definition of regional geomorphological specificities, which correspond to areas of higher diversity and richness. The results related to evenness did not allow for establishing such clear relationships with geomorphological units. However, the diversity and evenness indices, along with richness, provide a more comprehensive assessment of spatial diversity. These results are part of the assessment of Portugal's geodiversity and are essential for comparative analyses between various elements of geodiversity and with other natural and cultural elements.

Keywords: geodiversity, geomorphology units, diversity indices, grid system, quantitative assessment.

Resumo: Apresentam-se os resultados da avaliação de diversidade, riqueza e equidade geomorfológica de Portugal continental, baseada em 4 níveis hierárquicos de unidades geomorfológicas de Portugal Continental. Os índices foram calculados numa grelha analítica hexagonal, testando-se oito dimensões de células (1 km, 2 km, 5 km, 10 km, 15 km, 20 km, 25 km e 30 km). A dimensão de 10 km forneceu uma definição mais clara das especificidades geomorfológicas regionais, as quais correspondem às áreas de maior diversidade e riqueza. Os resultados relativos à equidade não permitiram estabelecer relações tão claras com as unidades geomorfológicas. Os índices de diversidade e equidade, juntamente com a riqueza, fornecem uma avaliação mais abrangente da diversidade espacial. Estes resultados fazem parte da avaliação da geodiversidade de Portugal e são fundamentais para análises comparativas entre os vários elementos da geodiversidade e com outros elementos naturais e culturais.

Palavras-chave: geodiversidade, unidades geomorfológicas, índices de diversidade, grelhas, avaliação quantitativa.

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1. Introduction

The concept of geodiversity was coined in 1993, by Sharples, under the perspective of geoconservation (as a synonym for geological and geomorphological conservation) and as a counterpoint to the concept of biodiversity, which was formally defined at the Convention on Biological Diversity, celebrated at the United Nations Conference on Environment and Development (Rio Conference), in 1992. Geoconservation is a value-laden concept that is used to identify specific elements of geodiversity for geological conservation, within the geological heritage (Gray, 2018). Geodiversity, on the other hand, is a neutral concept that describes the variety of abiotic phenomena on Earth, being often defined as the abiotic equivalent of biodiversity, describing the variety of geological, geomorphological, pedological and hydrological features and processes (Gray, 2013). There are several distinct approaches to the concept of geodiversity, and various methodologies for evaluation, including qualitative, quantitative, and qualitative-quantitative methods (Zwoliñski *et al.*, 2018).

The importance of quantitatively assessing the spatial patterns of geodiversity, as well as its relationship with biodiversity, has been highlighted by several authors, given the significant implications this knowledge can bring to land use management and environmental strategies.

The calculation of geodiversity indices is among the most used quantitative assessment method (Crisp *et al.*, 2021). Serrano e Flaño (2007) presented one of the most cited geodiversity indices, which relates the variety (richness) of abiotic elements with surface roughness, measured on geomorphological units. Pereira *et. al.* (2013) popularized the geodiversity index mapping based on the grid system, consisting of the sum of partial indices, each of them representing the variety of a geodiversity element (ex. lithology, geomorphology, hydrology, pedology), measured on a unit cell within the grid system.

The geodiversity index mapping is commonly used to determine the richness of the abiotic elements, although richness corresponds solely to one of two primary components that form the concept of diversity, the other being the relative amount of each distinct class (Ibánez e Brevik, 2022). Despite the increasing number of geodiversity assessment procedures reported in the last years, there is a lack of studies that evaluate spatial diversity in a broaden way, either by extending richness assessment to other existing indices, either by implementing new indices and new methodologies. Moreover, apart from the innovative geodiversity index based on kernel density developed by Forte *et al.* (2018) tested at a local scale (Mafra municipality) and the richness geodiversity index presented by Peixoto (2021) at a national scale, there are no significant geodiversity studies applied to Portuguese territory. The results here presented are part of a work that establishes an empirical methodology to select the most appropriate cell size to assess geodiversity, while using the grid system to calculate the geodiversity index (Lopes *et al.*, 2023). Besides richness, Simpson's (1949) and Shannon's (1949) diversity and evenness indices were applied to the geomorphology units map of mainland Portugal, a more detailed version of Pereira *et al.* (2014), by using a hexagonal analytical grid, through eight cell dimensions (1 km, 2 km, 5 km, 10 km, 15 km, 20 km, 25 km and 30 km).

2. Geomorphological units of mainland Portugal

The geomorphological units map of mainland Portugal at 1/500,000 scale by Pereira *et al.* (2014) organises the territory into three hierarchical levels of consistent and homogeneous geomorphological information (regarding dimension, age and genesis). The first level is the morphostructural units and comprehend three units, namely the Iberian Massif, Slightly Deformed Meso-Cenozoic Basins (Lusitanian and Algarve) and the non-deformed Tejo and Sado Cenozoic basins. The second level includes ten morphoscultural units which correspond to compartments initially generated by tectonic processes and modelled by weathering processes over the time. These units are distributed under the units from the previous level: the Iberian Massif (NW Iberian Plateaus and Mountains, Central Mountain Range, the SW Iberian Plateaus and Hills and Berlengas); Slightly Deformed Meso-Cenozoic Basins (Lusitanian Basin, Algarve Basin); Cenozoic Basins (Baixo Tejo and Alvalade, Douro, Guadiana, Coastal Plains). The third level includes 56 morphoscultural sub-units that subdivide the second level, corresponding to compartments modelled by specific weathering processes, delimited based on the analysis of relief patterns provided by the SRTM datasets, geological substrata and fieldwork.

The map developed for this work (Figura 1), at the same scale, contains a fourth level of more detailed geomorphological units and a reorganization in the limits of the upper levels. This fourth level corresponds to individualized landforms related to aggradation, erosion or denudation, such as river or marine plains, river or marine terraces or hills and ridges, presenting a total of 686 features that represent the geomorphological diversity of Portugal. The Mountains and Plateaus of the NW Iberia morphoscultural unit comprises the highest number of features, followed by the SW Iberian Plateaus and Hills and Coastal Plains units. The Peneda-Gerês Mountains, Peneda-Gerês Atlantic Front and Mirandela Tectonic Basin morphoscultural sub-units contain the highest number of individualized fourth-level landforms. In the SW Iberian Plateaus and Hills morphoscultural unit, the highest number of fourth-level units were identified in the Castelo Branco Plateau morphoscultural sub-unit. The Coastal Plains sub-unit, although not so extensive in area, has a very significative number of distinct features.

3. Materials and methods

The data regarding geomorphological diversity are part of a study that establishes an empirical approach to choose the most suitable cell size to determine a geodiversity index for Portugal mainland through a grid system (Lopes *et al.*, 2023). The geomorphological diversity of mainland Portugal was assessed according to Richness (RICH), Simpsons and Shannon diversity and evenness indices (SIDI, SIEI, SHDI, SHEI) using the geomorphological units of mainland Portugal as data source overlayed by a hexagonal analytical grid, tested along eight cell dimensions (1 km, 2 km, 5 km, 10 km, 15 km, 20 km, 25 km and 30 km). The correspondent formulas are presented in Table 1.

In this paper we focus on the results retrieved from the final geomorphological diversity maps, and in particularly on the complementary outcomes provided by the distinct indices. Richness measures the number of categories, disregarding their relative abundance or spatial arrangement, *i.e.*, the same richness value can relate to a variety of distinct evenness values, except when a single category is present. Evenness indices (SIEI and SHEI) measure the distribution of area among categories, where larger values imply greater proportional abundance of each-category, independently of richness. Evenness indices equal 1 when the observed richness equals perfect evenness. Evenness and diversity indices equal zero when the distribution of the area is dominated by one single category (no diversity, nor proportional abundancy). Diversity indices (SHDI and SIDI) increase with the number of categories (richness) and/or the proportionality of area distribution among different categories (evenness), being more sensible to richness than to evenness (although SIDI is relatively less sensitive to richness than SHDI).

GIS processing and calculations were performed in QGIS software, version 3.16.16.

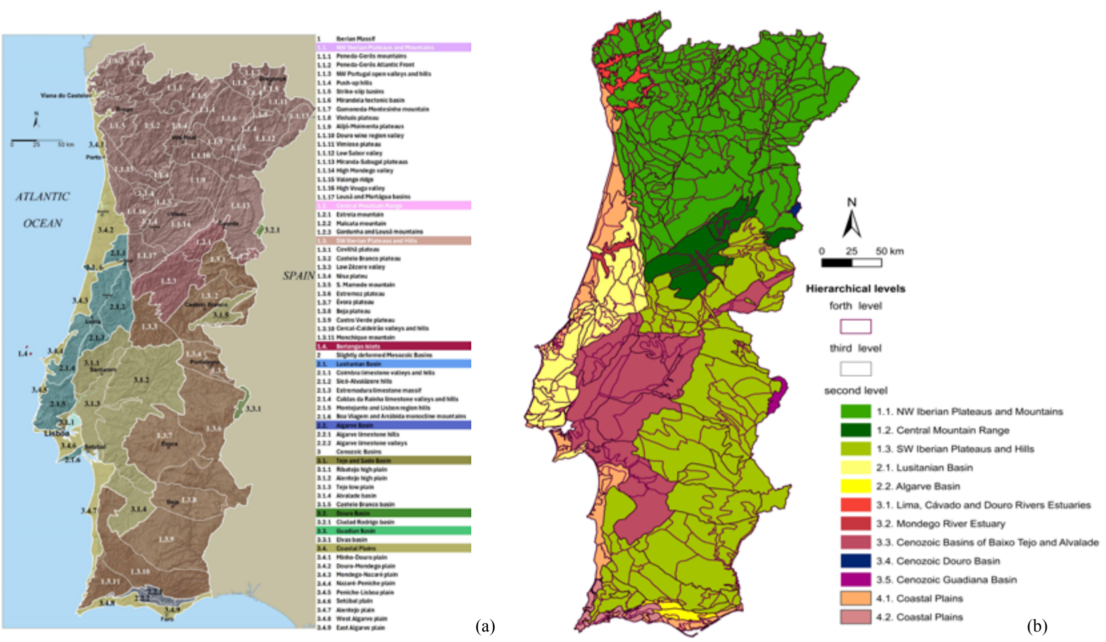

Figure 1. (a) Geomorphological units of mainland Portugal: three-hierarchical levels (Pereira *et al.*, 2014). (b) Geomorphological units map developed by detailing and reorganizing the previous version of Pereira *et al.* (2014), displaying four hierarchical levels, at a 1:500.000 scale.

Figura 1. (a) Unidades geomorfológicas de Portugal continental: três níveis hierárquicos adas unidades geomorfológicas desenvolvido, detalhando e reorganizando a versão anterior de Pereira *et al.* (2014), exibindo quatro níveis hierárquicos, à escala de 1:500.000.

Table 1. Richness, diversity and evenness indices' formulas used to assess the geomorphological diversity of mainland Portugal: m corresponds to the number of unique categories per unit area and P*i* corresponds to the proportion of area occupied by a category of type *i*.

Tabela 1. Fórmulas dos índices de riqueza, diversidade e equidade utilizadas para avaliar a diversidade geomorfológica de Portugal continental: m corresponde ao número de categorias únicas por unidade de área e Pi corresponde à proporção da área ocupada por uma categoria do tipo i.

Index	Formula	Range
Richness (RICH)	Rich=m	Rich > 0
Shannon's Diversity Index (SHDI)	$SHDI = -\sum_{i=1}^{m} (P_i \ln P_i)$	SHDI ≥ 0
Shannon's Evenness Index (SHEI)	$SHEI = \frac{-\sum_{i=1}^{m} (P_i \ln P_i)}{\ln m}$	0 ≤ SHEI ≤ 1
Simpson's Diversity Index (SIDI)	$SHDI = 1 - \sum_{i=1}^{m} P_i^2$	0 ≤ SIDI ≤ 1
Simpson's Evenness Index (SIEI)	$SIEI = \frac{1 - \sum_{i=1}^{m} P_i^2}{1 - (\frac{1}{m})}$	0 ≤ SIEI ≤ 1

4. Results and Discussion

The regional geomorphological specificities are identifiable at a 5 km cell size, becoming clearer at a 10 km cell size, despite a certain loss of spatial differentiation due to the decrease in spatial resolution (Figura 2).

Above the 10 km cell size, most of the diversity and richness elements become more generalized and aggregated. The results show that the areas with the highest diversity are linked to:

i) the second hierarchical level unit of NW Iberian Plateaus and Mountains, the third hierarchical level units of Peneda-Gerês Mountains, Peneda-Gerês Atlantic Front, Mirandela Tectonic Basin and Strike-slip Basins, Push-up Hills and Alijó-Moimenta Plateaus;

ii) the transition between the first level units of Meso-Cenozoic Basins and Slightly Deformed Meso-Cenozoic Basins with the Iberian Massif, corresponding to part of the shear zone that separates Ossa-Morena Zone and Central-Iberian Zone;

iii) the Lusitanian Basin, specifically within the third level units of Estremadura Limestone Massif, part of the Caldas da Rainha Limestone Valleys and Hills and of the Sicó-Alvaiázere Hills, and also within the Nazaré-Peniche Coastal Plain;

iv) the West and East Algarve Coastal Plains, in part of the SW Iberian Plateaus and Hills, within the Cercal-Caldeirão Valleys and Hills and Monchique Mountain, and in the Algarve Basin within the Algarve Limestone Hills and Algarve Limestone Valleys.

The results show that evenness and diversity indices seem to be more qualified as cell size indicators than richness (Lopes *et al.*, 2023). However, these indices also provide valuable insights into spatial diversity and contribute to a more comprehensive understanding of the data. Simpson's and Shannon's diversity and evenness indices complement the information provided by the richness index (Figura 3).

When a cell intersects three distinct geomorphological units, the richness value is 3, revealing very different SIDI, SIEI, SHDI, and SHEI values, function of the area distributions of the three units within each cell. Therefore, diversity and evenness indices, along with richness, provide a more comprehensive assessment of spatial diversity. Indeed, the upper cell, which has a richness value of 3, is slightly intersected by two of the three units, being predominantly represented by a single geomorphological unit. If the three units were equally distributed through the cell area, the richness value would "perfectly" describe the diversity within the cell area. The disproportionality of the areas occupied by the different units within the cell resulting in practically one single unit represented, is solely reflected by the other indices (0.01, 0.02, 0.05 and 0.04).

Since diversity indices reflect richness and proportionality of area distribution among different categories, they could provide by themselves a more accurate result than richness. As presented in Lopes *et al.* (2023) the strong correlation values (Spearman and Pearson) exhibited between richness and diversity indices confirmed the close dependency between those indices. On the other hand, the weak correlations between the richness and evenness indices highlighted their complementarity. Evenness indices, being independent of richness, can reach their maximum value even with a minimum richness value of 2 if the areas of both units are perfectly distributed throughout the cell. The complementarity of these indices can yield different results compared to diversity indices, contributing altogether to a more comprehensive assessment of spatial diversity.

5. Conclusions

The richness index is the most used index in geodiversity quantitative assessments, especially when using the grid system. Richness provides

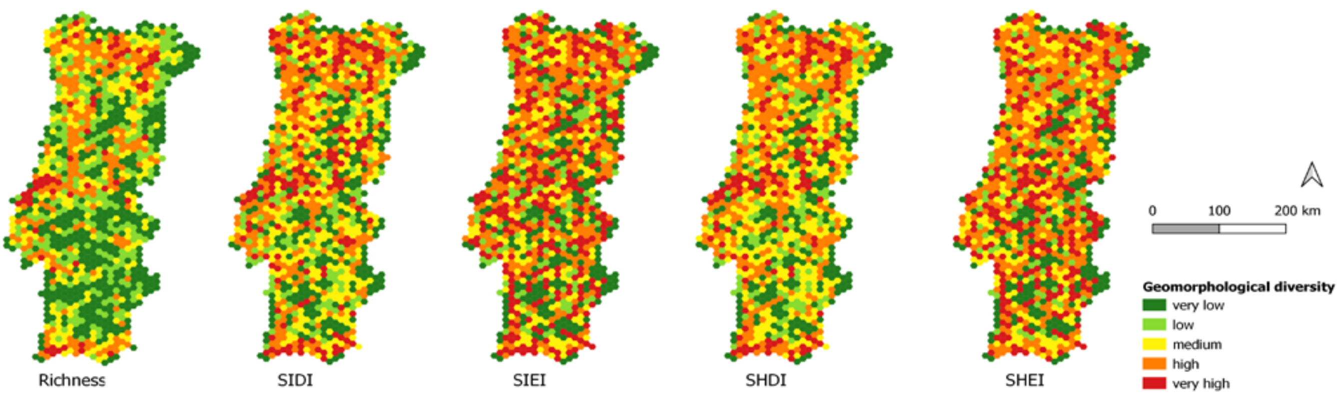

Figure 2. Geomorphological diversity indices of mainland Portugal. Based on richness, Shannon's and Simpson's diversity and evenness indices applied to the geomorphological units of mainland Portugal; measured with a cell size of 10 km; conventional diversity classes (very high, high, medium, low and very low) based on the Jenks natural breaks classification.

Figura 2. Índices de diversidade geomorfológica de Portugal continental. Com base nos índices de riqueza e de diversidade e equidade de Shannon e Simpson, aplicados às unidades geomorfológicas do continente português; medido numa célula de 10 km; classes de diversidade convencionais (muito alta, alta, média, baixa e muito baixa) baseadas na classificação de quebras naturais de Jenks.

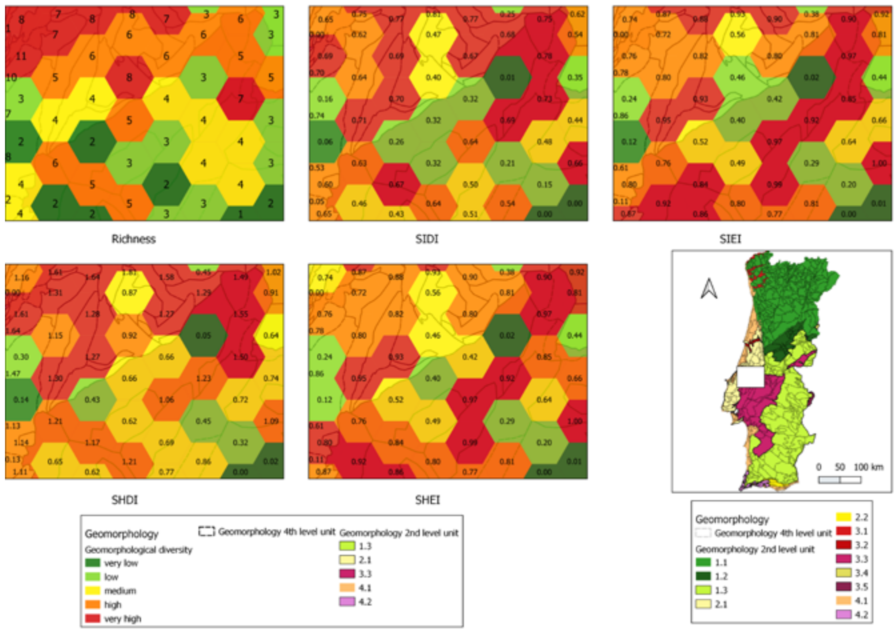

Figure 3: Detail of Richness, Simpsons's and Shannon's diversity and evenness indices (SIDI, SIEI, SHDI, SHEI) applied to the geomorphological units of mainland Portugal; measured with a cell size of 10 km; conventional diversity classes (very high, high, medium, low and very low) based on the Jenks natural breaks classification. Diversity and evenness indices, along with richness, provide complementary results within spatial diversity assessment.

Figura 3: Detalhe dos índices de riqueza e de diversidade de Simpson e de Shannon (SIDI, SIEI, SHDI, SHEI) aplicados às unidades geomorfológicas do continente português; medidos numa célula de 10 km; classes de diversidade convencionais (muito alta, alta, média, baixa e muito baixa) baseadas na classificação de quebras naturais de Jenks. Os índices de diversidade e de equidade, juntamente com o índice da riqueza, fornecem resultados complementares na avaliação da diversidade espacial.

clear, understandable, and comparable results when using maps to represent geodiversity. Diversity indices maps, particularly those resulting from the Simpson's diversity index (SHDI), support and emphasize the results from richness, being more accurate since it also reflects the proportionality of area distribution among the different categories. On the other hand, there is a clear complementarity between richness and evenness indices, which suggest that both indices could provide more information within geodiversity assessments, covering the compositional and structural components of diversity. The diversity and evenness indices, along with richness, provide a more comprehensive assessment of spatial diversity. These results are essential for comparative analyses between the various geodiversity elements and other natural and cultural elements of mainland Portugal.

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