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Assessing regional geodiversity: the Iberian Peninsula

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ABSTRACT: Geodiversity is a landscape characteristic related to the heterogeneity of the physical properties of the earth surface. In this work, we quantify and compare geodiversity in several geodynamic zones of the Iberian Peninsula. For this purpose, we have developed a geographic information system (GIS) procedure to carry out a regional terrain classification based on geodiversity factors. A classification process helped to produce a morphometric map (10 classes), a morphoclimatic map (five classes) and a geological map (15 classes). These three maps were combined using an overlay operation (union) to obtain the final terrain classification (419 classes), which was then applied to calculate diversity landscape indices. The latter were calculated using common landscape diversity indices (Patch Richness Density, Shannon's Diversity Index, Shannon's Evenness Index, Simpson's Diversity Index and Simpson's Evenness Index), provided by FRAGSTATS free software. These indices were calculated for the whole landscape of the main Iberian geological regions, thus revealing a close relationship between some index values and the geological and geomorphological characteristics. The highest diversity values are associated with Alpine collisional orogens and reactivated chains of the Precambrian-Palaeozoic massif. Intraplate orogen with sedimentary cover, characterized by extensive planation surfaces, have lower values. Mesozoic areas with no significant tectonic deformation and Cenozoic basins are characterized by the lowest diversity values. Amongst the latter, the major diversity is associated with the most dissected basins, which also present higher morphoclimatic variety. Though depending on the chosen scale and the landscape classification criteria, these indices provide an objective assessment of the regional geodiversity of Iberia. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: geodiversity; terrain classification; spatial pattern analysis; Iberian Peninsula; GIS; DEM; DTM

Introduction

The appearance of a landscape is a complex concept influenced not only by several physical and biological factors, but also by the observer's subjective perception. The physical factors, such as lithology, structure, landforms, processes and soils constitute the basis of a landscape and the key aspects to define geodiversity. In this way, geodiversity can be expressed as the heterogeneity of the geological and geomorphological properties of the earth's surface (Nieto, 2001; Gray, 2004, and references therein; Kozlowski, 2004; Carcavilla *et al.*, 2007; Bruschi, 2007; Serrano and Flaño, 2007; Panizza and Piacente, 2008). Physical unit characteristics and their spatial pattern on the earth's surface control and interact with ecological processes and biological elements (Barrio *et al.*, 1997; Stallins, 2006; Urban and Daniels, 2006), georesources and abiotic heritage (Gray, 2004; Carcavilla *et al.*, 2007; Bruschi, 2007), and human activity and culture (Panizza and Piacente, 2003).

The mapping and spatial statistical analysis of the physical units enable to quantify, describe and compare different landscapes, providing an objective and useful tool to understand the singularity and geocomplexity of landscapes. These analysis can be carried out among coeval landscapes in several locations (Raines, 2002), or throughout time, facilitating the characterization of the landscape evolution in a region (Benito, 2004).

The aim of this study is to assess the geodiversity of several geodynamic settings of the Iberian Peninsula, through (1) the characterization and classification of its main physical properties and (2) the quantification of geodiversity, considered as a spatial parameter which quantifies the amount of different elements constituting the landscape, and how such elements are distributed throughout the landscape. The quantification of diversity was carried out using the more representative diversity indices implemented in the FRAGSTATS spatial pattern program (McGarigal *et al.*, 2002), which we applied to a landscape terrain classification. The latter included the main geodiversity factors and was elaborated through geographical information system (GIS) techniques from the combination of morphometric, geological and morphoclimatic maps. These maps were elaborated from datasets having a suitable resolution for the different Iberian geological regions, such as SRTM3 DEM (NASA; Rodríguez *et al.*, 2005), WorldClim Database (Hijmans *et al.*, 2005) and a geological map at a scale of 1:1 000 000

(Gabaldón *et al.*, 1994). Climate and geological datasets were classified applying standard criteria, based on morphogenetic regions (Chorley *et al.*, 1984) and litho-chronology, respectively. Since there is not a standard method to classify morphometric areas (Guzzetti and Reichenbach, 1994; Miliaresis and Argialas, 1999; Dragut and Blaschke, 2006; Iwahashi and Pike, 2007, and references therein), we opted for a statistical classification, exploring the natural occurrence of morphometric parameters, in order to include the natural variety of regional topographic areas in the Iberian regions. From these classifications, we characterized the major Iberian regions from a geomorphological perspective, developing a method to quantify their regional geodiversity.

Study Area

The Iberian Peninsula constitutes a microplate situated in the convergence zone between the Eurasian and African tectonic plates, which collided and joined with the Mesomediterranean Plate. The Peninsula has an area of 582 480 km^2, where five major geological regions can be distinguished (Gabaldón *et al.*, 1994; Vera *et al.*, 2004). In the west of the Peninsula, Precambrian and Palaeozoic rocks of the Iberian Massif (first region, Figure 1A), belong to the Variscan Orogeny. A second region includes the Pyrenees and Cantabrian Range (Figures 1A and 1B), which were formed by the collision of the Iberian and European Plates, deforming and uplifting Mesozoic-Cenozoic sediments and part of the Iberian Massif. To the south and southeast of the Iberian Peninsula the Betic Chain defines a third region, which developed from the convergence of the Iberian and African plates. It is composed of Triassic to Miocene sediments deposited in the Iberian foreland, and sedimentary, metamorphic and magmatic rocks of the Mesomediterranean Plate. A fourth major region comprises the intraplate orogens (Iberian Chain and Catalonian Coastal Range), formed by the tectonic inversion of an Upper Permian-Mesozoic rift system during the Cenozoic Alpine orogeny. To the east of the Iberian

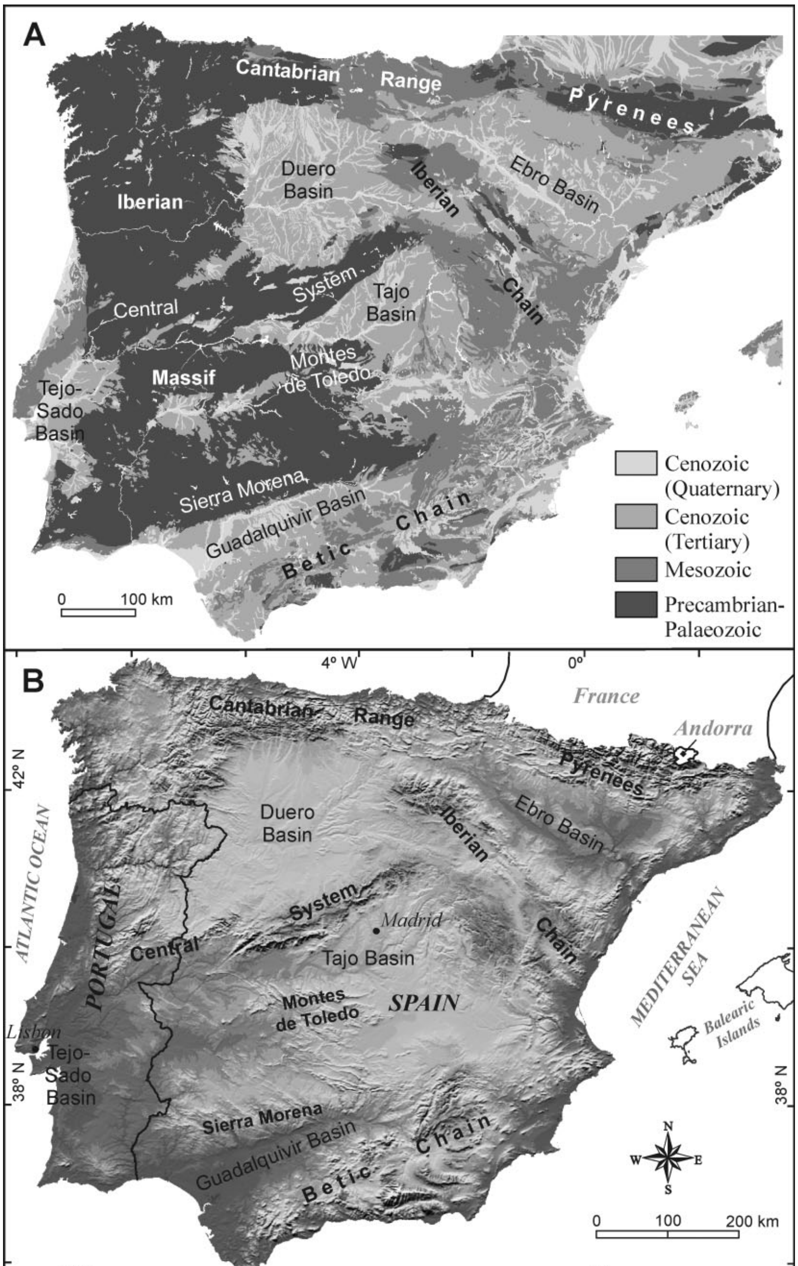

Figure 1. Geological and physiographic characteristics of the Iberian Peninsula. (A) General geological map of Iberia, simplified from Gabaldón *et al.* (1994). (B) Main topographic features of Iberia (shaded relief model derived from SRTM3 DEM).

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Massif and to the north of the Betic Chain, areas of Mesozoic rocks with no substantial deformation are also present. The fifth region is represented by the Cenozoic Basins (Figure 1A), characterized mainly by intracratonic basins (Duero and Tajo Basins), foreland basins (Ebro and Guadalquivir Basins), and intraorogenic basins (Betic and Iberian Ranges, Pyrenees). Tectonic stress fields related to the convergence of the Eurasian and African plates caused reactivation of pre-existing tectonic structures in the Iberian Massif, forming several mountain chains without sedimentary cover during the Cenozoic. These mountain ranges are located in the continental foreland area (North Portuguese Ranges, Central System, Montes de Toledo, Sierra Morena; Figures 1A and 1B).

These major geological regions determine the geomorphological characteristics of Iberia (Gutiérrez, 1994; Martín-Serrano *et al.*, 2005). The relief is characterized by mean slopes of 7·1° and a mean elevation of 647 m above sea level (a.s.l.) (source: SRTM3 DEM, 82 m × 82 m pixel size), caused by the predominance of the inland plateaux (Castilian Mesetas) and the mountain ranges over the lowlands (coastal stretch or the Guadalquivir Depression, Figure 1B).

Methods and Datasets

In order to estimate quantitatively geodiversity we started from an initial terrain classification so as to identify the physical heterogeneity of the topography of Iberia. This classification was elaborated using GIS techniques (ArcGIS 9·2), and has involved morphometric, geological and morphoclimatic regional classifications. The flowchart of this procedure is shown in Figure 2.

The morphometric map was generated by applying statistical classification techniques to a multi-layer model (Miliaresis and Argialas, 1999; Dragut and Blaschke, 2006; Iwahashi and Pike, 2007, and references therein), which was composed of morphometric variables obtained from the SRTM3 DEM (Shuttle Radar Topographic Mission; NASA; Rodríguez *et al.*, 2005; ftp://e0srp01u.ecs.nasa.gov/). Using this digital elevation model (DEM) with a spatial resolution of 82 m (UTM H30N ED50 projection), we obtained the main morphometric variables, which were analysed using linear regression in order to assess their interdependence (Figure 2). From this analysis, we selected elevation, slope, tangential curvature and roughness (dispersion

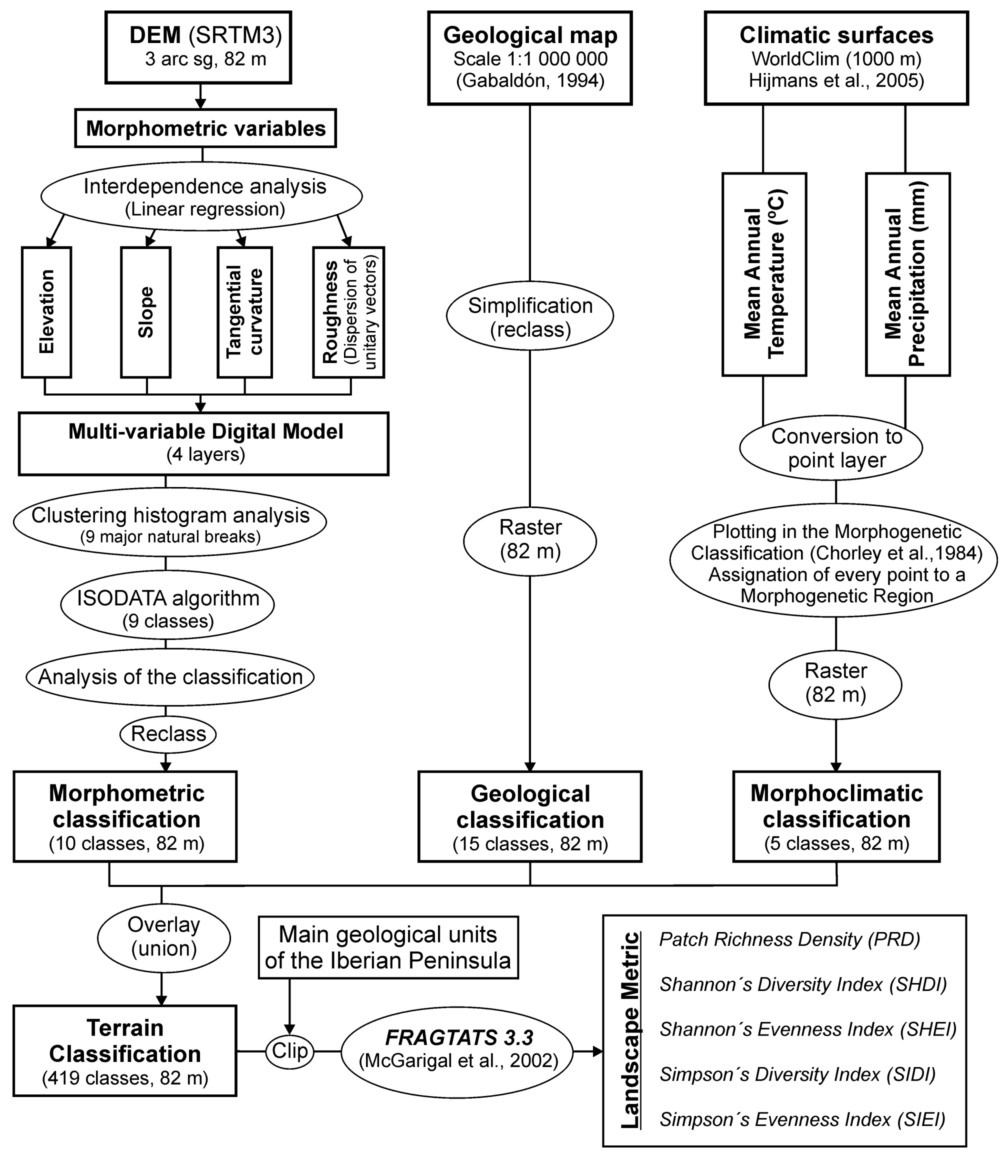

Figure 2. Methodological procedure used to assess regional geodiversity in the Iberian Peninsula. The geographical projection used in the procedure is UTM H30N ED50.

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of unit vectors normal to the surface; Hobson, 1972; Felicísimo, 1994) to construct the multi-layer model. This was then classified using the unsupervised ISODATA algorithm (Erdas Imagine 8·6). In this unsupervised algorithm the number of classes was determined using a previous clustering histogram (Figure 2), where we identified the natural occurrence of the major classes and their number (section 4·1). The resulting map from this classification was analysed by studying the morphometric and geomorphological definitions of the classes. Such interpretation allowed us to obtain the final morphometric classification (Figure 2), composed of categories of homogeneous properties at the working scale.

The geological classification was obtained from the geological map of the Iberian Peninsula at a scale of 1:1 000 000, produced by the Spanish Geological Survey (IGME) in collaboration with the Portuguese Geological Survey (Gabaldón *et al.*, 1994). This geological map was simplified considering the general geological classes, including also the types of rocks and their ages, and then converted to a raster map (Figure 2).

The morphoclimatic regions of Iberia were determined using the criteria proposed by Chorley *et al.* (1984), based on the mean annual temperature and precipitation, considering also the seasonality. The climatic data which we used in this classification correspond to the precipitation and temperature surfaces of the WorldClim Database (http://www.worldclim.org; Figure 2). Hijmans *et al.* (2005) elaborated these layers by means of interpolation from climatic records for the period 1950–2000, and using as independent variables the latitude, longitude and elevation (SRTM3 aggregated to 30 arc-second of spatial resolution, 1000 m). These precipitation and temperature raster surfaces were converted to a point data layer, which was plotted in the morphogenetic classification (Chorley *et al.*, 1984), assigning a morphogenetic region to every point.

These three regional classifications (morphometric, geological and morphoclimatic) were overlaid by performing a union operation, which enabled us to obtain the final terrain classification (Figure 2). Geodiversity measures from this classification were calculated using the landscape metric implemented in the freely accessible software FRAGSTATS (Figure 2; McGarigal *et al.*, 2002; http://www.umass.edu/landeco/research/fragstats/fragstats.html). This software was developed to quantify the characteristics of landscapes and its components in the field of Landscape Ecology. However, there is a set of statistical indices which are used for the description and comparison of any categorical digital map (Raines, 2002). Regarding diversity, a great variety of indices have been proposed to quantify the heterogeneity of categorical landscapes. In this work, we used and compared the results of the diversity indices which are employed most extensively in landscape analysis (see McGarigal *et al.*, 2002). These indices include Patch Richness Density (PRD), Shannon's Diversity Index (SHDI), Shannon's Evenness Index (SHEI), Simpson's Diversity Index (SIDI) and Simpson's Evenness Index (SIEI). The definition and formulation of each index is explained in a later section. The analysis was carried out for the whole Iberian Peninsula using standard methods provided by FRAGSTATS (McGarigal *et al.*, 2002).

Regional Terrain Classification

Many definitions of geodiversity have been proposed (Nieto, 2001; see definitions in Gray, 2004; Kozlowski, 2004; Panizza and Piacente, 2008), where geology, geomorphology and pedology are considered as the main geodiversity factors. In this way, we have developed a terrain classification, which constitutes a model for the Iberian regional geodiversity based on morphometric, morphoclimatic and geological properties, and indirectly, soil properties (Schaetzl and Anderson, 2006).

Morphometric classification

Morphometric classification has been carried out using a multi-layer model composed of height, slope, tangential curvature and roughness, which were derived from the free-access SRTM3 DEM. We selected these variables according to their influence on natural processes and landforms (Tejero *et al.*, 2006; Taud and Parrot, 2005; Wilson and Gallant, 2000; Moore *et al.*, 1991; Moore *et al.*, 1993), and their low interdependence (linear correlation coefficients R between 0·48 and 0·05). Slope, aspect and tangential curvature were generated using ArcGIS 9·2, while roughness was estimated from the dispersion of unit vectors normal to the surface (Hobson, 1972; Felicísimo, 1994). This method is based on the magnitude of vector sum R, calculated considering the eight neighbours nearest to a given point i (3×3 square window). The magnitude of R can be obtained by its rectangular coordinates x_i, y_i and z_i (Equation 1), which are defined by the slope (γ) and aspect (Φ) (Equation 2):

$$R = \sqrt{\left(\sum x_i\right)^2 + \left(\sum y_i\right)^2 + \left(\sum z_i\right)^2} \quad (1)$$

$$x_i = \sin \gamma_i \cdot \cos \Phi_i \quad y_i = \sin \gamma_i \cdot \sin \Phi_i \quad z_i = \cos \gamma_i \quad (2)$$

where R is reversibly proportional to the roughness: in terrains of minimum roughness, where the vectors are parallel (minimum dispersion), the sum of vectors reaches its maximum value, and vice versa. The magnitude of R, normalized by a sample size n, is used to calculate the spherical variance υ (Band, 1989; Equation 3), where the roughness varies between zero (minimum roughness) and one (maximum roughness).

$$\upsilon = 1 - \bar{R} = 1 - \frac{|R|}{n} \quad (3)$$

The classification of the multi-layer model was carried out using ISODATA algorithm (Interactive Self-Organizing Data Analysis Technique, Erdas Imagine 8·6). This algorithm performs clustering of the multivariate data to determine the characteristics of the natural groupings of cells. The user must specify beforehand the number of classes to perform this unsupervised classification. In this study, the number of classes was determined by means of a clustering histogram analysis, from an initial clustering with a large number of classes (Figure 3). The histogram curve of this clustering shows nine major reaches separated by natural breaks, which constitute major changes in the generality of the clusters thus defining major classes (Figure 3).

Each of the nine major morphometric classes (Figure 4), defines a geometric signature (Pike, 1988; Giles, 1997; Iwahashi and Pike, 2007). An initial analysis of these classes was carried out from the morphometric parameter distributions and from three-dimensional visual interpretation of the relief, using a digital anaglyph generated from the SRTM3 DEM (Benito, 2008). This analysis has allowed us to describe and interpret the morphometric regions, introducing a change with regards to the class which includes the bottom of narrow valleys and crests (Figure 4), characterized by maximum roughness and extreme curvatures. This class was divided into two classes according to curvatures: concave or negative values for the narrow valleys (Unit VII) and convex or positive values for the crests or ridges (Unit VIII) (Figure 5). In this way, the

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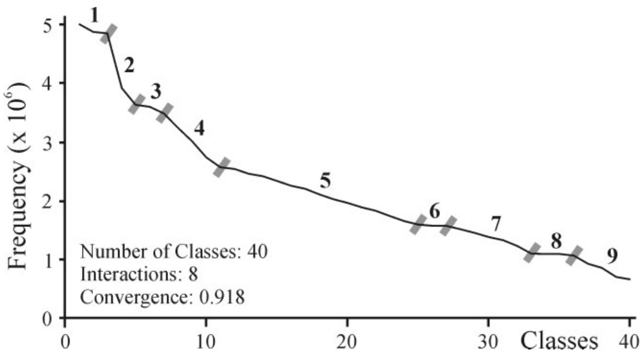

Figure 3. Interpretation of the clustering histogram curve in order to determine the natural of the terrain major classes (from one to nine). This histogram curve has been derived from an initial broad cluster of the multi-layer model composed of elevation, slope, tangential curvature and roughness (dispersion of unit vectors normal to the surface).

final classification shows 10 terrain units (Figure 5), which constitute a model for the morphometric regions of Iberia.

The distribution of these morphometric units conforms with the topographical characteristics of the major regions of the Iberian Peninsula (Gutiérrez, 1994; Figure 5 and Table I). The most extensive class corresponds to morphometric Class V (intermediate plateaux and plains), occupying 23% of the Iberian surface (Table I). This class dominates the landscape of the intracratonic basins (Duero Basin and Tajo Basin), in contrast to the Ebro and Guadalquivir foreland basins, where Classes I and II (lowest reliefs) cover more than 50% of the territory (Table I). In the Pyrenees and the Cantabrian Range (Table I), the more extensive classes include steep and high terrains (Classes IV, VI and X), whereas the landscape of the Iberian Range and Central System intraplate orogens are characterized by the dominance of high plateaux (Class IX, Table I). The Betic Chain, characterized by extensional tectonics (Martín-Algarra and Vera, 2004), presents high percentages of lowlands (Classes I and II), although plateaux and steep lands appear as well (Table I, Figure 5). The area of the Iberian Massif is occupied mostly by Classes I, II, III and V, corresponding to lower and intermediate plains (Table I).

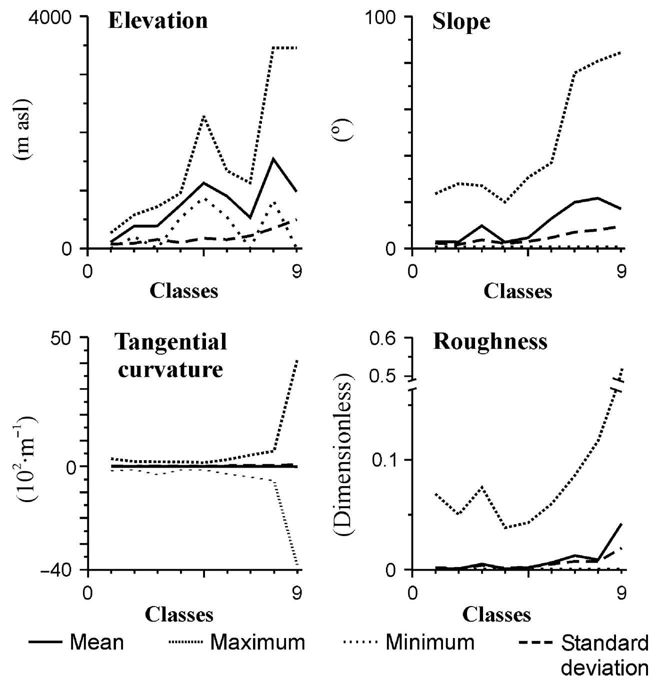

Figure 4. Morphometric parameter distributions of the nine classes derived from the application of the unsupervised classification technique (ISODATA algorithm) to the multi-layer model.

Morphoclimatic classification

Variations in latitude, continentality and elevation cause a wide variety of climatic conditions in the Iberian Peninsula (Font, 1983; Ninyerola *et al.*, 2000, 2005). Using the classification proposed by Chorley *et al.* (1984), and the climate surfaces of the WorldClim Database (Hijmans *et al.*, 2005; http://www.worldclim.org), we could define the morphogenetic regions of the Iberian Peninsula (i.e. Humid Mid-latitude, Semi-arid, Arid and Dry Continental; Figures 6A and 6B), except for two data zones plotted outside of the conditions proposed by Chorley *et al.* (1984) (Figure 6A). These unclassified data belong to some areas of the Pyrenees and the Serra da Estrela, where precipitation is overestimated due to the uncertainty caused

Table I. Distribution of the regional morphometric units in the Iberian Peninsula and its main geological regions. See Figure 5. Values are in percentages

	Morphometric classes: percentage of landscape (%)									
	Class I	Class II	Class III	Class IV	Class V	Class VI	Class VII	Class VIII	Class IX	Class X
Iberian Peninsula	15·0	16·3	11·4	6·6	23·0	9·5	1·2	0·9	10·6	5·4
Iberian Massif	11·4	22·2	17·1	8·6	18·1	9·1	1·4	0·9	5·8	5·3
Alpine Orogens										
Pyrenees	2·6	6·6	7·7	9·9	7·6	20·1	5·0	4·7	4·1	31·6
Cantabrian Range	6·6	5·0	13·7	22·2	8·8	14·7	4·6	3·6	6·9	13·9
Betic Range	17·1	12·5	13·0	8·4	14·7	12·5	1·5	1·4	10·7	8·2
Iberian Range	2·4	2·8	4·8	5·6	11·1	17·3	1·9	1·2	41·3	11·5
Central System	0·4	12·4	10·9	6·8	12·9	13·1	1·3	0·7	28·8	12·8
Mesozoic cover with no significant deformation	35·3	7·0	11·7	1·8	25·9	4·6	0·1	0·1	13·2	0·2
Cenozoic Basins										
Duero Basin	0·0	0·0	0·0	0·0	74·3	5·3	0·0	0·0	20·2	0·1
Ebro Basin	10·6	47·9	15·7	5·4	11·4	6·7	0·5	0·6	0·7	0·4
Tajo Basin	0·1	19·7	2·2	0·4	58·0	9·2	0·1	0·0	10·2	0·1
Guadalquivir Basin	78·9	14·2	4·4	0·1	2·0	0·4	0·0	0·0	0·0	0·0

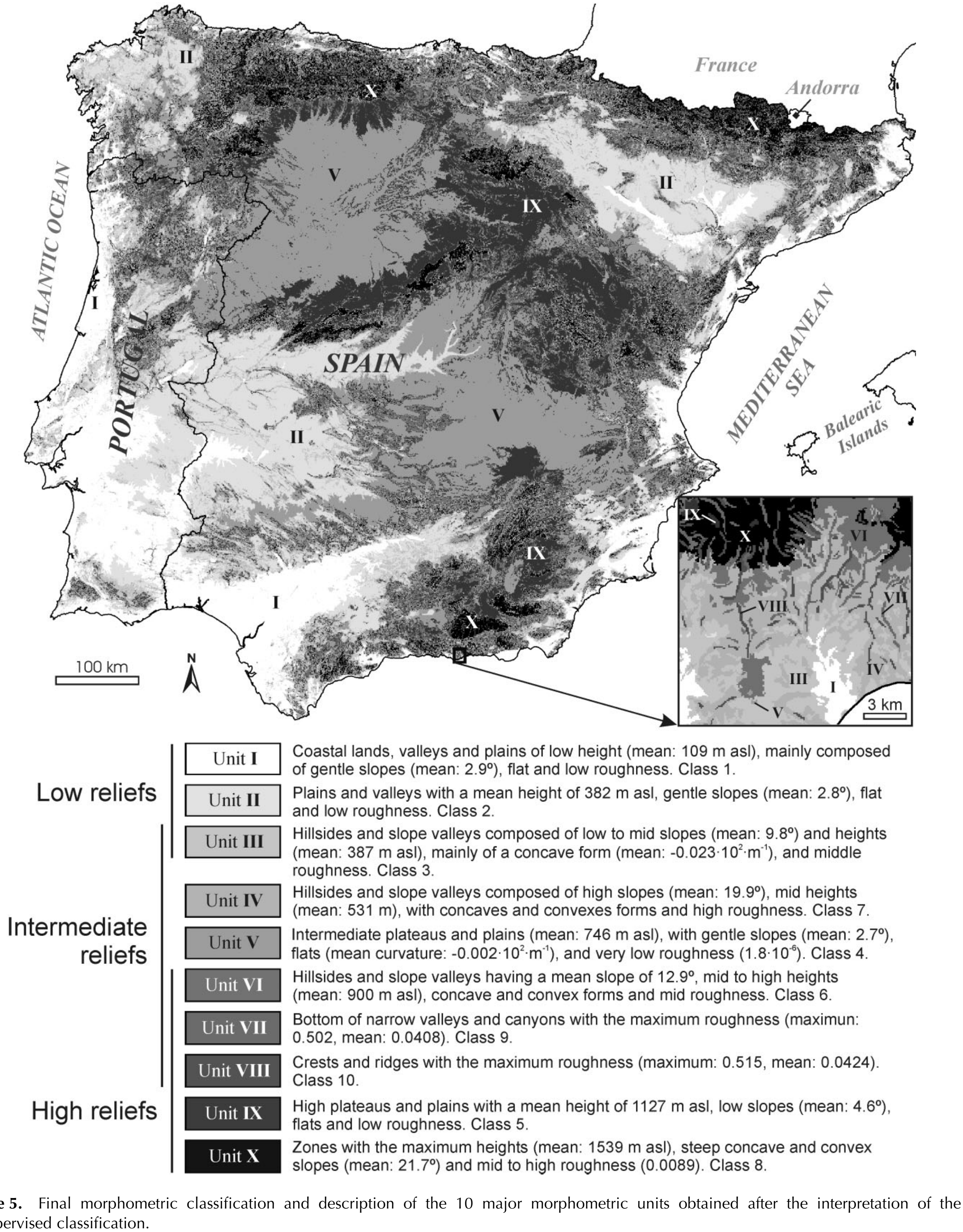

Figure 5. Final morphometric classification and description of the 10 major morphometric units obtained after the interpretation of the unsupervised classification.

by the mountainous terrain (Hijmans *et al.*, 2005). Consequently, these data were included in the Humid Mid-latitude Region, when the mean annual temperature is >0 ºC, and in the Periglacial Region when the mean annual temperature is <0 °C. In this way, we have obtained the final morphoclimatic classification defined by the five mentioned regions.

Despite the uncertainty in some mountainous areas, the application of these climatic data has improved significantly previous morphogenetic classifications, where the whole Iberian Peninsula was included in the Humid Mid-latitude Region (Chorley *et al.*, 1984). According to the WorldClim Database, most of Iberia (70·3%) belongs to the Semi-arid morphoclimatic Region (Figure 6B, Table II). The Semi-arid zones occupy high percentages in all of the geological units, and constitutes 100% of the Guadalquivir Basin (Table II). The Humid Mid-latitude Region extends mainly in the northern and north-western parts of the Iberian Massif and in the northern ranges (Cantabrian Range and Pyrenees), whereas the Dry-continental Region is

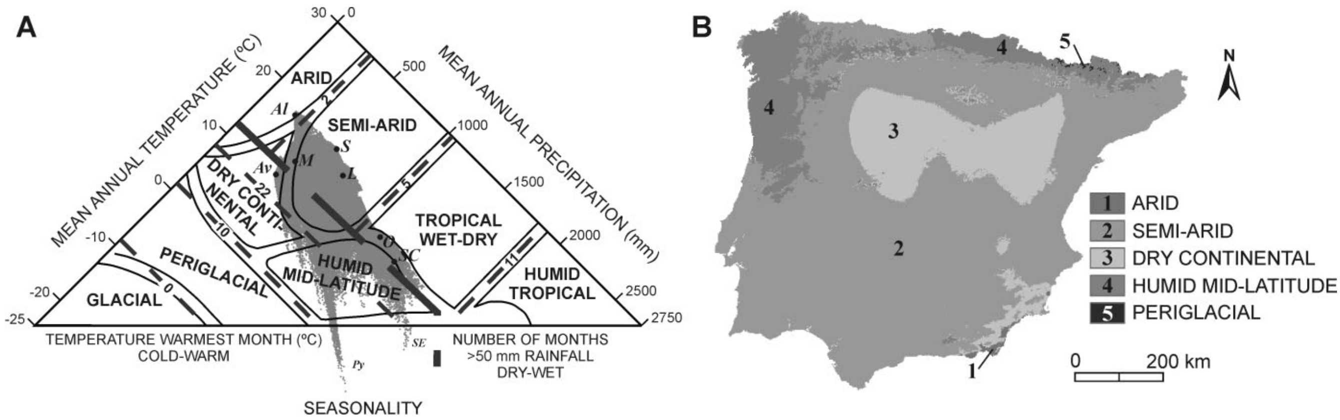

Figure 6. (A) Morphogenetic classes of the Iberian Peninsula using the classification proposed by Chorley *et al.* (1984). The climatic data correspond to the WorldClim Database (Hijmans *et al.*, 2005). Some cities: Al, Almeria; Av, Ávila; L, Lisbon; M, Madrid; O, Oporto; S, Sevilla; SC, Santiago de Compostela. Location of unclassified areas (see explanation in the text): Py, Pyrenees; SE, Serra da Estrella. (B) Distribution of the morphogenetic regions in the Iberian Peninsula.

Table II. Distribution of the morphogenetic types in the Iberian Peninsula and its main geological regions. See Figure 6 and explanation in the text. Values are in percentages

	Morphogenetic types: percentage of landscape (%)				
	Arid	Semi-arid	Dry Continental	Humid Mid-latitude	Peri-glacial
Iberian Peninsula	0·3	70·3	16·0	13·3	0·1
Iberian Massif	0·0	67·6	7·0	25·4	0·0
Alpine Orogens					
Pyrenees	0·0	48·6	2·1	47·8	1·4
Cantabrian Range	0·0	52·2	2·3	45·5	0·0
Betic Range	2·6	84·7	12·1	0·6	0·0
Iberian Range	0·0	57·9	41·4	0·8	0·0
Central System	0·0	39·2	46·6	14·2	0·0
Cenozoic Basins					
Duero Basin	0·0	38·8	61·2	0·0	0·0
Ebro Basin	0·0	79·8	19·8	0·4	0·0
Tajo Basin	0·0	80·4	19·6	0·0	0·0
Guadalquivir Basin	0·0	100·0	0·0	0·0	0·0

more characteristic of the inland high plateaux (Central System, Iberian Chain and Duero and Tajo Basins). Arid and Periglacial Regions are scarcely represented (Table II), being situated respectively in the south-eastern part of the Betic Chain (Almería), and at the highest peaks of the Pyrenees (Figures 6A and B).

Geological classification

In order to include the lithological, chronological and structural properties in the geodiversity classification we used the Geological Map of the Iberian Peninsula (Gabaldón *et al.*, 1994). This map is composed of 102 geological units which extend from the Precambrian to the Quaternary (Figure 1A), and includes the main tectonic structures. Due to the regional approach and scale of this work, we have simplified this map using the general type of rocks (sedimentary, metamorphic, plutonic and volcanic) combined with their general ages (Quaternary, Tertiary, Mesozoic, Palaeozoic and Precambrian). This classification presents 13 litho-chronological units (Table III), besides tectonic structures and hydrological elements (main rivers and water bodies).

The Peninsula is dominated by Cenozoic and Mesozoic sedimentary rocks (Table III, Figure 1A), together with metamorphic and plutonic rocks located in the Iberian Massif and in some Alpine Orogens. The volcanic units are less frequent (Table III). The rock age is dominated by the Cenozoic (Tertiary basins and Quaternary) and Palaeozoic (Iberian Massif), although Mesozoic and Precambrian also have an important representation (Figure 1A, Table III).

Final terrain classification

Once the morphometric, morphoclimatic and geological maps were elaborated, the last step consisted in combining these three spatial datasets, using an overlay union operation. From this operation we obtained a terrain classification represented by 419 discrete classes (Figure 7A).

The areal fractions of the derived classes are shown in Figure 7B. The surface morphology of the most widespread lithological materials in Iberia, corresponding to sedimentary rocks of Tertiary age (geological unit 11; Table III), is dominated by the slopes of intermediate relief (morphometric unit IV; Figure 7B-I), and to a lesser degree by coastal lands, valleys and plains of low reliefs (morphometric units I and II). These morphometric units predominate also on the Quaternary sediments, while in the Mesozoic sedimentary rocks, slopes

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Table III. Proportion of the rock types and ages in the Iberian Peninsula landscape. Values are in percentages

Ages	Lithology							
	Sedimentary	†	Metamorphic	†	Volcanic	†	Plutonic	†
Cenozoic (Quaternary)	14·0	13	–		0·1	12	–	
Cenozoic (Tertiary)	30·6	11	–		0·1	10	–	
Mesozoic	16·7	9	–		–		0·2	8
Palaeozoic	7·5	7	9·5	6	0·5	5	10·0	4
Precambrian	–		8·4	3	0·2	2	1·1	1

† Litho-chronological units of the geological classification, besides those of the tectonic structures (unit 14) and the main hydrological elements (unit 0).

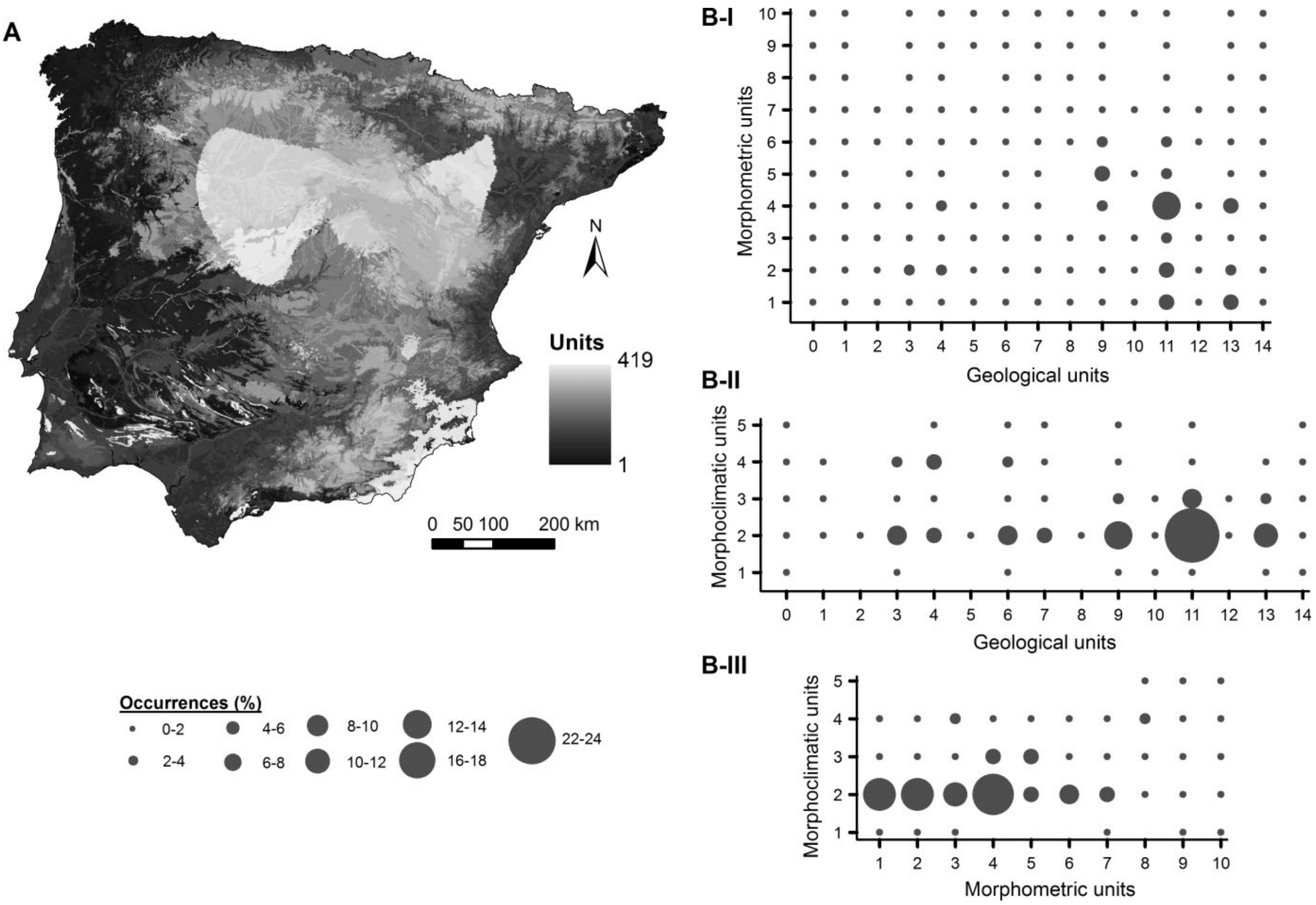

Figure 7. Final terrain classification based on the overlay of the morphometric, geological and morphoclimatic classifications. (A) Map of the final terrain classification. (B) Occurrences in the overlay operations: (B-I) occurrences between the geological and the morphometric units; (B-II) occurrences between the geological and the morphoclimatic units; (B-III) occurrences between the morphometric and the morphoclimatic units. The description of the morphometric, morphoclimatic and geological units is given in Figures 5 and 6 and Table III, respectively.

and plateaux of intermediate relief are the most frequent (Figure 7B-I). With regards to the remaining geological units, the morphometric units present a uniform distribution, except for the gaps associated mainly with the volcanic rocks (Figure 7B-I), which are scarcely represented in the Iberian geology (Table III). Semi-arid conditions are dominant on most of the geological units (Figure 7B-II), especially on the Tertiary sediments (Figure 7B-I). The latter also present a high percentage of Dry Continental morphoclimatic areas. The plutonic and metamorphic rocks of Precambrian and Palaeozoic age (geological units 3, 4 and 6) are characterized mainly by humid mid-latitude conditions (Figure 7B-II), characteristic of the north and northwest of Iberia. The Semi-arid morphoclimatic Region dominates over the low and intermediate reliefs (Figure 7B-III), while dry continental conditions are more frequent in the slopes and plateaux of the morphometric units IV and V. The Humid Mid-latitude morphoclimatic Region presents a uniform distribution over the morphometric units (Figure 7B-III). However, Peri-glacial and Arid Regions show a more limited extent. The former is associated exclusively with high reliefs in the Pyrenees (morphoclimatic units VIII, IX and X), whereas arid conditions are related to low relief and high relief of the Betic Chain (Figure 7B-III).

Other terrain classifications could be carried out depending on different research aims or working scales. However this classification represents a model of the terrain variability, which combines the properties and distribution of the geomorphological features in Iberia at a regional scale (Tables II–IV, Figure 7). The techniques used to classify the Iberian Peninsula can be easily applied to other regions since they are based on geological and morphoclimatic standard criteria and the natural occurrence of morphometric parameters.

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Table IV. Set of landscape metrics selected to estimate geodiversity

Index	Formulation	Range	Units
Patch Richness Density (PRD)	$\text{PRD} = \frac{m}{A}(10^4)(10^2)$	PRD > 0, without limit	Number per 100 hectares
Shannon's Diversity Index (SHDI)	$\text{SHDI} = -\sum_{i=1}^{m}(P_i \ln P_i)$	SHDI ≥ 0, without limit	Information
Shannon's Evenness Index (SHEI)	$\text{SHEI} = -\sum_{i=1}^{m}(P_i \ln P_i)/\ln m$	0 ≤ SHEI ≤ 1	None
Simpson's Diversity Index (SIDI)	$\text{SIDI} = 1 - \sum_{i=1}^{m} P_i^2$	0 ≤ SIDI ≤ 1	None
Simpson's Evenness Index (SIEI)	$\text{SIEI} = 1 - \sum_{i=1}^{m} P_i^2 \Big/ 1 - \left(\frac{1}{m}\right)$	0 ≤ SIEI ≤ 1	None

Formulation parameters: m, number of patch units (classes); A, total landscape area (in m^2); P_i, proportion of the landscape occupied by patch type i.

Spatial Geodiversity Quantification

The geodiversity of the Iberian landscape has been estimated using FRAGSTATS (McGarigal *et al.*, 2002). This software quantifies the geometric and spatial configuration of landscape classifications, operating at three information levels: patch (an individual area of a map unit), class (a map unit) and landscape (the map or mosaic). Patch metrics, such as area, perimeter or density, include low level information and constitute the computational basis for several indices at high levels (class and landscape). Diversity is considered a landscape property defined by two components: richness and evenness (Spellerberg and Fedor, 2003). Richness constitutes the compositional component of diversity and refers to the number of different classes in a categorical map. Evenness corresponds to the structural component of diversity and quantifies the distribution of the area among the different classes.

There is a great variety of indices, each of which measures diversity in a different way according to their weight in either one diversity component. In order to assess geodiversity we have applied diversity landscape metrics, which quantify richness, evenness and diversity using different formulations (Table IV, McGarigal *et al.*, 2002). Richness is a parameter partially controlled by the scale, since larger areas are generally more heterogeneous than comparable smaller areas. In an attempt to compare landscapes with different areas (Table IV), we have applied PRD, which standardizes richness on a per area basis.

Two very widely used diversity indices are SHDI and SIDI. SHDI is based on the Theory of Communication (Shannon and Weaver, 1975), which considers diversity as equivalent to the entropy or degree of uncertainty to predict a determined patch type in the landscape (Table IV). The SHDI absolute value is not particularly meaningful being used as a relative index for comparing different landscapes (McGarigal *et al.*, 2002). SHDI is more sensitive to richness than evenness, while SIDI is less sensitive to the presence of rare types, placing more weight on the common patch types. Specifically, the value of SIDI represents the likelihood that any two cells selected randomly would be different patch types (Table IV).

With regards to evenness, we have applied the SHEI and the SIEI. These indices emphasize the evenness component of their respective diversity indices, and are expressed as the observed diversity divided by the maximum possible diversity for a given patch richness (Table IV).

This set of quantitative indices has been applied to the proposed terrain classification and separately to each factor considered in this terrain classification. In this way, we have quantified the regional diversity of the landscape corresponding to the Iberian Peninsula and its main geological regions at the scale considered for this study (Table V). This analysis was carried out in order to compare the geodiversity variations among regions (Table V).

Results and Discussions

According to the proposed terrain classification, PRD highest values occur in the Pyrenean Ranges and Central System, and show similar values in other Alpine orogens (Betic and Iberian Ranges) and the Cenozoic Basins. Extensive geological regions, such as the Iberian Massif (or the whole Iberian Peninsula), present the lowest values (Table V). In a first comparative analysis, considering the area of these regions, a substantial inverse correlation between PRD values and area can be observed (Table V). This implies that the largest geological regions tend to have the lowest PRD values. This high dependence of areal extent indicates that PRD is not a very suitable index to compare landscapes with very different areas. Similar to other richness indices, PRD is influenced by the number of classes and does not consider the relative abundance of classes or their spatial configuration. Such characteristic suggests that richness indices are insufficient to compare geological complexity among different landscapes, since they do not provide information about the structure and are strongly influenced by the area.

The geodiversity of the Iberian Peninsula has been estimated as SHDI = 4·5 or SIDI = 0·98 (Table V), whereas its main geological regions vary from 1·4 to 4·3 with regards to the SHDI, and from 0·68 to 0·97 in the case of the SIDI. Highest diversity values are associated with reactivated old geological terrains (Iberian Massif) followed by Alpine orogens systems (Figure 7). Collisional orogens present high values (SHDI = 3·2–4·3, SIDI = 0·96–0·98), with the Cantabrian Range being prominent (where Palaeozoic and Mesozoic rocks are widely represented, Figure 1A), and showing similar high values for the Betic Chain and the Spanish part of the Pyrenees (Table V and Figure 6). However, intraplate orogens show disparate values. The Iberian Range constitutes the orogen with the lowest diversity values, determined by a low diversity in morphometric classes (Table V), extensively dominated by high plateaux (planation surfaces). However, the whole landscape of the Central System presents SHDI and SIDI values on the same level as collisional orogens (Figure 7). This high geodiversity in the Alpine chains without sedimentary cover contributes significantly to the elevated diversity values of the Iberian Massif.

Alternatively, Cenozoic basins present the lowest diversity values (Table V and Figure 7). Foreland basins are characterized by the extreme values, controlled by different geomorphological evolution and climatic conditions: the Ebro Basin reaches the

Table V. Geodiversity measures in the Iberian Peninsula

	Area (km²)	PRD			SHDI			SHEI			SIDI			SIEI		
		M	G	MGC	M	G	MGC	M	G	MGC	M	G	MGC	M	G	MGC
Iberian Peninsula	582 481	0·0001	0·0000	0·0004	0·711	1·974	4·534	0·342	0·729	0·751	0·857	0·828	0·981	0·952	0·887	0·983
Iberian Massif	208 373	0·0000	0·0000	0·0007	2·047	1·754	4·307	0·889	0·665	0·752	0·853	0·790	0·978	0·948	0·851	0·981
Alpine Orogens																
Pyrenees	24 245	0·0002	0·0002	0·0036	2·008	1·416	3·743	0·872	0·615	0·693	0·826	0·644	0·958	0·918	0·716	0·963
Cantabrian Range	43 256	0·0001	0·0001	0·0028	2·152	1·715	4·286	0·935	0·781	0·789	0·868	0·776	0·978	0·965	0·873	0·982
Betic Range	72 020	0·0001	0·0001	0·0013	2·144	1·519	3·846	0·931	0·592	0·700	0·875	0·733	0·968	0·973	0·794	0·972
Iberian Range	48 352	0·0001	0·0001	0·0011	1·789	0·829	3·164	0·777	0·360	0·623	0·766	0·367	0·917	0·852	0·408	0·923
Central System	28 836	0·0001	0·0001	0·0023	1·946	1·521	4·006	0·845	0·634	0·729	0·835	0·695	0·970	0·928	0·765	0·974
Mesozoic with no significant deformation		0·0000	0·0000	0·0004	1·665	0·614	2·338	0·723	0·256	0·494	0·770	0·286	0·848	0·855	0·315	0·855
Cenozoic Basins																
Duero Basin	49 186	0·0001	0·0001	0·0010	0·711	0·675	2·018	0·342	0·293	0·422	0·404	0·439	0·814	0·462	0·487	0·821
Ebro Basin	40 998	0·0001	0·0001	0·0012	1·583	0·649	2·641	0·688	0·282	0·533	0·714	0·374	0·890	0·793	0·416	0·897
Tajo Basin	27 777	0·0002	0·0002	0·0018	1·218	0·662	2·281	0·529	0·287	0·475	0·606	0·386	0·804	0·673	0·429	0·811
Guadalquivir Basin	15 780	0·0001	0·0001	0·0007	0·710	0·825	1·439	0·323	0·344	0·362	0·356	0·530	0·681	0·400	0·583	0·694

Results of the indices calculations in the Iberian Peninsula and its main geological regions: M, morphometric classification; G, geological classification; MGC, final terrain classification based on the overlay of the morphometric, geological and morphoclimatic classifications.

highest SHDI and SIDI values among Cenozoic basins (Figure 7), mainly due to the deepest incision of drainage network during the Quaternary, which increases the diversity of morphometric classes (Table V). In the Guadalquivir Basin, morphometric diversity is lower (mostly lowlands of morphometric Class I, Table I) in the same way as climatic variety, represented by only one morphogenetic region (Table II). The latter determines the lowest final diversity values of the Guadalquivir Basin (Table V, Figure 7). Intracratonic basins present intermediate values, although in this case SHDI and SIDI show different diversities. The SHDI presents clearly higher values in the Tajo Basin than in the Duero Basin (Figure 7). This may be controlled by an important increase in the morphometric SHDI diversity in the Tajo Basin with respect to the Duero Basin (Table V), where 74·3% of the surface is characterized by intermediate plateaux (Class V, Table I). Nevertheless, with regards to the SIDI, the Duero Basin presents slightly higher diversity values than the Tajo Basin (Figure 7). In this case, the greater morphometric variety in the Tajo Basin has a lower influence, since SIDI is less sensitive to the presence of rare types, while the higher geological diversity and a more regular distribution of the morphoclimatic regions in the Duero Basin have a greater weight (Table V and Figure 2).

The areas occupied by Mesozoic sedimentary cover with no deformation present similar low SHDI values as Cenozoic basins (Figure 7A) in contrast to deformed terrains, indicating that orogenic processes constitute a determining factor in the increase of geodiversity.

The results obtained from the application of evenness indices show limited relative variations regarding diversity values (Table V, Figure 8), although the main relationships are maintained. These variations are related to the SHEI values of the largest area regions (Iberian Massif and the whole Peninsula), which reduce their relative values in relation to the other regions (Figure 9).

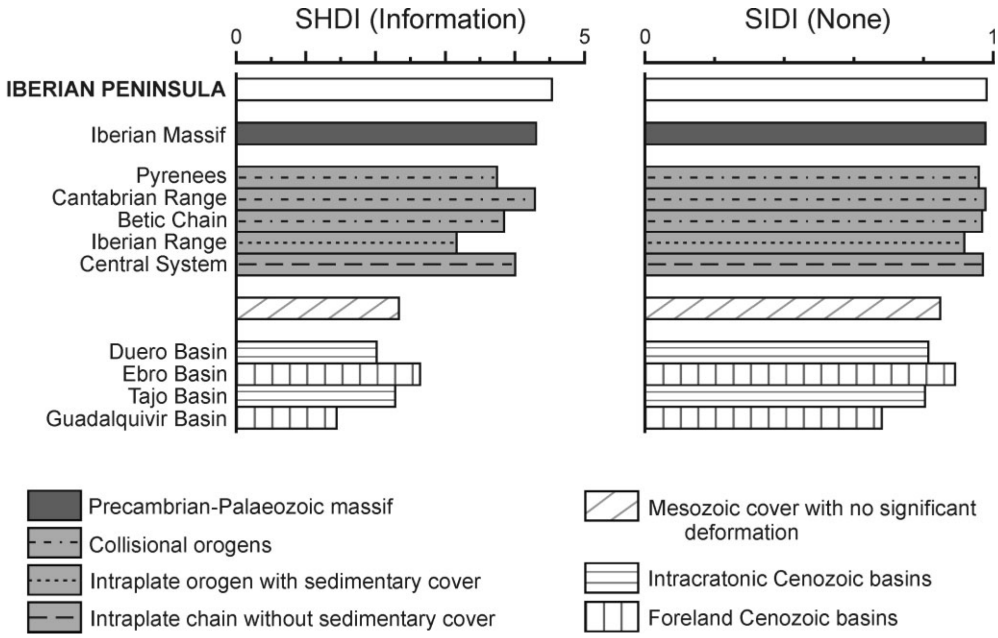

Figure 8. Diversity measures and geodynamic styles of the main geological regions of the Iberian Peninsula. SHDI, Shannon's Diversity Index (units: information); SIDI, Simpson's Diversity Index (dimensionless).

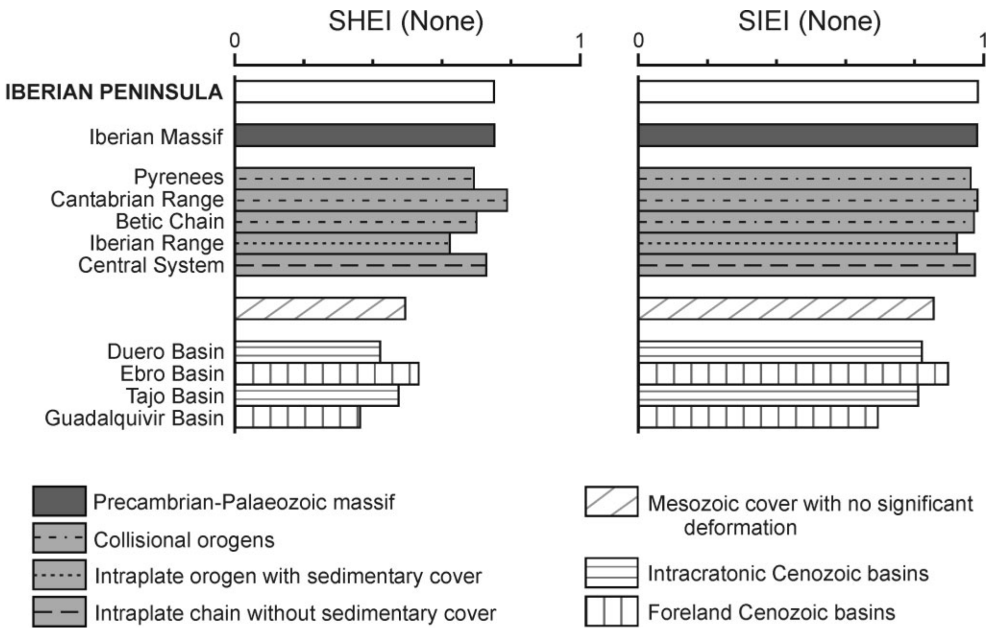

Figure 9. Evenness measures and geodynamic styles of the main geological regions of the Iberian Peninsula. SHEI, Shannon's Evenness Index (dimensionless); SIEI, Simpson's Evenness Index (dimensionless).

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In this case, the highest diversity values correspond to the Cantabrian Range (SHEI = 0·79, SIEI = 0·98), followed by the Iberian Massif and the Central System. The collisional ranges (Pyrenees and Betic Chain) show high evenness values too, whereas the Iberian Range presents again the lowest value among the Alpine orogens, due to its lowest morphometric heterogeneity (Table I). The Mesozoic outcrops without significant deformation and the Cenozoic basins present the lowest SHEI and SIEI values, showing similar proportional relations as the respective diversity values (Figures 8 and 9).

Diversity and evenness values present a clear relationship with the geodynamic evolution of the analysed landscapes, and their variations can be explained according to the particular geological and geomorphological characteristics of each region. Thus, these indices represent a useful tool to compare geocomplexity in contemporary landscapes, or throughout time (Benito, 2004). However, some important aspects should be taken into account when using these metric indices. Diversity and evenness indices do not consider the importance of individual classes or uniqueness, quantifying exclusively the variety and arrangement of patch types in the landscape. Thus, metric indices are not absolute measures and the computed values are a function of how the landscape is defined, especially with regards to the classification criteria and the scale, which determine geodiversity at differents levels (Nieto, 2001). Comparable landscapes must be defined using the same resolution and criteria, depending on the phenomena under analysis. In this way, the assessment of geodiversity should start by determining the heterogeneity of the factors used to define the landscape (McGarigal *et al.*, 2002). We have used a model for regional geodiversity, whose computed diversity values cannot be extrapolated directly to be used for other detailed scales without further analysis, but similar methodology could be employed to assess geodiversity at more detailed scales.

Conclusions

In these last years, several methodologies to assess geodiversity have been developed (Carcavilla *et al.*, 2007; Bruschi, 2007; Serrano and Flaño, 2007), in order to provide objective tools for geoconservation and management of the abiotic heritage. In this work, we have tested landscape diversity indices (MacGarigal *et al.*, 2002), to assess regional geodiversity in the Iberian Peninsula. The results indicate that these spatial diversity indices may be very useful to assess geodiversity, if they are applied in a comparative analysis for landscapes having the same criteria and spatial resolution.

Using GIS techniques, such as multi-layer statistical classification and dataset cross-tabulation, we have developed an objective terrain classification for the Iberian Peninsula, based on morphometric, geological and climatic criteria, which are applicable to other areas. Morphometric and climatic data were extracted from global databases (SRTM3 and WorldClim Database), which presented a suitable resolution to analyse regional areas, while geological information was provided from a regional geological map. The final terrain classification represents a model of the regional earth surface variability and allowed us to categorize the mentioned properties in the main geological regions of Iberia. The latter must constitute the first stage to assess geodiversity since it is essential to understand landscapes and to interpret the diversity index values.

The terrain classification was applied to compute richness, diversity and evenness indices, in order to assess quantitatively the current regional geodiversity among the main geological regions of Iberia. Nevertheless, the comparison of landscapes of different origins and ages is also possible. Richness is a basic component of diversity but presents limitations to analyse landscapes of diverse areal extent. In this way, PRD did not allow us to perform a suitable comparison of Iberian landscapes. However, the applied diversity and evenness indices (SHDI, SHEI, SIDI, SIEI), showed similar results in most cases, presenting a close association with the distribution of the geological, geomorphological and climatic characteristics of the Iberian regions. In recent terrains with no significant tectonics, geodiversity values increase mainly with higher morphoclimatic variety and deeply incised regions, causing a major morphological heterogeneity. However, the highest diversity and evenness values are related to deformed terrains. In this case, higher diversities are mainly associated with ranges where reactivated old massifs outcrop, resulting in a large structural and lithological complexity. However, the lowest diversity values are related to lower morphological variety in areas where planation surfaces dominate.

These results provide an objective approach to the relative regional geodiversity in Iberia. Nevertheless, diversity indices do not provide information about uniqueness. Thus, in studies which focus on specific elements of geodiversity, the information provided by these indices should be complemented with analysis concerning the distinct elements in the landscapes. In the same way, diversity index information can be combined with other spatial pattern indices in order to achieve a better understanding of landscape spatial configuration.

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