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ORIGINAL ARTICLE

Assessment of Geodiversity in the Southern Part of the Central Iberian Zone (Jaén Province): Usefulness for Delimiting and Managing Natural Protected Areas

A. Fernández[1] · T. Fernández[2] · D. I. Pereira[3] · L. M. Nieto[1]

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Abstract
To explore the relationship between geodiversity and borders of natural protected areas, we studied the northern part of Jaén Province (southern Spain), where the southern sector of the Central Iberian Massif, the Betic Cordillera and the Guadalquivir foreland basin come together. Moreover, several natural protected areas (NPAs) are located here. To approach the topic, we defined the geodiversity index as the sum of partial indices: lithological, geomorphological, palaeontological, pedological, minerals, hydrology and geosites. This made it possible to derive a map of the geodiversity index and a map of geodiversity gradient. Analysis of their distribution shows that almost 80% of the territory has values of medium, high and very high geodiversity, but these zones are situated outside the borders of the NPAs. A similar study considering two biological indices (endangered species and biodiversity) shows a good correlation between the limits of NPAs and the higher values of these indices. Thus, an absence of correlation between the geodiversity index and biological indices is clearly detected. These results are not in agreement with the definition of NPAs in the current Spanish laws of nature conservation.

Keywords Geodiversity · Biodiversity · Central Iberian Zone · GIS · Geodiversity index · Natural protected areas

Introduction

Geodiversity is a recent concept in the scope of earth sciences (Nieto 2001; Panizza 2009; Brilha et al. 2018). After an early period under different proposals (Forte 2014), now the fundamental ideas of Nieto (2001) and Gray (2004, 2013) are accepted. According to Gray (2004, 2013), geodiversity is *the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes*. Forte (2014) presents a state of the art of the different definitions proposed for this concept.

Regardless of the specific definition at hand, geodiversity is understood to be an intrinsic territorial feature that contributes to establishing its geological interest. It materialises in geological elements (outcrops, landscapes, kinds of soils…) to be studied individually and then interrelated. This means that geodiversity, as a continuous attribute of a region, can also be analysed from a geostatistical perspective (Carcavilla 2012). By studying the terrain as objectively as possible and comparing areas with different geodiversity, one may learn how to develop sustainable land uses, appropriate to the nature of the geological elements that make it up (Gordon et al. 2012).

Assessment of geodiversity may be approached from two perspectives: qualitative and quantitative (Brilha et al. 2018). The qualitative point of view relies on expert knowledge and description of the geodiversity elements of a region. Although this approach does not generate geodiversity maps per se, they can be derived from geological maps of the area. In other words, this type of assessment provides data about the spatial distribution of geological elements, but not about their variety.

✉ L. M. Nieto
lmnieto@ujaen.es

[1] Departamento de Geología and Centro de Estudios Avanzados en Ciencias de la Tierra, University of Jaén, Jaén, Spain

[2] Departamento de Ingeniería Cartográfica, Geodésica y Fotogrametría and Centro de Estudios Avanzados en Ciencias de la Tierra, University of Jaén, Jaén, Spain

[3] Institute of Earth Sciences, Pole of the University of Minho, Campus de Gualtar, Braga, Portugal

The quantitative assessment aims to numerically reflect the spatial variability of the geological elements. These methods, founded on numerical analysis, enable one to identify the diversity and spatial distribution of the geodiversity elements in a region. As in any geological research, some data (e.g. mineral and palaeontological sites, geosite features, lithological data, geomorphological features) come from fieldwork undertaken previously by different research teams. Yet most are the result of mapping the diversity, frequency and distribution of elements. Using GIS tools, the partial or total geodiversity index is obtained, showing the concentration of specific geological features in the natural environment. Serrano and Ruiz-Flaño (2007) define a geodiversity index (G_d) as a function of the roughness of a geomorphological unit. Carcavilla et al. (2007) consider the intrinsic geodiversity (G_i) as the number of classes of geodiversity (kinds of different geological elements) that are in a territory and the frequency with which they crop out.

Recently, Pereira et al. (2013) proposed an assessment methodology based on the continuous nature of geodiversity and the possibility of defining geodiversity gradients. They consider several partial numerical indices (i.e. partial geodiversity indices) obtained by considering a series of geodiversity elements (lithology, geomorphology, soil…). The sum of all partial geodiversity indices makes up the geodiversity index. Data processing with GIS tools provides maps of partial or total indices of geodiversity, i.e. gradient geodiversity maps (Silva et al. 2013, 2015). Araujo and Pereira (2018) further refined this method to arrive at a hydric resource index. Forte et al. (2018) applied the kernel density procedure to assess geodiversity, improving comparative analysis of regions with different geological settings and diverse scales. Zwoliński et al. (2018) made a meta-analysis of the most important quantitative assessment methods.

Gray (2008) defines geodiversity hot spots as areas of the Earth's surface featuring a high geodiversity index. These hot spots correspond to areas identified from the gradient of geodiversity maps, designed with any of the quantitative assessment procedures mentioned above. They serve to define zoning and uses of a territory, as well as to borderline natural protected areas. The geodiversity hot spots should lie in the central part or *core zone* of the natural protected areas, while areas having a low geodiversity index, *peripheral zones*, would surround the core zone.

The goals of this research are to apply a method based on Pereira et al. (2013), improved by Silva et al. (2013, 2015), Araujo and Pereira (2018) and Forte et al. (2018), to an area in the north of Jaén Province (Fig. 1a, b). From a geological point of view, the confluence of the Central Iberian Zone, Prebetic (Betic External Zone) and Guadalquivir foreland basin is highlighted (Figs. 1c and 2). This zone is characterised by the existence of three natural parks (Sierra de Andújar, Despeñaperros and Sierras de Cazorla, Segura y Las Villas; in the rest of this paper, they will be referred to as SA-NP, D-NP and SCSV-NP, respectively), a natural monument (Los Órganos de Despeñaperros, within D-NP) and a natural area (La Cascada de la Cimbarra, in the rest of paper CC-NA; Fig. 1b). The relationships regarding the locations of these natural protected areas (NPAs) and the presence of geodiversity hot spots are studied in view of the map of geodiversity gradients developed. The geodiversity map is compared with some maps of biodiversity to establish associations between geodiversity and biodiversity. Finally, we underline the importance of the geodiversity index and the corresponding maps for drawing the boundaries of natural protected areas and for their management.

Geographical, Geological and Geomorphological Settings

Geographical Features

Geographically, the north of the Jaén Province belongs to the Sierra Morena region. It is characterised by smooth hills with low slopes. The average height above sea level is around 845 m. There are large surfaces of the territory with non-modified Mediterranean forest. The major towns of the area (Fig. 1b) are Linares with 57,810 inhabitants, Andújar (population of 37,110 inhabitants), Bailén (17,820) and La Carolina (15,310), all according to the 2018 population census database. Agricultural wealth, especially olive groves, is the main economic activity of the zone.

Geological Setting

Rocks dated from Precambrian to Quaternary crop out in the region dealt with in this paper, although the Palaeozoic rocks show higher surficial exposure (Fig. 2), belonging to the Central Iberian Zone, a morphotectonic unit of the Iberian Massif (Variscan Orogen). They are sedimentary, metamorphic and plutonic rocks. In addition, substantial outcrops of Mesozoic sedimentary rocks appear in this area. They correspond mainly to undeformed sedimentary cover of the Iberian Massif, made up of Triassic and Lower Jurassic materials, and to the Prebetic (Betic External Zone), which presents some outcrops of Jurassic and Cretaceous rocks in the easternmost sector (Figs. 1c and 2). Finally, sedimentary rocks from the Cenozoic and Quaternary also appear in the south of the study region, belonging to the Guadalquivir foreland basin.

The Precambrian materials (U1, Fig. 2) belong to the Schist-Greywacke complex (see references in Martínez-Catalán et al. 2004). They are monotonous pelite-sandstone series without precise dating; however, according to Martínez-Catalán et al. (2004), some authors date them as Upper Vendian-Lower Cambrian based on the existence of

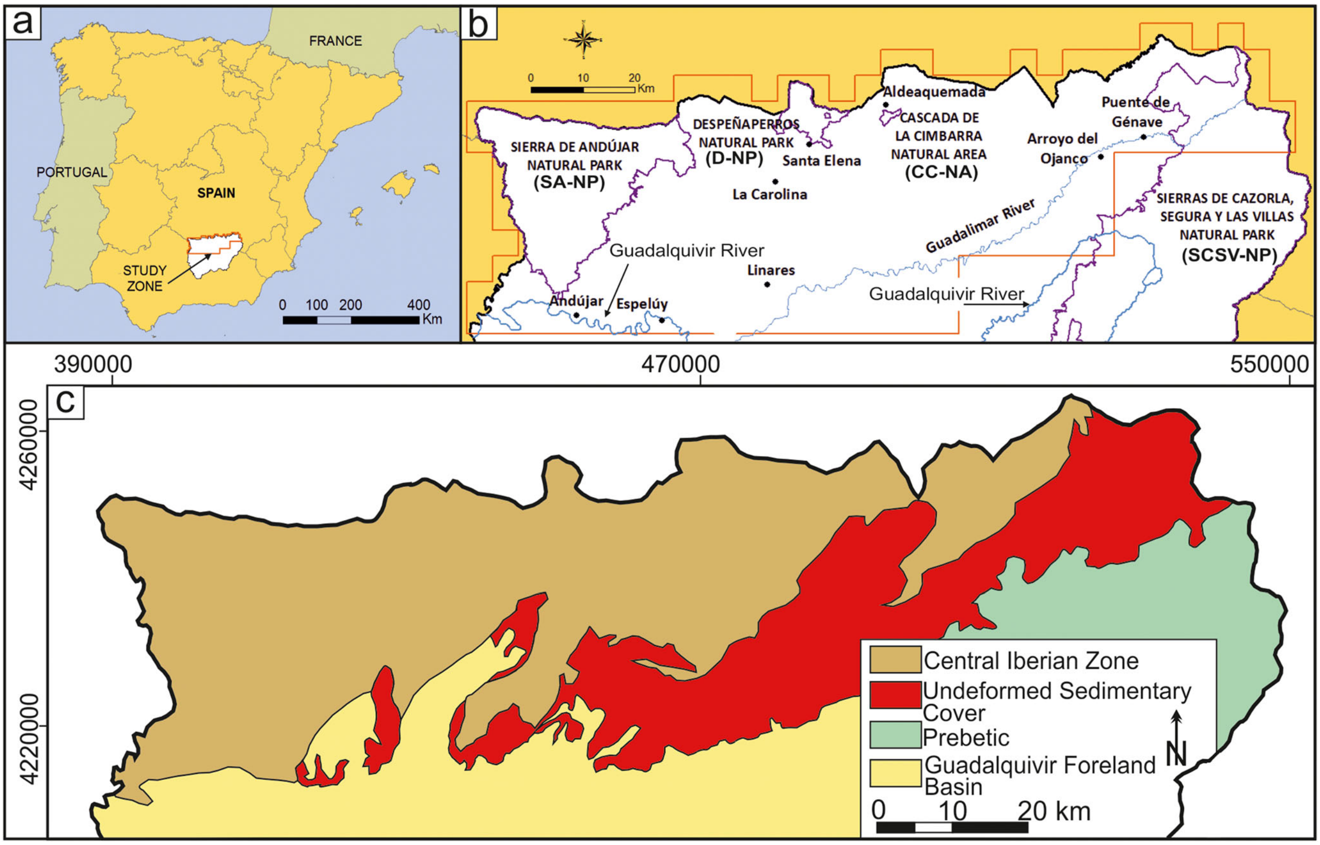

Fig. 1 Geographic and geological location. **a** Geographic location of Jaén Province, southern Spain, and the studied area. **b** Main localities and geographical features of the studied area with locations of the natural protected areas (NPAs): Sierra de Andújar Natural Park (SA-NP); Despeñaperros Natural Park (D-NP); Sierra de Cazorla, Segura y Las Villas Natural Park (SCSV-NP); and Cascada de La Cimbarra Natural Area (CC-NA). **c** Sketch with the main geological units differentiated in the north of Jaén Province considered in this paper

ichnofossils and in view of U-Pb isotopes of the detrital zircons. They crop out in the core of some folds.

Above the Precambrian rocks, a discordant succession of quartzites, shales and sandstones—named the pre-orogenic sequence—crops out, dated as Ordovician-Devonian (see references in Martínez-Catalán et al. 2004). These lithologies are grouped into several lithostratigraphic units of varying thicknesses (U2 to U13, Fig. 2).

Found overlying the pre-orogenic sequence is the syn-orogenic sequence, made up of a 6000-m-thick unit with alternating greywackes and shales (Culm Facies, U17, Fig. 2) and intercalations of volcanic and plutonic rocks at their bottom (U14 to U16, Fig. 2). This sequence has been dated as Lower Carboniferous (Mississippian). It is represented only in the southernmost part of the Central Iberian Zone, near the plutonic rocks (Los Pedroches Batholite, U18, U19, Fig. 2; see references in Martínez-Catalán et al. 2004). The plutonic rocks and dykes (U20, Fig. 2) that intruded the Palaeozoic succession are tardi-post kinematic intrusive bodies (Larrea et al. 2013). The axis of the intrusive bodies is WNW-ESE, parallel to the Variscan structures. The dykes are tardi-post-Variscan and Eo-Alpine rocks (U19 and U20, Fig. 2). They are economically interesting because they have Pb-Zn-(Ag) mineralisations, mined in the Linares-La Carolina District at the end of the nineteenth and twentieth centuries.

The largest tectonic structures in the Schist-Greywacke complex are folds and thrusts, the latter having a N100E strike and dip 70°–80° to the south (Martínez-Catalán et al. 2004). They developed as a consequence of Variscan Orogeny in the Carboniferous (Mississippian). The folds have axial surfaces dipping to the SSW, showing N-vergence. They are asymmetrical cylindrical folds with an E-W axis whose southern limb is more developed. The distance of thrusting (N100E, 70°–80° S) could be as much as tens of kilometres, and it cuts the folds. The plutonic rocks (U18, Fig. 2) intersect both kinds of tectonic structures and favour the development of a metamorphic contact zone around the plutonic bodies.

Siliciclastic rocks, dated as Triassic (U21, Fig. 2), and carbonates of the Upper Triassic to Lower Jurassic (U22 and U24, respectively; Fig. 2) make up the undeformed sedimentary cover (Vera and Martín-Algarra 2004). They are discordant over the Precambrian and Palaeozoic rocks, also over the plutonic rocks. These Upper Triassic and Lower Jurassic sedimentary rocks were tectonically deformed when they cropped out in the external zones (forming well-developed epidermic thrusting structures). Thus, some Prebetic outcrops made up

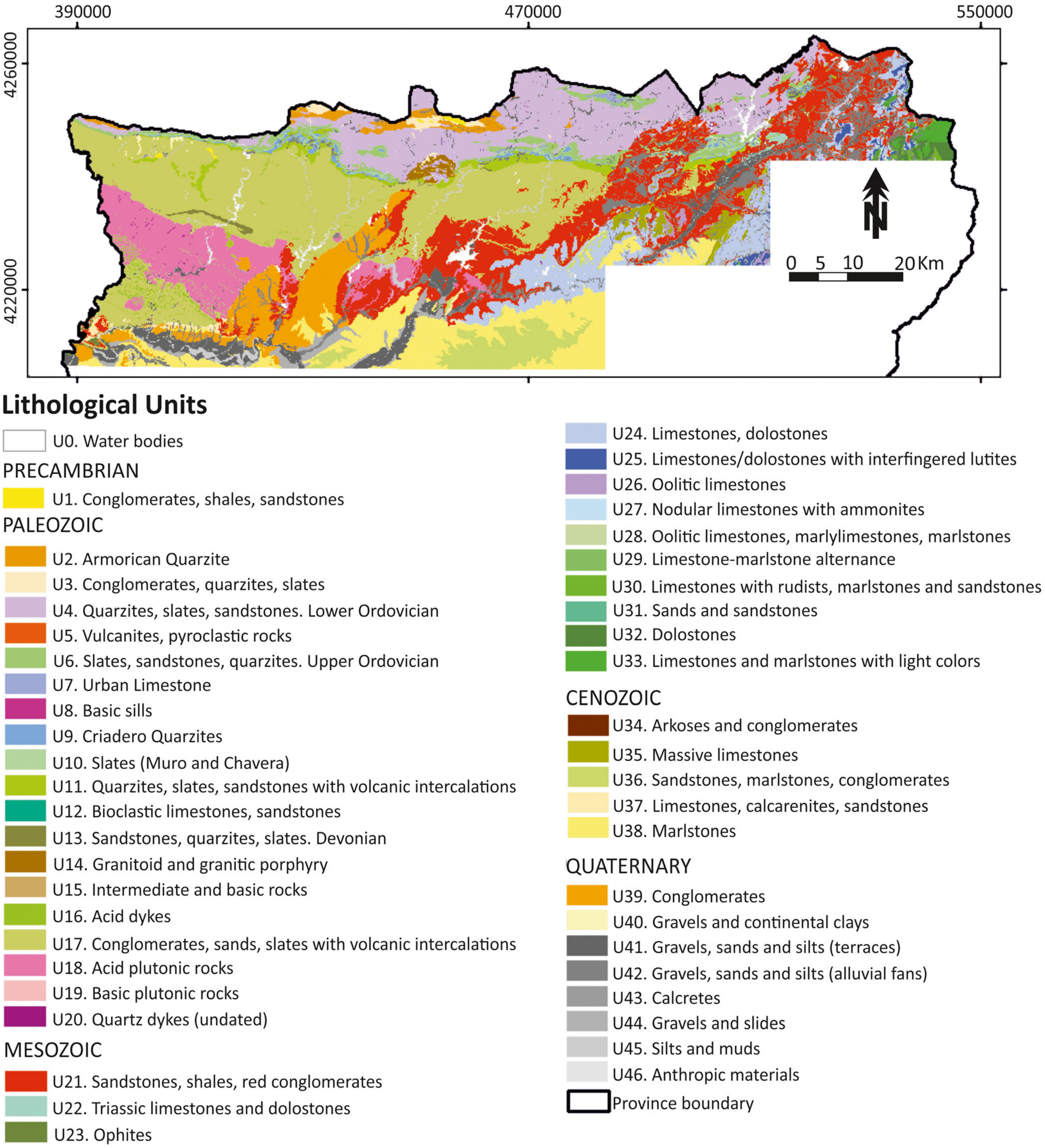

Fig. 2 Maps of lithological units studied in the northern part of Jaén Province, especially those cropping out in the southern Central Iberian Zone, Prebetic and Guadalquivir foreland basin

of carbonate rocks from the Jurassic (U25 to U28, Fig. 2) and Cretaceous (U29 to U33, Fig. 2) can be found in the easternmost part of the considered area.

The younger rocks in the study area are Neogene rocks (U34 to U38, Fig. 2) and Quaternary materials (U39 to U46, Fig. 2). Mudstones, sandstones and marls from the Neogene (Upper Miocene-Pliocene) crop out in the south, in the Guadalquivir foreland basin, and lie discordantly above the aforementioned rocks. The Quaternary materials are sediments related to present fluvial dynamics, slope sediments or tufas associated with spring carbonate water. Like the underlying Neogene rocks, they are discordant over older rocks.

Geomorphological Setting

The landforms and landscape of the analysed region are controlled by tectonic structures and/or the lithological composition of each of the geological units considered (Central-Iberian Zone, undeformed sedimentary cover, Prebetic and Guadalquivir foreland basin).

The landscape of the Central-Iberian Zone can be defined as Appalachian (Lillo et al. 1998; Larrea et al. 2013), mainly controlled by quartzite levels. These materials develop crest morphologies or homoclines; in the latter landform, chevrons are developed when shales are intercalated in quartzites. Gorges and stream channels with high or even vertical slopes are abundant. Their development is related to the formation of the Guadalquivir foreland basin in the Late Miocene. As a consequence, the Palaeozoic rocks stayed in a high position with regard to this foreland basin.

The area occupied by undeformed sedimentary cover features (table hills, *mesas*) controlled by the horizontal position of these rocks and the presence of hard sandstones, more resistant to erosion than lutites. Karst landforms develop where this unit is made up of Jurassic carbonates, mainly karren morphologies.

As in the Central-Iberian Zone, Prebetic landscapes are controlled by the lithology and tectonic structure of thrusting and folding. The dominance of carbonates is determinant for the development of several kinds of endo- and exo-karst morphologies (karrens, dolines, sinks, caves).

Finally, in the Guadalquivir foreland basin, the geomorphology is controlled by the dynamics of the Guadalquivir River, by its tributaries and by the lithology of the outcropping rocks. The Guadalquivir River springs up in the Prebetic (SCSV-PN), and it flows to the west close to the Central Iberian Zone, eroding the Upper Miocene-Pliocene sedimentary rocks that made the foreland basin. The erosion processes formed table hills or *mesas* because sandstones and/or calcarenites appear interfingered in the lutites. These more competent rocks shape the upper part of the hills, giving them the characteristic horizontal morphology at their tops.

Methodology

This study follows the methodology developed by Pereira et al. (2013), afterward improved by Silva et al. (2013, 2015) and Araujo and Pereira (2018). These authors respectively drew geodiversity maps of the Paraná State, the Xingu drainage basin and the Ceará State in Brazil. Our starting point was defining different partial indices based on available maps of lithology, geomorphology, soils, minerals, fossils and hydrology. The item geosites is now proposed as a new partial index in this paper.

For each index, the number of different units defined by a regular grid was counted. The size of each square of this grid is 5 km × 5 km (25 km^2), defined according to the methodology expounded by Hengl (2006). In total, 250 squares were considered, taking into account the size of the study area. A larger grid size could not guarantee sufficient detail, and a smaller grid size would not have obtained accurate results for the scale of the maps used. The sum of these partial indices in each square gives, as a result, the geodiversity index per square. All the procedures and map design techniques were carried out using ArcGIS 10.3 software. Figure 3 shows the procedure used to obtain the lithological index. The methodology can be extrapolated to the indices considered in this paper. Represented in addition is the normalisation to natural breaks according to the proposal by Jenks (1967).

In each map of Fig. 4, the numbers within the squares are the absolute value of the feature represented in this map, but the legend presents the normalisation by means of natural breaks to five values: 1 (very low), 2 (low), 3 (medium), 4 (high) and 5 (very high). The geodiversity index is the sum of the normalised values.

Geodiversity Index

To calculate the geodiversity index, seven partial indices were taken into account: lithological, geomorphological, palaeontological, pedological, minerals and hydrology, plus geosites. The hydrology index was divided into three sub-indices, namely hierarchy of rivers, aquifers and rainfalls. All partial indices and sub-indices are explained below.

Lithological Index

For this index, 1:50,000-scale digital-based geological maps (MAGNA 50; Table 1) published by the Spanish Geological Survey (*Instituto Geológico y Minero de España* (IGME), www.igme.es) were used. For each lithological unit, a category was designated (see legend in Fig. 2; e.g. vulcanites and pyroclastic rocks were assigned to unit 5 (U5)). Once all units had been classified, dissolve tools (software ArcGIS) were used to delete all duplicated units so they would not be counted more than once. Next, the lithological units were linked with the grid shape file and the number of lithological occurrences per square was calculated (Fig. 3). Finally, the shape file was classified according to the number of units by natural breaks classification (Jenks 1967) as very low (1), low (2), medium (3), high (4) and very high (5), depicted in Figs. 3 and 4 a.

Geomorphological Index

For the geomorphological index, a 1:400,000 geomorphological map of Andalusia was used. This map comes in vector

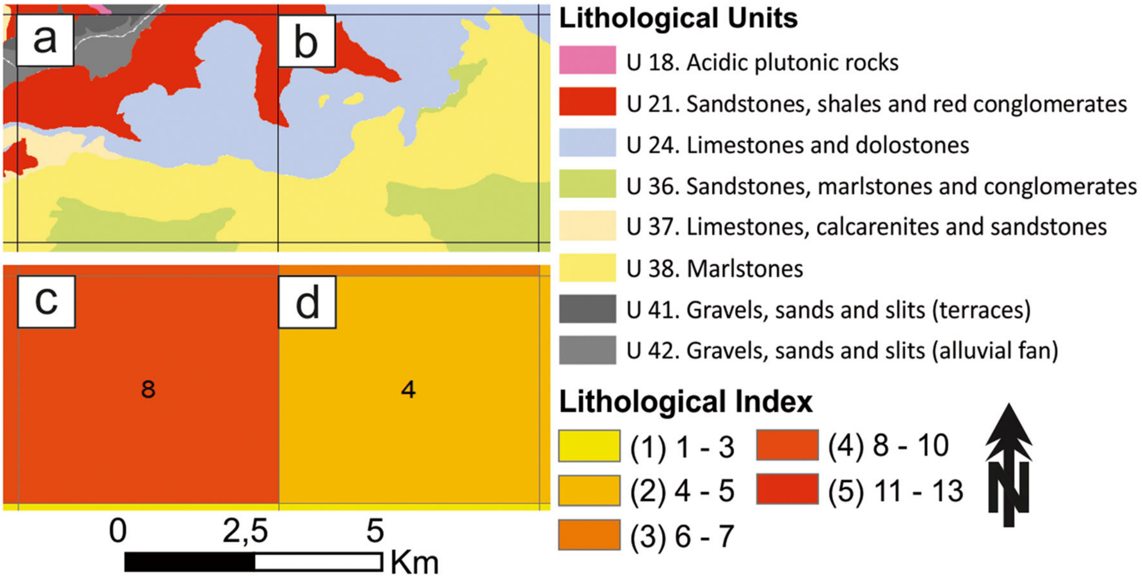

Fig. 3 Example of lithological index assessment in a 5 km × 5 km square size. Above, different colours represent lithological units (**a** and **b**). Below, numbers represent the sum of different lithologies in each square (8 in **c**, 4 in **d**). The lithological indices of both squares are shown

shape file format and was downloaded from the Environmental Information Network of Andalusia (*Red de Información Ambiental de Andalucía* (REDIAM, Consejería de Medio Ambiente 2005), www.juntadeandalucia.es/medioambiente/rediam). This map was made from a compilation of geomorphological maps of the MAGNA 50, fit with LANDSAT images. The procedure was identical to the one followed for the lithological index: the geomorphological map was linked to the grid shape file, then the different geomorphological units per square were counted and classified into five orders (Fig. 4b).

Palaeontological Index

To gauge palaeontological diversity, lithological units with some presence of fossils were identified based on the reports of the MAGNA 50 geological map. Inside each lithology with fossils, the number of genera or species (trilobites, graptolites, brachiopods, pteridophytes, etc.) was recorded likewise according to palaeontological reports from MAGNA 50. In the paper of Araujo and Pereira (2018), the total number of fossil species or genera per square was counted, and data were classified into five orders as for the previous indices (Fig. 4c). In the present paper, the genera or species fossils for each square were counted. Thus, some squares have a 0 fossil record while others have as many as 182. In the palaeozoic rocks, the presence of the palaeontological site is very irregular, mainly restricted to some shale lithological units. In the undeformed sedimentary cover, there is an absence of fossils, and in the Prebetic, only some genera of invertebrates were recognised, particularly in the Lower Cretaceous rocks. In the Guadalquivir foreland basin, planktonic foraminifera are the most abundant fossils; no other kinds of fossils are recorded in the area.

Pedological Index

The quantification of soil units entailed reference to the pedological map of Andalusia in vector format at a scale of 1:400,000, published in 2005 by the Agriculture Department of the Andalusian Government (*Consejería de Agricultura, Junta de Andalucía*, www.juntadeandalucia.es/agriculturaypesca/gdpu/, Consejería de Agricultura 2005) and the Spanish National Research Council (*Consejo Superior de Investigaciones Científicas* (CSIC), www.csic.es). Soil classification is established in terms of cartographic units typified by Food and Alimentation Organization (FAO) criteria from 1974, and the European map of soils from 1985. The procedure for pedological partial index calculation was similar to that described for previous indices. The number of different soil occurrences counted for each square was subsequently classified into five orders, with reference to the natural breaks classifier (Fig. 4d).

Minerals Index

Quantification of minerals was based on the metallogenic map of Andalusia at a scale of 1:400,000, published by IGME and the Department of Economy, Innovation and Science of the Andalusian Government (*Consejería de Economía, Innovación y Ciencia, Junta de Andalucía*, www.juntadeandalucia.es/economiaconocimientoempresasyuniversidad, IGME and Consejería de Economía, Innovación y Ciencia 2011). The number of mineral occurrences was quantified, taking into

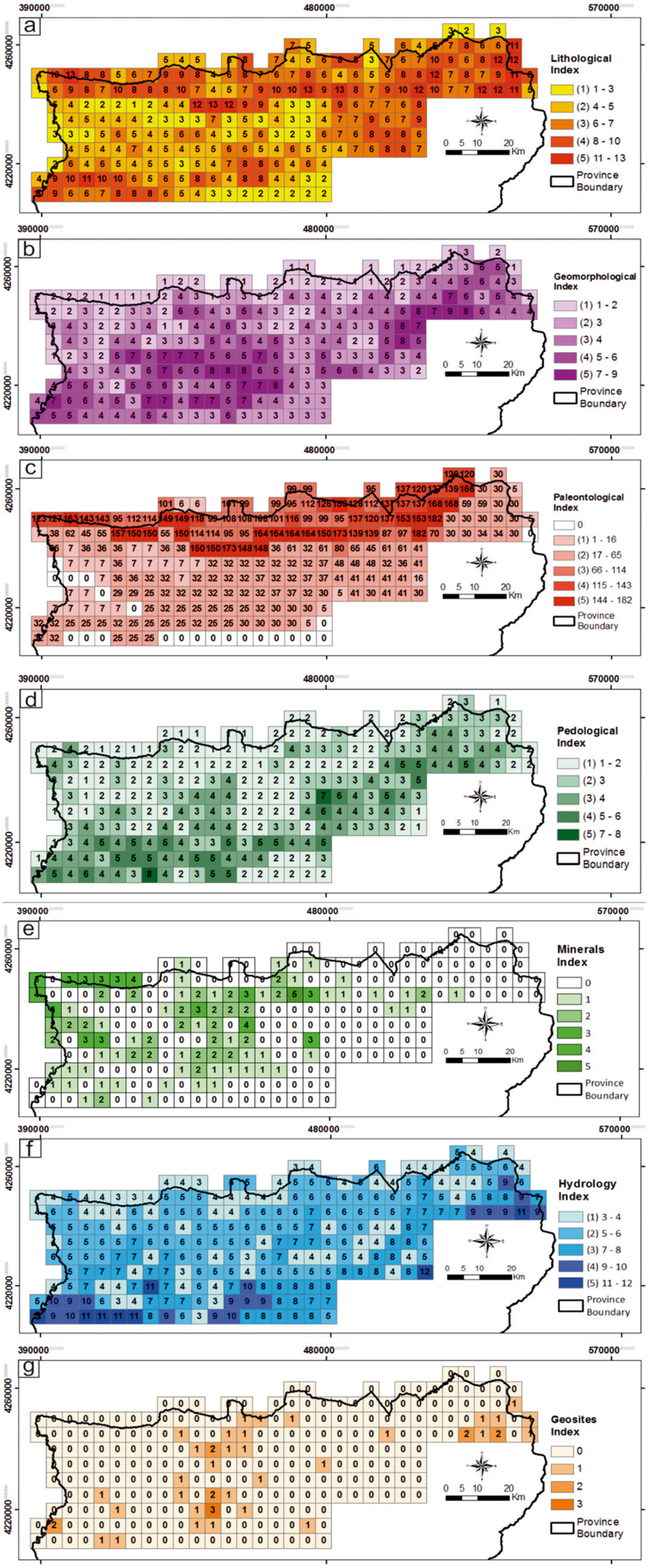

Fig. 4 Maps of partial diversity indices, each one with corresponding values of indices. **a** Lithological index. **b** Geomorphological index. **c** Palaeontological index. **d** Pedological index. **e** Minerals index. **f** Hydrology index. **g** Geosites index

Table 1 Bibliographic data of the MAGNA 50 maps used in this study

Name of the maps (MAGNA 50)	Authors	Date of publication
840 - Bienservida	Leyva F, Matas J, Jerez-Mir F, Cabra P, Gurtiérrez-Marco JC, Rodríguez RM	2009
860 - Fuencaliente	Insúa-Márquez M, Palero F, Delgado-Quesada M, Fernandez-Ruiz J, Sánchez R, Liñán E, García-Alcalde G, Vilas E, Palacios-Medrán T, Soria FJ, Carvajal A, Gracia-Prieto J, Olivares J, Cantos R	2008
861 - Solana del Pino	Ramírez JI, Palero F, Pieren A, Olivé-Davó A, Hernández-Samaniego A, Dabrio C	2010
862 - Santa Elena	Lillo J, Olivé-Davó A, Pieren A	1998
863 - Aldeaquemada	Hernández-Samaniego A, Ramírez-Merino JI, Dabrio CJ, Gutiérrez-Marco JC, Carreras-Suárez F	Unpublished
864 - Venta de los Santos	Matas-González J, Leyva F, Cabra P, Granados LF, Gutiérrez-Marco JC, Rodríguez RM	2009
865 - Siles	Benito MI, Fernández-Gianotti J, Leyva F, Matas-González J, Núñez-Lago B, de Torres Pérez-Hidalgo TJ, Nozal-Martín F	2001
866 - Yeste	Fernández-Gianotti J, Perucha-Atienza MA, Benito MI, Rodríguez-Estrella T, Nozal-Martín F	2001
882 - Cardeña	Quesada C, Cueto LA, Fernández-Ruiz FJ, Larrea FJ	2013
883 - Virgen de la Cabeza	Larrea FJ, Fernández-Ruiz FJ, Cueto LA, Quesada C	2013
884 - La Carolina	Castelló-Montori R, Orviz-Castro P	1976
885 - Santisteban del Puerto	Orviz-Castro P, Castelló-Montori R, Martínez del Olmo W	1976
886 - Beas de Segura	Fernández-Gianotti J, Benito MI, Núñez-Lago B, Torres Pérez-Hidalgo TJ, Cabra P, Leyva F, Matas J, Roldán F	2001
903 - Montoro	Amengot de Pedro J, Moreno de Castro E, Pérez-Domínguez H, Castelló-Montori R, Ramírez-Copeiro J	1973
904 - Andújar	Larrea FJ, Santisteban-Navarro JI, Cueto LA, Quesada C, Fernández-Ruiz FJ, Martín-Serrano A	2013
905 - Linares	Azcárate-Martín JE, Esnaola-Gómez JM, Maldonado M	1977
906 - Úbeda	Azcárate-Martín JE, Espejo-Molina JA	1977

All maps have a scale of 1:50,000 and were published by *Instituto Geológico y Minero de España* (IGME, Spanish Geological Service)

account that, in this case, the shape file is composed of points, not of polygons, as with previous indices. Yet for the purpose of index calculation, the number of different resources per square was counted rather than the total number of elements. Otherwise, the procedure followed was the same, and finally, a grid classified in five orders was obtained (Fig. 4e).

Hydrology Index

The hydrology index is given by the sum of three sub-indices: hierarchy of rivers, aquifers and annual average rainfalls. It can be defined as the diversity indicator of the water resources in a territory. The hierarchy of rivers can be conditioned by the lithologies where the fluvial streams flow (Araujo and Pereira 2018). If the erosion resistance is higher, the fluvial streams are fewer; hence, there is a lesser hierarchy of streams. On the contrary, when the resistance to erosion is weak, the hierarchy of fluvial streams may be well developed. The aquifer sub-index is directly related to the permeability of the rocks and to the annual average rainfalls. If permeability is low, the surficial run-off can be important (high value of hierarchy of rivers sub-index) and, consequently, aquifers are not present (low value of aquifer sub-index); when the rocks are permeable, surficial run-off is limited and aquifers will be abundant. Finally, the annual average rainfall sub-index informs about the water available for run-off or infiltration in aquifers.

The fluvial hierarchy sub-index was calculated, taking as a starting point the vector shape file of the hydrographic network (from the 2008 topographic map of Andalusia at a scale of 1:100,000), which was adapted to fit the surface water database of the Environment Department of the Andalusian Government (*Consejería de Medio Ambiente, Junta de Andalucía*, www.juntadeandalucia.es/medioambiente). This shape file was cut around the study zone, and the hierarchy of rivers was established according to the methodology of Strahler (1952, 1957). Rivers without a tributary were classified as first-order rivers. The classification grows when similar-order rivers intersect, producing a higher-order river, and so on. Nevertheless, when two rivers of different orders intersect, for instance a second-order river with a fourth-order river, the river of the higher order prevails. To quantify the fluvial hierarchy in our case, the river with the greatest order was selected for each grid. Squares without rivers were assigned zero value. Lastly, data were classified into five categories.

The aquifer sub-index was obtained through reference to the vector layer of the aquifer system registered in the Groundwater Information System (*Sistema de Información de Aguas Subterráneas*, SIAS) of the IGME, adjusted for Andalusia in 2017 by the REDIAM at a scale of 1:400,000. Based on the methodology of Araujo and Pereira (2018), the relative area, percentage-wise, occupied by aquifers in each square was measured. That is, taking into account that each square has 25 km², if the area occupied by an aquifer is 17 km², the percentage is 68%. These data were broken down into five classes.

The third sub-index has to do with annual average rainfalls. Data used were mean annual rainfalls between 1940 and 2016, from REDIAM, in raster format with a resolution of 100 m × 100 m (corresponding to a reference scale of 1:400,000 to 1:500,000). To arrive at the sub-index, the arithmetic mean was calculated for each square, after which the values were classified in five intervals according to the rainfall range of the square.

The sum of these three sub-indices (classified from 1 to 5) gave as a result the hydrology map index, which was turned into five categories using a natural breaks classifier (Fig. 4f).

Geosites Index

According to Gray (2013, 2018) or Brilha et al. (2018), the geosites that make up the geoheritage are parts of identified geodiversity with values deserving attention, and their conservation is important to gain knowledge of the geological history of the area where they crop out. To create the index of geosites, the vector layer of geosites (*Áreas de Interés Geológico*) of the REDIAM was complemented and updated using the Spanish Geosites Catalogue (*Inventario Español de Lugares de Interés Geológico* (ILEIG)), produced by IGME in 2016. The procedure was similar to the one followed for the minerals index. In this case, the number of geological sites in each square was counted, and the values obtained were broken down into five classes (Fig. 4g).

Geodiversity Index

The geodiversity index map was derived from the sum of all previous partial indices for each square, then classified. The grid map obtained reflects five classes of geodiversity: very low (1), low (2), medium (3), high (4) and very high (5) (Fig. 5).

The geodiversity map (Fig. 5) can be presented in a more continuous way, taking the geodiversity index previously calculated for each square's centre and then applying a Gaussian kriging interpolation method, as described by Araujo and Pereira (2018). This correlation of the values of each square centroid with the nearest neighbours generates intermediate values; a gradient geodiversity map (Fig. 6), again with five classes, can then be developed—very low, low, medium, high and very high.

Endangered Species Index and Biodiversity Map

For the purposes of this research, further maps were consulted (e.g. the endangered species maps for animal and vegetal species (Fig. 7) and the biodiversity map of Fig. 8). The endangered species map (Fig. 7) was derived from the vector map distributing protected fauna and flora in a 5 km × 5 km grid (REDIAM, www.juntadeandalucia.es/medioambiente/rediam, Consejería de Medio Ambiente 2005), and the number of endangered species per square was calculated by means of GIS tools. As in some previous maps, all duplicated species inside one same square were deleted using the dissolve tool. Finally, data were classified by natural breaks (Jenks 1967) into five categories (Fig. 7).

The biodiversity map (Fig. 8) was obtained from the biodiversity layer in vector format from the REDIAM (www.juntadeandalucia.es/medioambiente/rediam), which is based on the Atlas of Andalucía at a scale of 1:400,000 of the Department of Environment and the Department of Public Works and Transports of the Andalusian Government (Consejería de Medio Ambiente and Consejería de Obras Públicas y Transportes 2005). It was likewise reclassified into five levels (very low, low, medium, high and very high; Fig. 8)

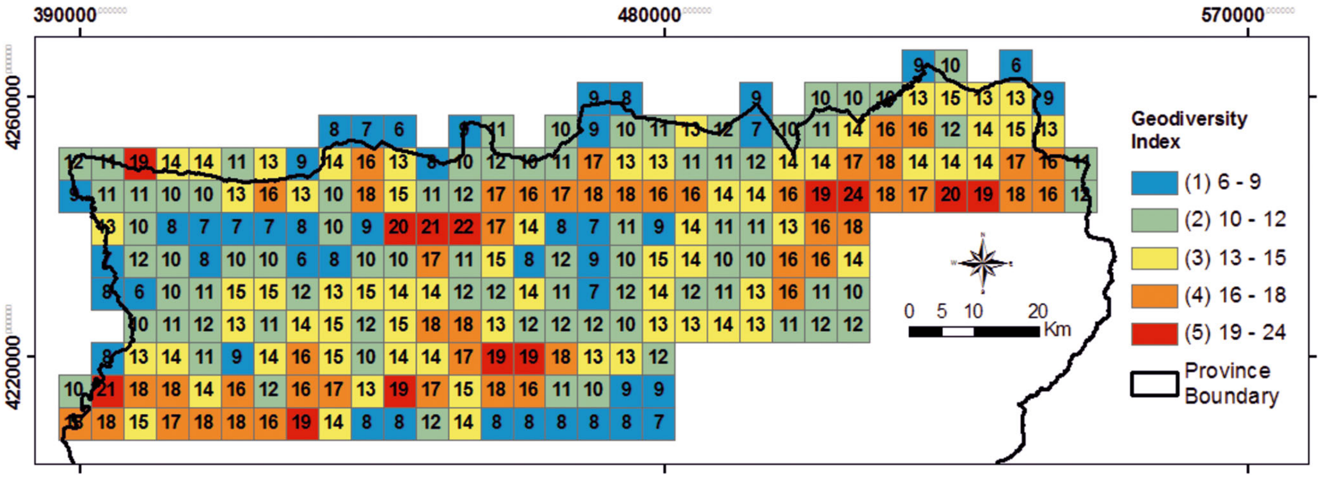

Fig. 5 Geodiversity index obtained from the sum of previous partial indices shown in Fig. 4

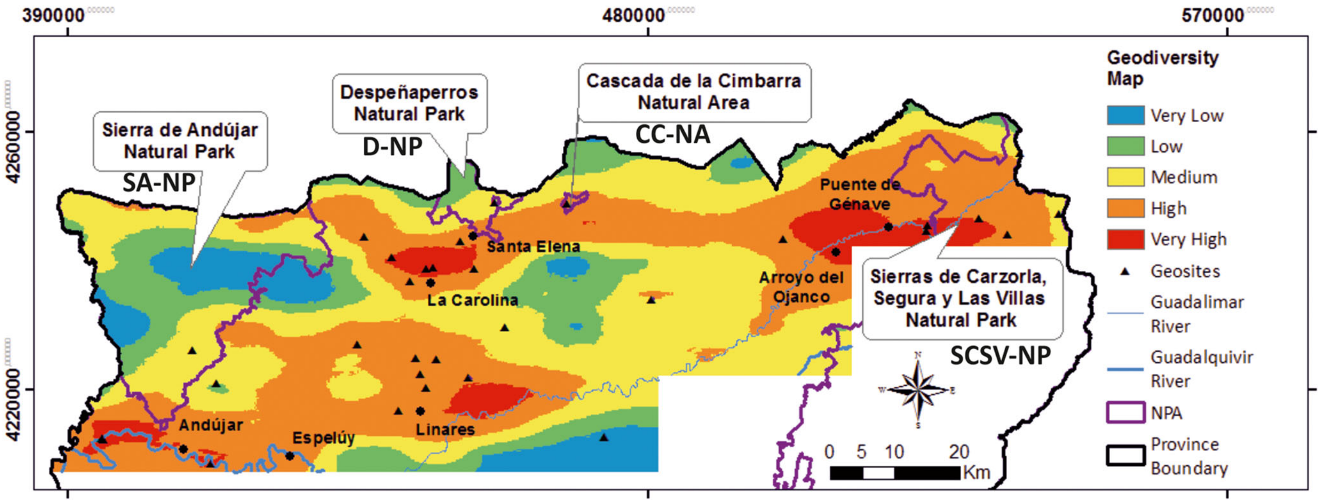

Fig. 6 Gradient geodiversity map obtained through kriging interpolation of the geodiversity index map of Fig. 5. The location of geosites is shown in this map. The bordering of the natural protected areas located in the study region is superimposed: Sierra de Andújar Natural Park (SA-NP); Despeñaperros Natural Park (D-NP); Sierra de Cazorla, Segura y Las Villas Natural Park (SCSV-NP); and Cascada de La Cimbarra Natural Area (CC-NA)

based on the diversity of plant communities at structural, phytocenotic and forest cover levels and on the diversity of fauna species (considering only vertebrates).

Correlation Analyses

To complete the previous studies, the correlation analysis between geodiversity partial indices was carried out to determine their interdependence (Table 2). Similarly, geodiversity, biodiversity and endangered species maps were correlated to establish relationships among them, for instance to check if geodiversity influences biodiversity and/or endangered species.

Finally, the shape file with NPAs was overlapped with these maps to see whether these areas are determined or defined by geodiversity (Fig. 6), endangered species (Fig. 7) and/or biodiversity (Fig. 8). The areas corresponding to the classes of these maps in the protected areas were computed, then compared with the class areas calculated in the overall maps.

Results

Lithological Index

Lithological diversity (Fig. 4a) varies between 1 and 13 points. There are various squares with the highest score (13). Most of them are located in the northern part of the study area, the Central Iberian Zone, where both metapelitic and igneous rocks crop out. Specifically, a first hot spot appears in the northwest, within the SA-NP (Fig. 4a), and others are found in La Carolina municipality, close to CC-NA (central part),

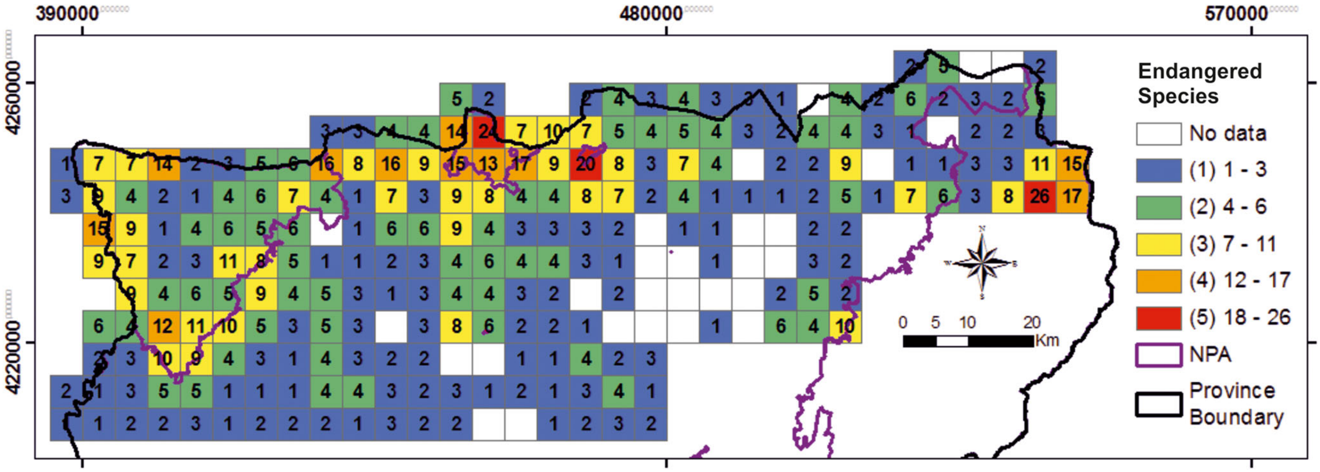

Fig. 7 Map of endangered species index with a 5 km × 5 km grid. In each square, the number of endangered species is shown. Borders of the natural protected areas located in the study region are superimposed

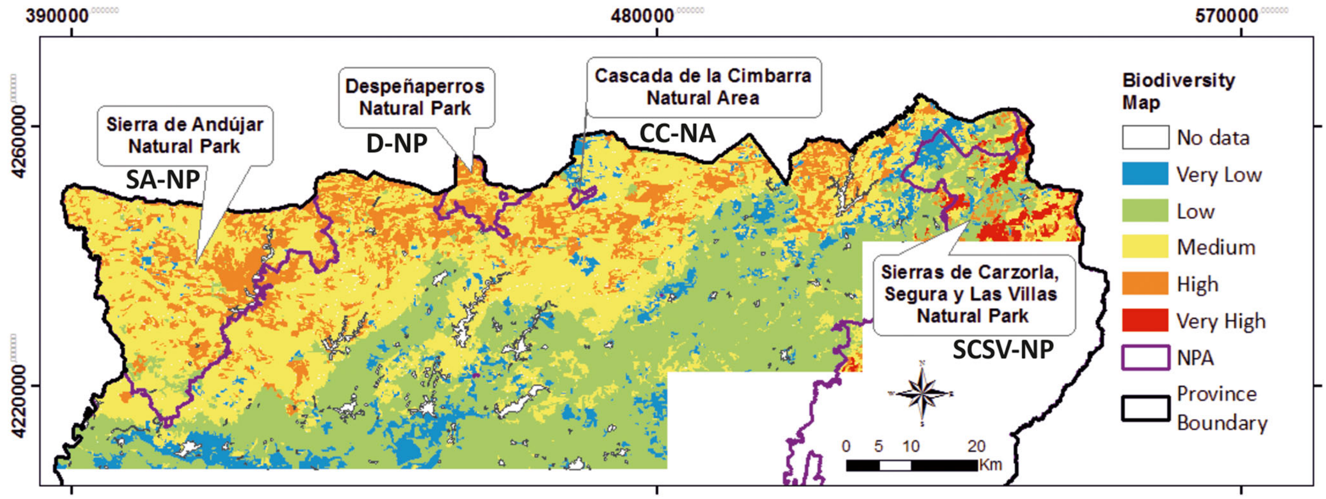

Fig. 8 Biodiversity map of the North of Jaén Province. Borders of the natural protected areas located in the study region are superimposed: Sierra de Andújar Natural Park (SA-NP); Despeñaperros Natural Park (D-NP); Sierra de Cazorla, Segura y Las Villas Natural Park (SCSV-NP); and Cascada de La Cimbarra Natural Area (CC-NA)

and in the surrounding Aldeaquemada area. All consist of repeated cycles involving shales, quartzites and volcanic rocks of Ordovician to Silurian periods. Plutonic rocks (granites to basic rocks) intrude the great variety of lithologies in this area. Some quaternary outcrops (alluvial and colluvial) contribute to this variety.

There are further hot spots in the northeast, coinciding with the SCSV-NP. They feature a variety of lithologies in the confluence area of the Prebetic domain (limestones, dolostones, clays and marls), the undeformed sedimentary cover of the Iberian Massif (clays, sandstones, conglomerates and even carbonate rocks) and the Iberian Massif itself (metapelitic and plutonic rocks), along with Quaternary material outcrops (Figs. 1 and 2).

The lowest values were obtained in the middle and the southeastern parts of the map, showing large outcrops of homogeneous rocks of the Iberian Massif (carboniferous metapelites, Fig. 2) or the Guadalquivir foreland basin (Miocene marls, Fig. 2). These homogeneous areas having lower values for the lithological index (Fig. 4a) are interrupted by transitional areas between the three morphotectonic domains and by the presence of Quaternary materials (river terraces, alluvial and colluvial materials; Fig. 2).

Geomorphological Index

The geomorphological index (Fig. 4b) ranges from 1 to 9. Two zones with high geomorphological diversity are evident on the map. The first is in the northeastern sector, largely coinciding with the course of the Guadalimar River and reaching the maximum value of all the areas (9) in the square centred in Puente de Génave township, near the boundary between outcrops of rocks from the Central Iberian Zone and the Prebetic (Fig. 1b,

Table 2 Correlations among the partial geodiversity indices and between them and the geodiversity index, biodiversity and endangered species

Pearson correlation coefficient	Lithological	Geomorphological	Palaeontological	Pedological	Minerals	Hydrology	Geosites	Geodiversity	Biodiversity
Geomorphological	_0.158*_								
Palaeontological	_0.503**_	_− 0.184**_							
Pedological	_0.169**_	_0.500**_	_− 0.173**_						
Minerals	0.011	− 0.022	_0.148*_	− 0.122					
Hydrology	_0.141*_	_0.397**_	_− 0.249**_	_0.324**_	_− 0.190**_				
Geosites	_0.172**_	_0.218**_	0.003	_0.126*_	0.116	0.099			
Geodiversity	− 0.050	0.045	− 0.028	− 0.034	− 0.052	0.090	0.069		
Biodiversity	0.093	_− 0.311**_	_0.293**_	_− 0.367**_	_0.150*_	_− 0.209**_	− 0.028	0.022	
Species	_0.139*_	_− 0.208**_	_0.189**_	_− 0.247**_	_0.145*_	0.001	0.085	− 0.047	_0.414**_

The values in italic show significant correlations

*Means that the correlation between pairs of indices is significant at the p level equal to 0.05

**Means that the correlation is significant at the p level equal to 0.01

c). In this zone, several geomorphological units converge: mountain relief in carbonate and metapelitic rocks, a karstic landscape and different types of hills, besides terraces and flood plains in some sectors. The other one (Fig. 4b), located in the south and central parts of the study area, corresponds to the southern area of Central Iberian Zone. This is a transitional area between the mountain relief of the Iberian Massif, the table landscapes of undeformed sedimentary cover and the hills of the Guadalquivir basin, together with terraces and flood plains of the tributary rivers of the Guadalquivir (Figs. 1b and 2).

The northern and western sectors of the map (Fig. 4b), where the mountain relief is more monotonous, and the south with homogeneous hill landscapes distribute the squares with the lowest scores.

Palaeontological Index

Most of the map (Fig. 4c) presents very low to low values. Only in the northern strip do high and very high values prevail (Fig. 4c). A great difference between minimum (0) and maximum (182) values is observed, reflecting lithologies with a high number of fossil species—trilobites, lamp shells, echinoderms, molluscs, ichnofossils—all from the Lower Ordovician quartzites and shales, and vegetal remains, especially in Lower Carboniferous shales with Culm Facies. The highest scores were obtained in the northeast, close to Puente de Génave and Arroyo del Ojanco municipalities, where the aforementioned Lower Ordovician quartzites and other lithologies (shales and sandstones) with abundant fossils crop out (Figs. 1b and 2).

Pedological Index

Soil diversity (Fig. 4d) scores range from 1 to 8. Higher values appear in transitional zones between calcic and eutric soils (both Cambisols and Luvisols), related to a carbonate or pelitic substratum, while in the southern and eastern sectors (Fig. 4d), the higher values mark the courses of the Guadalquivir and Guadalimar rivers (Figs. 1b and 2). The maximum value was achieved by only one square, located next to Espelúy village (close to Linares). Here, in addition to the Luvisols and Cambisols, Fluvisols crop out, related to alluvial deposits of the Guadalquivir River.

Minerals Index

The minerals index (Fig. 4e) varies from 1 to 5. A higher number of mineral occurrences appear in the middle of the map, where La Carolina-Linares Mining District was located (mainly Pb, Sn and Ag). The maximum value is reached in a single square located close to CC-NA (Fig. 4e; Figs. 1b and 2). Other high values to the northwest coincide with the borderline between Jaén and Ciudad Real provinces, where the mining district (Pb and Sn) of Puertollano is located.

Hydrology Index

Higher values were obtained in the south and east of the map (Fig. 4f), where main rivers and some aquifers are located. Accordingly, in the southern central and western parts of the area, the Guadalquivir River reaches its maximum hierarchy and porous aquifers are present, associated with Miocene sandstones or alluvial deposits (Fig. 2). In the eastern sector (Fig. 4f), higher values are related to karstic aquifers and the abundant rainfall in the SCSV-NP. There, the highest value (12) was achieved. In contrast, low values of hydrological sub-indices predominate in the northern sector (Fig. 4f).

Geosites Index

This index (Fig. 4g) obtained the lowest values of all the parameters considered, varying between 0 and 3. A lack of geosites catalogued to date in the Spanish catalogue (*Inventario Español de Lugares de Interés Geológico* (IELIG); www.igme.es) would explain the values obtained, despite the existence of places of great geological wealth within Jaén Province. The highest concentration of geosites (3) is next to Linares City, related to abandoned mines of Pb and Ag (Fig. 4g).

Geodiversity Index

In turn, the geodiversity index, obtained by summing up all of the previous normalised indices, ranges from 6 to 24 (Fig. 5). Overall, the index shows a very heterogeneous distribution, with several hot spots (in the sense proposed by Gray 2008, 2013) spread over different sectors of the study area, mainly in the southern and northeastern sectors (Figs. 5 and 6). The highest value is attained in a square close to Arroyo del Ojanco Town, where lithological, geomorphological, palaeontological and pedological indices present high values (Figs. 5 and 6). This hot spot is centred in the northeastern sector, where the hydrology index is also high (Fig. 4f).

Other northern sectors with high values are found near CC-NA, and there is a hot spot in the SA-NP, both tied to the lithological, palaeontological and minerals indices (Figs. 5 and 6). The southern and eastern sectors contain some disperse hot spots, for instance east of Linares and west of Andújar (Figs. 1b and 2), largely reflecting the lithological, geomorphological, pedological and hydrology indices (Figs. 5 and 6).

Endangered Species and Biodiversity Indices

The endangered species index (Fig. 7) has a distribution with some high values in the northern, but especially in the eastern part, coinciding with the SCSV-NP (Figs. 7 and 8). The lowest values of the index pertain to the southern part, within the Guadalquivir foreland basin (Fig. 7).

The biodiversity index (Fig. 8) shows high values in the northern and, especially, in the eastern sector of the study area. The northern part coincides with the Central Iberian Zone and with some natural protected areas such as SA-NP, D-NP and CC-NA. The eastern part, where the maximum values are reached (Fig. 8), coincides with the SCSV-NP. The minimum values are found to the south, in the Guadalquivir foreland basin (Fig. 8).

Interpretation: Correlation Analyses

The correlation coefficients between indices are shown in Table 2. Regarding geodiversity components, several indices present correlations with a significance level of 0.01 (confidence level of 0.99): lithological index with palaeontological one (presenting the maximum correlation coefficient, close to 0.5), pedological and geosites indices; geomorphological index with pedological index (coefficient also near 0.5), geomorphological and geosites indices; and pedological and hydrology indices. Meanwhile, other indices present correlations with a significant level of 0.05 (confidence level of 0.95): lithological index with geomorphological and hydrology indices, and palaeontological index with geosites index. Finally, negative correlations exist between the palaeontological index with geomorphological, pedological and hydrology indices, and minerals with hydrology index.

The lithological index therefore represents a central position, since it is connected to most indices. It is coherent with the fact that lithology is a direct determinant of the palaeontological index (the calculation of this index is based on lithological units), and that lithology influences soils, geomorphology, hydrology and geosites. Besides, the indices more closely linked to external processes, such as pedological, geomorphological and hydrology ones, influence each other. The finding that geosites are related to lithological and geomorphological units also seems logical. No correlations or negative correlations (meaningless) are seen between the palaeontological index and external factors indices (soil, geomorphology and hydrology; Table 2). At any rate, despite their significance, the values of correlation coefficients are not very high, in no case exceeding 0.5; thus, the individual indices cannot be considered redundant, each one contributing in a relevant way to the geodiversity index.

Likewise indicated in Table 2 are the coefficients showing the relationships between geodiversity, biodiversity and endangered species. It is seen that the geodiversity index and its components are not related with the biodiversity and endangered species index (a slight correlation appears with palaeontological index). In other words, it cannot be said that geodiversity influences biodiversity and the presence of endangered species. Meanwhile, the biodiversity and the endangered species indices present values for the correlation coefficient close to 0.5, meaning the two variables are significantly interrelated: one shows the concentration of animal and vegetal endangered species (Fig. 7), usually owing to anthropic causes, whereas the other one represents biodiversity in the broadest sense (Fig. 8). Again, higher values for both indices mark natural protected areas such as SA-NP, D-NP, SCSV-NP and CC-NA.

The negative correlation (Table 2) between the geomorphological index and biodiversity can be interpreted as evidence that the biodiversity of the studied area is dependent upon its geomorphological features, in the sense that a greater value of the geomorphological index could limit the ecosystem development as consequence of the development of new habitats to be colonised. It means a temporary reduction in the biodiversity of the zone (Parks and Mulligan 2010; Tukiainen et al. 2016). No association between the endangered species index and other abiotic indices can be established, because the definition of endangered species is related to the anthropogenic influence. However, the negative correlation between endangered species and geomorphology index could also be interpreted following Tukiainen et al. (2016). These authors show that the number of endangered species is inversely related to the geomorphology index, because the geomorphological features of a region condition the variety of nutrients and resources; in areas where the geomorphology index is low, there are limited nutrients and resources, hence more endangered species.

When overlapping the shape file of NPAs with the gradient geodiversity map (Fig. 6), it becomes evident that NPAs do not coincide with higher values of geodiversity. For this reason, geodiversity, as it has been defined, was not decisive—or at least was not the main consideration—in the definition and delimitation of these NPAs. According to the histogram of Fig. 9 a, where the percentage of area occupied by each class of geodiversity is represented, over 42% of the territory has a high or very high geodiversity class. If medium geodiversity is furthermore included, the percentage amounts to almost 80%. When only the geodiversity inside natural protected areas is taken into account (Fig. 9b), high and very high geodiversity values are under 30%, whereas if a medium level is considered, the percentage is 52%. These results confirm the null or limited influence of geodiversity in the delimitation of NPAs.

Overlapping the shape file of the NPAs with the biodiversity index map reveals a clear coincidence, unlike the case of geodiversity (Fig. 6). It could be said that biodiversity is the determinant in the definition of NPAs. The percentage occupied by the classes of high and very high biodiversity indices (Fig. 10a) is about 15%, and together

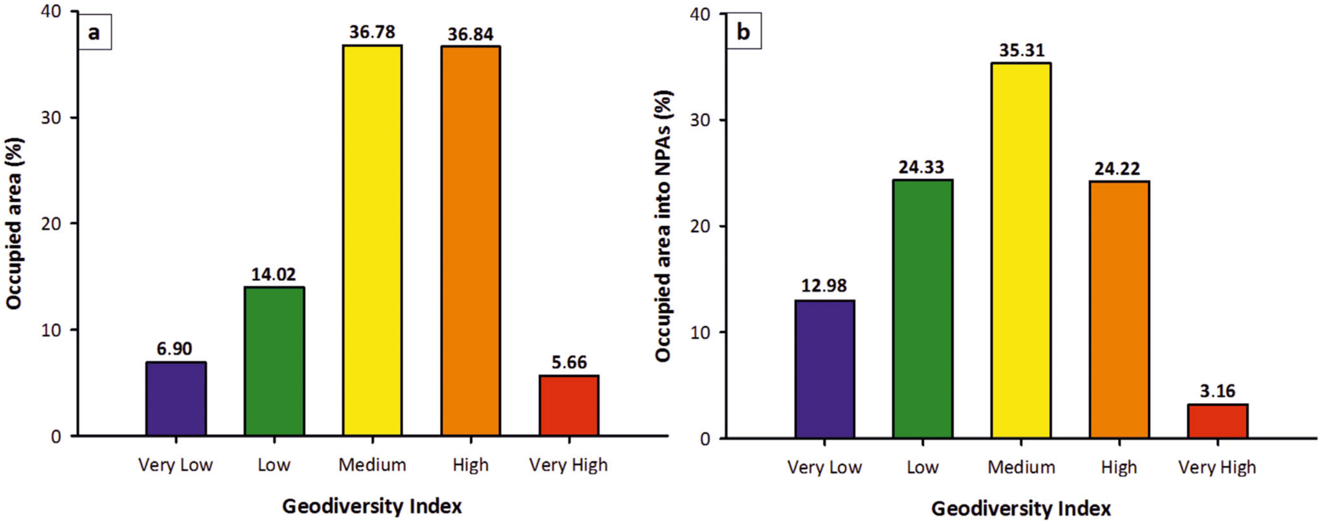

Fig. 9 Histograms representing the percentage of occupied area for each class of geodiversity. **a** Total studied area. **b** Occupied area divided into NPAs

with medium biodiversity class, it reaches 55%. However, if only the biodiversity inside natural protected areas is considered (Fig. 10b), high and very high biodiversity values increase to 30%, and when including the medium level, the value is close to 85%. Regardless of the absolute percentage values, the percentages of the classes of medium to very high biodiversity increase in the NPAs, thus confirming the influence of biodiversity in the delimitation of NPAs of the northern sector of Jaén Province.

Discussion: Use of the Geodiversity Index in Delimiting Natural Protected Areas

In view of the above results, geodiversity was not considered essential for delimiting the natural protected areas within the studied region (SA-NP, D-NP, SCSV-NP and CC-NA; Fig. 6). Their borders are, however, in agreement with the endangered species index (Fig. 7) and the distribution of biodiversity (Figs. 8 and 10). Such findings support the extended notion that geodiversity and biodiversity are separate attributes of natural diversity and therefore can be studied and preserved individually (e.g. Carcavilla et al. 2007; Gray 2013; Matthews 2014; Peña et al. 2017).

According to the conception of natural diversity expressed by several authors (Huggett 1995; Cottle 2004; Gray 2013), it comprises biotic and abiotic elements of the Earth's modern-day system. Despite the close relationship between these components of natural diversity, the elements of geodiversity cannot be attributed to appropriate protection figures. This makes it hard to detect associations between them and makes their management complex.

Meanwhile, according to Resolutions 4040 (International Union for Conservation of Nature, IUCN 2008), 5048 (IUCN

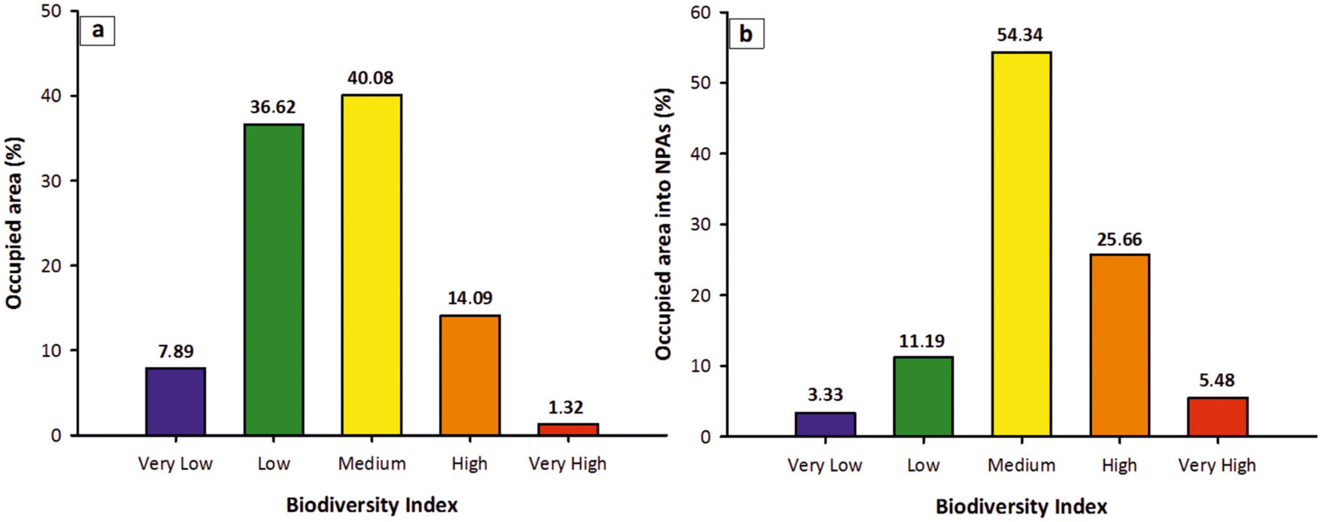

Fig. 10 Histograms representing the percentage of occupied area for each class of biodiversity. **a** Total studied area. **b** Occupied area divided into NPAs

2012) and 6083 (IUCN 2016), geodiversity is a part of natural diversity and should therefore be considered in the assessment and management of natural protected areas (Gordon et al. 2018). The concept of natural protected areas under Spanish Natural Heritage and Biodiversity Law (BOE num. 299, from December 14, 2007) is in line with the IUCN resolutions, although the Spanish law was published previously. In article 27 of this law, the natural protected areas take in national territories, continental water and marine territorial waters included in the economic zone and the continental shelf, to achieve at least one of these two targets: (a) to contain representative natural elements or systems that are endangered or hold interest from ecological, scientific, scenic, geological or teaching points of view and (b) to be devoted to the protection and maintenance of the biological diversity, geodiversity and the natural and cultural associated resources. Clearly, geodiversity is a key element of the natural diversity represented in NPAs. Yet these natural protected areas were designated according to the old Spanish law for conservation of the natural areas and of the wild flora and fauna (BOE num. 74, March 28, 1989), where natural diversity is held to pertain only to biotic aspects. This means it is necessary to update the patterns for designating natural protected areas in Spain, in view of their current definition.

Conclusions

The northern part of Jaén Province (southern Spain) is a very appropriate zone for studies on geodiversity assessment and the location of the natural protected areas (NPAs), because three main geological domains converge there: the southern part of Central Iberian Zone (Variscan Orogen), the Prebetic (Betic Orogen) and, between them, the Guadalquivir foreland basin. In addition, it harbours three natural parks, one natural monument and one natural area.

Our study assesses geodiversity following the methodology of Pereira et al. (2013). Several partial geodiversity indices were defined (lithological, geomorphological, palaeontological, pedological, minerals and hydrology). Moreover, this paper proposes the use of a geosite index, based on the consideration that they contain part of the identified geodiversity. The geodiversity index is understood as the sum of all partial indices. It is depicted in a geodiversity index map and in a geodiversity gradient map presenting several hot spots. The maximum values are located mainly in the southern (near Guadalquivir River) and northeastern (Arroyo del Ojanco) sectors. By placing the NPA map with its borders over each of the two above maps, the delimitations can be compared. The first conclusion is that there is an absence of correspondence between the NPAs and the geodiversity hot spots, or areas with a high to very high geodiversity index.

However, considering only the maps of endangered species index and biodiversity index, a good correspondence between the bordering of NPAs and the high or very high values of both biological indices is detected. To confirm this result, a correlation analysis was carried out, calculating the Pearson coefficient between these two indices and the geodiversity index. Again, there was a lack of correlation.

The results of our analysis are not in concordance with the present-day bordering of NPAs defined under former (now-revoked) laws regarding nature conservation. In light of this finding, a revision of the boundaries of these NPAs should be undertaken. Furthermore, areas with a higher concentration of geosites, and even isolated geosites, should be considered as natural protected areas.

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References

Araujo AM, Pereira DI (2018) A new methodological contribution for the geodiversity assessment: applicability to Ceará State (Brazil). Geoheritage 10:591–605. https://doi.org/10.1007/S12371-017-0250-3

Brilha J, Gray M, Pereira DI, Pereira P (2018) Geodiversity: an integrative review as a contribution to the sustainable management of the whole of nature. Environ Sci Policy 86:19–28

Carcavilla L (2012) Geoconservación. Catarata, Madrid

Carcavilla L, López-Martínez J, Durán-Valsero JJ (2007) Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con los espacios naturales protegidos. IGME, Madrid

Consejería de Agricultura (2005) Mapa Edafológico de Andalucía a escala 1:400,000. www.juntadeandalucia.es/agriculturaypesca/gdpu/

Consejería de Medio Ambiente (2005) REDIAM: Mapa Geomorfológico de Andalucía a escala 1:400,000. www.juntadeandalucia.es/medioambiente/rediam

Consejería de Medio Ambiente and Consejería de Obras Públicas y Transportes (2005) Atlas de Andalucía, vol 2. Junta de Andalucía, Sevilla

Cottle R (2004) Linking geology and biodiversity. English Nature research reports. English Nature, Peterborough

Forte JP (2014) Avaliação quantitative da geodiversidade: desenvolvimento de instrumentos metodológicos com aplicação ao ordenamento do territorio, PhD Thesis, Universidade do Minho

Forte JP, Brilha J, Pereira DI, Nolasco M (2018) Kernel density applied to the quantitative assessment of geodiversity. Geoheritage 10:205–2017

Gordon JE, Barron HF, Hanson JD, Thomas MF (2012) Engaging with geodiversity—why it matters. Proc Geol Assoc 123:1–6

Gordon JE, Crofts R, Díaz-Martínez E, Woo KS (2018) Enhancing the role of geoconservation in protected area management and nature conservation. Geoheritage 10:191–203. https://doi.org/10.1007/s12371-017-0240-5

Gray M (2004) Geodiversity: valuing and conserving abiotic nature. Wiley-Blackwell, London

Gray M (2008) Geodiversity: developing the paradigm. Proc Geol Assoc 119:287–298

Gray M (2013) Geodiversity: valuing and conserving abiotic nature, 2nd edn. Wiley-Blackwell, London

Gray M (2018) Geodiversity: the backbone of geoheritage and geoconservation. In: Reynard E, Brilha J (eds) Geoheritage. Elsevier, Amsterdam, pp 13–26

Hengl T (2006) Finding the right pixel size. Comput Geosci 32:1283–1298

Huggett RJ (1995) Geoecology: an evolutionary approach. Routledge, London

IGME and Consejería de Economía, Innovación y Ciencia (2011) Mapa de rocas y minerales industriales de Andalucía a escala 1:400,000. www.juntadeandalucia.es/economiaconocimientoempresasyuniversidad

IUCN (2008) Resolutions and recommendations adopted at the 4th IUCN World Conservation Congress. Resolution 4040: conservation of geodiversity and geological heritage. IUCN, Gland, Swiss. Available at https://portals.iucn.org/library/node/44190

IUCN (2012) Resolutions and Recommendations, World Conservation Congress, Jeju, Republic of Korea. Resolution 5048: valuing and conserving geoheritage within the IUCN Programme 2013-2016. IUCN, Gland, Swiss. Available at: http://portals.iucn.org/library/node/44015

IUCN (2016) Resolutions and recommendations, World Conservation Congress, Hawaii, USA. Resolution 6083: conservation of moveable geological heritage. IUCN, Gland, Swiss. Available at: https://portals.iucn.org/library/node/46500

Jenks GF (1967) The data model concept in statistical mapping. International Yearbook of Cartography 7:186–190

Larrea FJ, Santisteban JI, Cueto LA, Quesada C, Fernández-Ruiz FJ, Martín-Serrano A (2013) Mapa Geológico de España, escala 1:50.000, 2ª serie (MAGNA). Hoja n° 904 Andújar. Instituto Geológico y Minero de España, Madrid. www.igme.es

Lillo FJ, Pieren A, Hernández-Samaniego A, Ólive-Davo A, Carreras Suárez F, Gutiérrez-Marco JC, Sarmiento GN, Fernández-Remolar DC (1998) Mapa Geológico de España, escala 1:50.000, 2ª serie (MAGNA). Hoja n° 862 Santa Elena. Instituto Geológico y Minero de España, Madrid. www.igme.es

Martínez-Catalán JR, Martínez-Poyatos D, Bea F (2004) Zona Centroibérica. In: Vera JA (ed), Geología de España, SGE-IGME, pp 68–133

Matthews TJ (2014) Integrating geoconservation and biodiversity conservation: theoretical foundations and conservation recommendations in a European Union context. Geoheritage 6:57–70

Nieto LM (2001) Geodiversidad: propuesta de una definición integradora. Bol Geol Min 112:3–12

Panizza M (2009) The geomorphodiversity of the dolomites (Italy): a key of geoheritage assessment. Geoheritage 1:33–42

Parks KE, Mulligan M (2010) On the relationship between a resource based measure of geodiversity and broad scale biodiversity patterns. Biodivers Conserv 19:2751–2766. https://doi.org/10.1007/s10531-010-9876-z

Peña L, Monge-Ganuzas M, Onaindia M, Fernández de Manuel B, Mendía M (2017) A holistic approach including biological and geological criteria for integrative management in protected areas. Environ Manag 59:325–337

Pereira DI, Pereira P, Brilha J, Santos L (2013) Geodiversity assessment of Paraná State (Brazil): an innovative approach. Environ Manag 52:541–552

Serrano E, Ruiz-Flaño P (2007) Geodiversidad: concepto, evaluación y aplicación territorial. El caso de Tiermes Caracena (Soria). Boletín de la AGE 45:79–98

Silva JP, Pereira DI, Aguiar AM, Rodrigues C (2013) Geodiversity assessment of the Xingu drainage basin. Journal Maps 9(2):254–262

Silva JP, Pereira DI, Rodriguez C (2015) Mapping and analysis of geodiversity indices in the Xingu River basin, Amazonia, Brazil. Geoheritage 7:337–350

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Geol Soc Am Bull 63(11):1117–1142

Strahler AN (1957) Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union 38(6):913–920

Tukiainen H, Bailey JJ, Field R, Kangas K, Hjort J (2016) Combining geodiversity with climate and topography to account for threatened species richness. Conserv Biol 31:364–375. https://doi.org/10.1111/cobi.12799

Vera JA, Martín-Algarra M (2004) Cordillera Bética y Baleares. Rasgos General. Divisiones mayores y nomenclatura. In: Vera JA (ed) Geología de España. SGE-IGME, pp 348–350

Zwoliński Z, Najwer A, Giardino M (2018) Methods for assessing geodiversity. In: Reynard E, Brilha J (eds) Geoheritage. Elsevier, Amsterdam, pp 27–51