



Assessment of Geodiversity at the Confluence of Different Geological Domains and Delimitation of Natural Protected Areas (Examples from Southern Spain)

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Abstract

Geodiversity and biodiversity have been assessed in an area of the province of Jaén (Southern Spain), the first one from the consideration of partial indices based on lithology, geomorphology, pedology, hydrology, palaeontology, mineralogy and geosites; biodiversity is also regarded from previous data, considering a biodiversity index and endangered species index. This area shows the contact between the Guadalquivir Basin and the Betic External Zones. In addition, several natural protected areas have been defined, among which the Cazorla, Segura and Las Villas Natural Park (where mainly Prebetic materials outcrop) and the Sierra Mágina Natural Park (made up of Subbetic materials) stand out. The high and very high values of geodiversity have been located in an area where mainly Subbetic materials outcrop, including the Sierra Mágina Natural Park, and which coincides to a large extent with the front of the Betic External Zones and its contact with the Guadalquivir Basin. However, the Cazorla, Segura and Las Villas Natural Park is outside this area of high or very high geodiversity. Both natural parks fit well in areas where biodiversity and endangered species are important. These differences between the geodiversity values and the boundaries of these natural areas allow suggesting that, for delimitation of any natural protected area, its boundaries should be defined based on knowledge of the geodiversity and biodiversity of the region where the natural area is located.

Keywords Geodiversity · Biodiversity · Geodiversity gradient · Natural protected area

Introduction

Geodiversity is a term used as analogue to biodiversity, but the development of both concepts has been very different. In fact, the delimitation of natural protected areas (NPAs) has generally been supported on the concept of biodiversity and associated terminology (ecosystems, habitats, protected species, endangered species). The need to consider geodiversity when defining or managing NPAs gained importance especially from the 2008 and 2012 Congresses of the International Union for Conservation of Nature (IUCN), where resolutions 4.040 and 5.048,

respectively, highlighted that geodiversity is part of nature and that geological heritage is an element of natural heritage, on an equal order that biodiversity is. Recently, Worboys et al. (2019) have edited a book on the management of protected natural areas where biodiversity, geodiversity and geological heritage are considered as basic elements in NPA management protocols, nature conservation and socioeconomic development of the region in which they are located. In this sense, Santos et al. (2020) and Gordon et al. (2022ab) indicate that the consideration of geodiversity and geoheritage should be key topics in nature conservation strategies. The identification of the geological values of a region, together with its risk of degradation, makes it possible to carry out zonation of the territory in order to propose specific management measures for each area considered. Thus, geodiversity, in which representative and unique elements of the analysed region are regarded, could be a first criterion for ranking the territory, once its valuation is known. On the other hand, geological heritage, made up of inventoried geological elements with

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specific values (scientific, educational, cultural, touristic, etc.), could also be a good tool for the establishment of such zonation and prioritisation of the territory. Depending on the values that each geological element possesses, specific protocols for use and management could be established, the ultimate aim of which would be to conserve, in the best possible way, the state of these sites. In this sense, Schrodtt et al. (2019) proposed the concept of essential geodiversity variables (EGVs) as abiotic processes that are relevant to the knowledge of natural resources, human well-being and ecosystem quality, complementing other essential biological variables.

The consolidation of the geodiversity concept in the nature conservation domain is related to the definition of sustainable development (www.un.org/sustainabledevelopment). This led geology to adopt a perspective focused on the relationship between the human being and the environment, especially in the sustainable use of natural resources, avoiding and preventing natural hazards and minimising the degradation of nature (Carcavilla et al. 2007; Reynard et al. 2009; Panizza 2009; Pellitero et al. 2011; Cameron 2022; Pereira Balaguer et al. 2022).

Geodiversity is an intrinsic property of the territory that makes it possible to establish the variability in the geological features (materials and processes) that characterise it (Nieto 2001; Gray 2004; Panizza 2009; Brilha 2016; Brilha et al. 2018). It is embodied in certain tangible geological elements (outcrops, geofoms, grouping of geological elements). These tangible and discrete elements should not be studied in isolation, but by attending to their interrelationships, which leads to the analysis of geodiversity at very different scales, from the global (continents and oceans) to the elemental (atoms and ions) (Alahuhta et al. 2018; Brilha et al. 2018; Gordon et al. 2022a, b; Gray 2013, 2018, 2019, 2021). This has involved the development of several geodiversity assessment procedures. Among them, the most objective is based on the consideration of diverse geological elements, each of them arranged in a layer of a geographic information system (GIS; Pereira et al. 2013; Silva et al. 2013, 2015; Araujo and Pereira 2018; Fernández et al. 2020). Regardless of the different geodiversity valuation procedures, they all seek to achieve several objectives, such as the sustainability of economic activities carried out in the territory, territorial planning, complementing environmental information, delimiting geosites and/or geoparks and proposing strategies for the use and management of the two latter (Kuleta 2018).

Just as biodiversity provides ecosystem services, geodiversity supplies a series of geosystem services that support anthropogenic activity and are closely related to biodiversity (Gray 2004, 2013). An important tool for developing these services is the valuation of the geodiversity from the perspective of the EGV and biodiversity of the territory analysed. Therefore, areas with special value that may require

specific action protocols (management and conservation) can be delimited.

The goal of this research is to analyse the role of geodiversity as part of the natural environment and to understand its function in the delimitation of natural protected areas (NPAs) together with biodiversity, seeking to achieve the goals outlined by Kuleta (2018). For this purpose, these features will be analysed in the southern and eastern part of the province of Jaén, where the Sierra Mágina Natural Park (SMNP) and Cazorla, Segura and Las Villas (CSVNP), among other NPAs, are located. To achieve this objective, geodiversity in the studied area will be evaluated using GIS tools; the distribution of biodiversity (defining a biodiversity index) and endangered species (endangered species index) will be considered; the correlation between the different indices of geodiversity and biodiversity will be analysed and possible geodiversity hot spots (in the sense of Gray 2013) in this area will be delimited, as well as their relationship with the delimitation of the NPAs already defined.

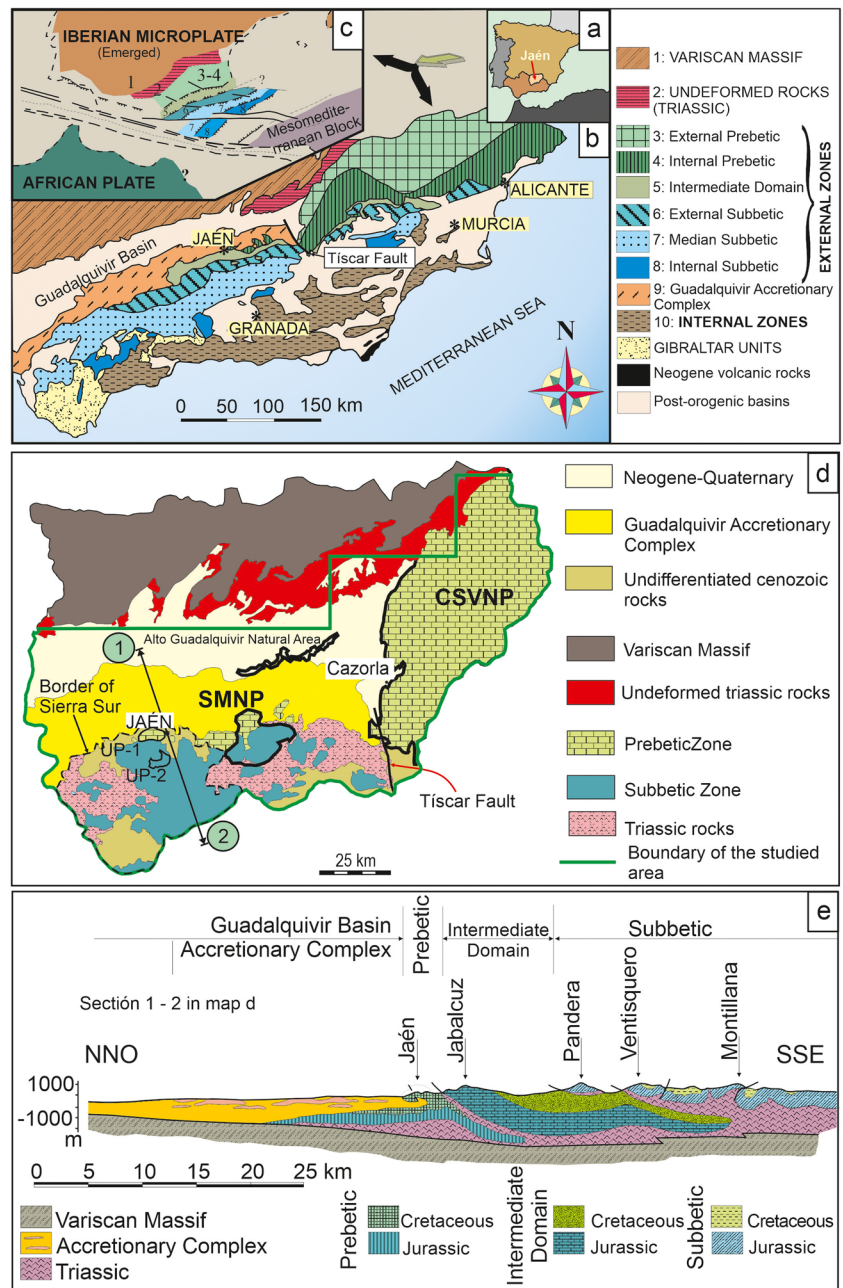
Geological Setting

The area under study belong to the province of Jaén (Fig. 1a, b, c, d), where three major geological domains can be distinguished. From north to south, are the Variscan Massif (geographically represented by Sierra Morena), the Guadalquivir Basin (represented by the valley of the same river) and the Betic External Zone (BEZ), which extends to the east and south of the Guadalquivir Basin (Ruiz-Ortiz et al. 2001; Vera 1994; Vera and Martín-Algarra 2004). The geodiversity of the former was analysed in Fernández et al. (2020), so it will not be discussed in the present research, limiting the area covered to the southern and eastern sectors of the province (Fig. 1d), which comprise the BEZ and the Guadalquivir Basin (Fig. 1b, d, e).

The Guadalquivir Basin is mainly made up of marls, marlstones and sandstones from the Upper Miocene to Pliocene, although over these materials there is a great diversity of continental sediments and sedimentary rocks of Pleistocene and Holocene (Vera and Martín-Algarra 2004). From a structural perspective, two large units can be distinguished in this geological domain, to the north, the Autochthonous Unit and, to the south of the former, the Accretionary Complex (Pérez-Valera et al. 2017). The Autochthonous Unit is composed of materials from the Upper Miocene to Pliocene, not deformed, discordantly over the underlying units (igneous and/or metamorphic rocks of the Variscan Massif, Triassic undeformed rocks and materials of the Accretionary Complex; Fig. 1b, d). To the south, in the mountainous front of the BEZ, the Guadalquivir Accretionary Complex (Pérez-Valera et al. 2017) is disposed, formerly called Olisthostromic Unit (see, for example Vera and Martín-Algarra 2004). The Accretionary Complex forms a large oblique prism, which has its

Fig. 1 Geographical and geological situation of the province of Jaén and the studied area.

a Geographical location. **b** Geological sketch of the Betic Cordillera. **c** Palaeogeographical reconstruction of the South Iberian Palaeomargin in the Late Jurassic. **d** Geological sketch of the province of Jaén. The contours of the different natural areas considered in this document have been drawn. CSVNP, Cazorla, Segura and Las Villas Natural Park; SMNP, Sierra Mágina Natural Park; UP-1, Santa Catalina Periurban Park; UP-2, Monte de la Sierra Periurban Park. **e** Geological Section 1–2 marked in **d** showing the structural relationships between the different geological domains considered in the studied area



continuity throughout the Betic-Rif Orogen; it consists of Miocene sediments, Triassic evaporitic units and Cretaceous marls and marly limestones, which were accreted during the westward displacement of the Alborán Domain (Pérez-Valera et al. 2017). From a regional perspective, the Guadalquivir Basin is considered as the foreland basin to the Betic Orogen.

The BEZ is part of the Betic Orogen, whose paroxysmal stage took place between the late Burdigalian and early Tortonian (Vera and Martín-Algarra 2004). Two large tectonopalaogeographic units can be distinguished, the Prebetic to the north, and the Subbetic, to the south of the former (Fig. 1). In the province of Jaén, the Prebetic is

represented by the Cazorla, Segura and Las Villas mountain ranges, as well as by a series of isolated reliefs to the west of the Tíscar Fault and in the south of the city of Jaén. The Subbetic (Fig. 1) is located in the southern part of the province and always to the west of the Tíscar Fault (Fig. 1d). Representative reliefs of this tectonopalaogeographic domain are the Jabalcuz, La Pandera, El Ventisquero, Montillana, Mágina, Almadén and all the reliefs that make up the region called Sierra Sur de Jaén (Fig. 1d, e).

The rocks that crop out in the Prebetic are limestones deposited in a shallow platform developed in the Palaeomargin of the Iberian Microplate (Fig. 1c). The age of these

materials is mainly Jurassic and Cretaceous, although occasionally materials up to the Miocene have been recognised (Vera 1994; Vera and Martín-Algarra 2004; Ruiz-Ortiz et al. 2001; Nieto et al. 2010). An important part of these limestones was dolomitised in late stages of the evolution of the mountain range. The Meso-Cenozoic sequence is disposed on continental materials from Triassic, which can be correlated with the Triassic undeformed rocks, discordant on the Palaeozoic rocks of the Variscan Massif.

The Subbetic is made up of Jurassic and Cretaceous materials, although others from the Palaeocene-Oligocene and even Lower Miocene have been occasionally recognised. We can also find Triassic materials with Muschelkalk and Keuper facies, the latter being the ones with the greatest surficial extension (e.g. Ruiz-Ortiz et al. 2001; Vera and Martín-Algarra 2004).

The most representative materials of the Subbetic are dolostones of diagenetic origin and several types of limestones, marly limestones and marls, both Jurassic and Cretaceous. This diversity of carbonates, together with a complex stratigraphy, where several unconformities and a piggyback structure are found (Vera and Martín-Algarra 2004), has allowed us to recognise different tectonopalaeogeographic subunits, characterised by particular sedimentary dynamics during the Mesozoic, called, from north to south, the Intermediate Domain, External Subbetic, Median Subbetic and Internal Subbetic (Fig. 1b, e).

Geomorphological Setting

In the studied region, the geomorphological features are controlled by lithology and/or tectonics (Gutiérrez-Elorza 1994). In the Guadalquivir Basin, the geomorphological features are different depending on whether the Autochthonous Unit or the Accretionary Complex is considered. In the former, with horizontal materials, lithological control predominates, giving reliefs in table hills (mesas) due to the greater resistance to erosion presented by thicker sandstone levels, which are arranged on clayey, silty or marl rocks. In the Accretionary Complex, the geomorphological control is related to the lithology and the thrust structures. In general, there is a hilly relief that, irregularly, shows escarpments and slopes related to the appearance of blocks of limestone materials, of Muschelkalk facies or Jurassic limestones. The dynamic of the Guadalquivir river and its tributaries model all these geomorphological features, reinforcing them on many occasions due to erosive processes, especially in the upper part of its hydrographic basin which is located in the Prebetic (eastern part of the province of Jaén, Fig. 1b, d), or softening it due to sedimentation of both fluvial bars and silts in the floodplain, in the western part of the considered area (Gutiérrez-Elorza 1994).

In the BEZ, geomorphology is also controlled by lithology and geological structures, large folds and thrusts (op.

cit.). In the Prebetic, where there are important volumes of carbonates, morphologies due to the presence of large folds (slopes, valleys squeezed between consecutive anticlines) are superimposed by a strong development of endo- and exo-karstic morphologies (karrens, dolines, sinks, caves). In the Subbetic, the geomorphological controls are similar to those of the Prebetic, but the important volumes of marls and marly limestones, together with the presence of several fault systems that cut the different tectonic units, favour the development of wide valleys among which strong reliefs made up of dolostones and limestones from the Jurassic stand out. In the latter, several karstic structures are also developed.

Main Natural Protected Areas: the Natural Parks

Cazorla, Segura and Las Villas Natural Park (CSVNP)

The Cazorla, Segura and Las Villas Natural Park (hereinafter CSVNP) was declared by Decree 10/1986, of 5 February, by the Junta de Andalucía (Regional Government). It is located in the easternmost part of the province of Jaén, bordering the province of Granada and the Autonomous Community of Castilla-La Mancha.

Its surface area is spread over 23 municipalities in the province of Jaén. Its large surface area, making it the largest protected area in Andalusia and the Iberian Peninsula, together with the orographic and geographical diversity that characterise it, determines a wide variability within the natural area itself, ranging from river valley contexts to medium and high mountain areas. From a geological point of view, this protected area is totally immersed in the Prebetic, showing stratigraphic and palaeontological records, structural and geomorphological features characteristic of this geological domain (Fig. 1). These geological features strongly control its bio-environmental properties, so that the presence of several habitats and species of flora and fauna can be noted, making this space one of the areas of ecological interest in the region.

In 1983, it was internationally recognised by its declaration as a Biosphere Reserve within the UNESCO MaB Programme, constituting one of the largest reserves in Spain. This NPA forms part of the European Ecological Network Natura 2000, as established in article 3.1 of the Habitats Directive, and article 42.1 of Law 42/2007, of 13 December, on Natural Heritage and Biodiversity.

Sierra Mágina Natural Park (SMNP)

The Sierra Mágina Natural Park (SMNP) is located to the southeast of the Jaén city (Fig. 1). It covers an area of 19,961 ha. It is located between the Guadalquivir Basin to the north and the Subbetic mountains to the south.

From a geological point of view, the SMNP is located entirely in the Subbetic (Fig. 1). The rocks of which it is composed are different types of carbonates with ages ranging from the Lower Jurassic to the Upper Cretaceous. In view of its structure, made up of large-radius folds and several units superimposed by thrusting, the geomorphology is characterised by large ramps in the upper part of which there is a good development of karst structures. These features mean that the park has peaks of over 2000 m above sea level, which explains that the vegetation is made up of different species at different altitudes.

The prevailing climate, where the humid winds that penetrate through the Guadalquivir Valley reach these carbonate massifs rather weakened, justifies the dominance of sclerophyllous vegetation. The areas of greatest faunistic interest are the high mountain slopes at altitudes of over 1400 m, where birds of prey nest.

The natural park has been designated as a Special Protection Area for Birds (SPA) since 2003, in accordance with Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds. It is part of the European Ecological Network “Natura 2000” established by Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

Materials and Methodology

Materials

The materials used in this research are limited to geological, biological and geographical information, from which the different partial indices of geodiversity and biodiversity will be calculated, as well as the software used for data processing and analysis. Table 1 shows the source of the information used in this document. The geological data comes from the geological maps of the MAGNA50 series, both from the

vector layer resulting from the digitisation and harmonisation of the MAGNA50 sheets (GEODE, Continuous Digital Geological Mapping; <https://info.igme.es/cartografiadigital/geologica/Geode.aspx?language=es>) and from the information shown in the corresponding memories (Table 2 and Fig. 2). ArcGIS software ver. 10.8 has been used to process the original maps and to obtain the maps corresponding to the different indices considered in this paper. In some cases, the Microsoft Excel spreadsheet has been used.

Methodology

The methodology is based on the proposed by Pereira et al. (2013), improved by Silva et al. (2013, 2015), Araujo and Pereira (2018) and Fernández et al. (2020). The geodiversity index (Gi) results from the sum of the partial indices: lithological, geomorphological, pedological, minerals, palaeontological, hydrological and geosites. These partial indices can be named as EGV in the sense of Schrodt et al. (2019). Biodiversity and endangered species maps have also been considered and will be compared with the geodiversity index. For all indices, a square grid of 25 km² (5 km × 5 km) was defined in Shapefile format (hereafter SHP), according to the procedure of Hengl (2006). For the studied area, a total of 365 grid squares were obtained.

Geodiversity Index (Gi)

To calculate this index, the partial lithological, geomorphological, pedological, mineralogical, palaeontological, geosites and hydrological indices are added together. The latter is the sum of three sub-indices: hierarchy of river flows, aquifers and precipitation.

Lithologic Index To calculate this partial index, it has been used information from the continuous digital geological cartography at scale 1:50,000 (GEODE) corresponding to

Table 1 Sources and formats of the geospatial information used in this paper. The average rainfalls and endangered species maps have a raster format. They should therefore be characterised by their resolution, 500 × 500 m for the first and 5 × 5 km for the second

Data	Format	Scale	URL
Lithology	Vector	1:50,000	MAGNA50 Series: www.igme.es
Geomorphology		1:400,000	REDIAM: https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam
Pedology		1:400,000	
Mineralogy	–	1:50,000	MAGNA50 Series: www.igme.es
Palaeontology	–	1:50,000	
Geosites	KMZ	–	REDIAM: https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam
River channels	Vector	1:100,000	DERA: https://www.juntadeandalucia.es/institutodeestadisticaycartografia/DERA/index.htm
Aquifers		1:100,000	
Average rainfalls	Raster	–	REDIAM: https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam
Biodiversity	Vector	1:400,000	
Endangered species	Raster	–	

Table 2 Bibliographic data of the MAGNA 50 maps used in this study. All maps have a scale of 1:50,000 and were published by Instituto Geológico y Minero de España (IGME, Spanish Geological Service)

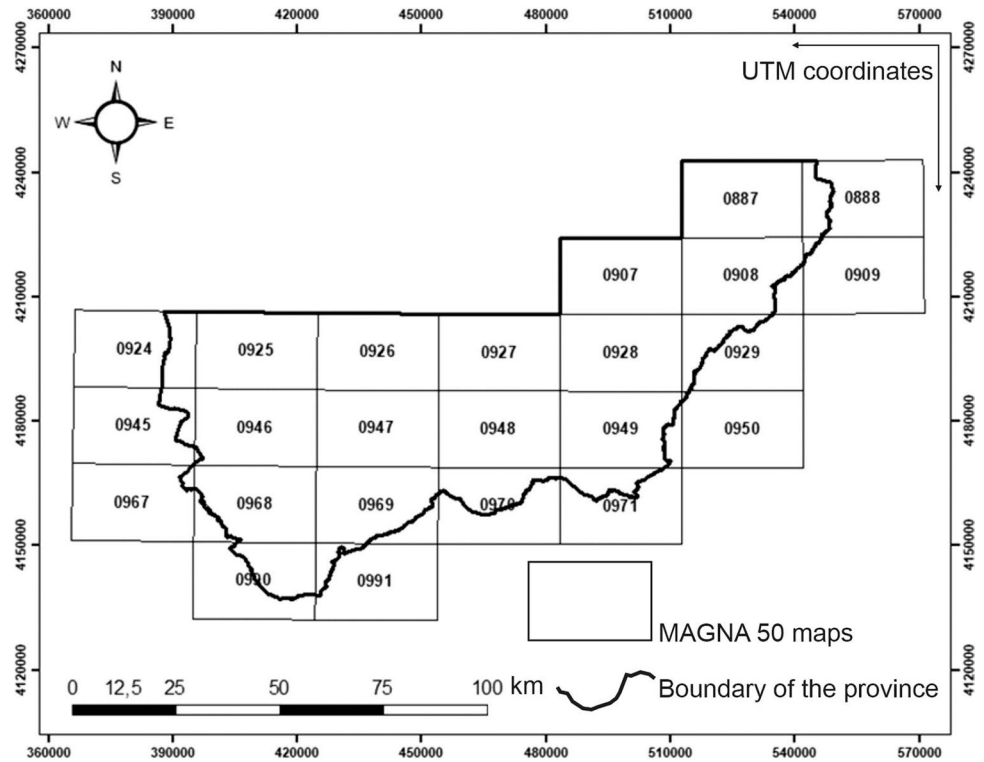
MAGNA50	Authors	Date of publication
887—Orcera	López-Garrido AC, González Donoso J M ^a , Linares A, García Hernández M	1975
888—Yetas de abajo	Jerez Mir L, Abril Hurtado J, Hernández Rodríguez E, Olaverri Capdevila T	1981
907—Villacarrillo	Martínez W, Nuñez A, Cabañas I, Perconig, E, Callejones L, Bretones R, Bárcena F, López J, Guigon I, Grambast L	1974
908—Santiago de la Espada	Dabrio C J, González Donoso J M ^a , Linares A, García Hernández M	1975
909—Nerpio	López-Garrido AC, Dabrio C J, Granados Granados LF, Trinidad del Pan Arana	1979
927—Baeza	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Jerez Mir L, Rodríguez Fernandez J, Donoso JM, Linares Rodríguez D, Serrano Lozano F, Martínez Gallego, J, Granados Granados L, Aguado Merlo R, Martín Pérez JA, Serrat Congost D and García Cortés A	1991
928—Cazorla	García Cortes A, Trio Maseda M, García Hernández M, López Garrido AC, Aguilar Ortiz P, Esteban Arlegui, J	1994
929—San Clemente	Fernández-Gianotti J, Lupiani Moreno E, Roldán García FJ, Villalobos Megía M	2007
945—Castro del río	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Rodríguez Fernández J, González Donoso JM, Linares Rodríguez D, Serrano Lozano F, Martínez Gallego, J, Aguado Merlo R, Martín Pérez JA, Serrat Congost D and García Cortés A	1992
946—Martos	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Jerez Mir L, Rodríguez Fernandez J, Donoso JM, Linares Rodríguez D, Serrano Lozano F, Martínez Gallego, J, Granados Granados L, Aguado Merlo R, Martín Pérez JA, Serrat Congost D and García Cortés A	1991
947—Jaén	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Jerez Mir L, Rodríguez Fernandez J, González Donoso JM, Linares Rodríguez D, Serrano Lozano F, Martínez Gallego, J, Granados Granados L, Aguado Merlo R, Martín Pérez JA, Serrat Congost D and García Cortés A	1991
948—Torres	Aguilar M, Alvaro M, Del Olmo P, Hernández-Samiengo A, Ramírez del Pozo J, Soler M, Ruiz Roig P and García Cortés A	1991
949—Pozo Alcón	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Contreras López E, Martín Penela A, Martín Pérez JA, Aguado Merlo R, Bouchra El Mamoune, Hidalgo Ruíz J and Fernández-Gianotti J	2006
950—Huéscar	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Contreras López E, Martín Penela A, Martín Pérez JA, Aguado Merlo R, Bouchra El Mamoune, Hidalgo Ruíz J and Fernández-Gianotti J	2006
967—Baena	Roldán García FJ, Ruiz Ortiz PA, Molina Cámara JM, Rodríguez Fernández J, González Donoso JM, Linares Rodríguez D, Serrano Lozano F, Martínez Gallego J, Ruiz López JL, Garrido Megías A, Zazo Cardeña C, Goy Goy JL, Banea Pérez J and García Cortés A	1988
968—Alcaudete	García Cortes A, Trio Maseda M, Rodríguez Fernandez J, Ruiz Ortiz PA, Molina Cámara JM, Aguilar Ortiz P, Cabañas Lozano I, González Donoso JM, Linares Rodriguez D, Serrano Lozano F, Mansilla Izquierdo H and Quintero Amador I	1992
969—Valdepeñas de Jaén	Ruiz Reig P, Díaz de Neira JA, Enrile Albir A, Hernaiz Huerta PP, López Olmedo F, González Lastra J, Zamorano Cáceres M, Aguilar P, Ramírez del Pozo J, Díaz de Federico A and Puga Rodríguez E	1991
970—Huelma	Ruiz Reig P, Díaz de Neira JA, Enrile Albir A, López Olmedo F, González Lastra J, Zamorano Cáceres M, Ramírez del Pozo J, Díaz de Federico A, Puga Rodríguez E, Centeno J and Fernández, P	1991
971—Cuevas del Campo	Roldán García FJ, Lupiani Moreno E, Villalobos Megía M, Hidalgo Ruíz J, Mingorance S, Sánchez Carretero R, Martín Penela A, Serrano Lozano F, Martín Pérez JA, Aguado Merlo R, Bouchra El Mamoune, Torres Pérez-Hidalgo T and Fernández-Gianotti J	2009
990—Alcalá la Real	Ruiz Reig P, Díaz de Neira JA, Enrile Albir A, Hernaiz Huerta PP, López Olmedo F, González Lastra J, Zamorano Cáceres M, Aguilar P, Ramírez del Pozo J, Díaz de Federico A and Puga Rodríguez E	1991
991—Iznalloz	Díaz de Neira JA, Enrile Albir A, López Olmedo F, Hernaiz Huerta PP, González Lastra J, Zamorano Cáceres M, Aguilar P, Ramírez del Pozo J, Rivas P, Díaz de Federico A, Puga Rodríguez P, Centeno J, Fernández P and Ruiz Reig P	1991

the digitisation of the geological maps at scale 1:50,000 (MAGNA) (Table 2; Fig. 2), published by the Geological Survey of Spain (Spanish named as IGME; Table 1). In order to obtain this index, an analysis was made of all the lithologies collected in them and they were grouped by age

in order to define homogeneous lithological units for the studied area (Fig. 3).

On the previous map (Fig. 3), the preliminary defined grid was superimposed and the number of lithologic units per grid square was counted according to the procedure described in

Fig. 2 Map with the grids corresponding to the MAGNA50 used in the studied area (see Table 2)



Fernández et al. (2020). As a result, the lithological index of that grid square is obtained (Fig. 4a). The numerical indices found were grouped according to the natural breaks classification method of Jenks (1967), establishing five classes: very low (1), low (2), medium (3), high (4) and very high (5), shown in each of the maps of the partial geodiversity indices (Fig. 4) and in the map of geodiversity index (Fig. 5a).

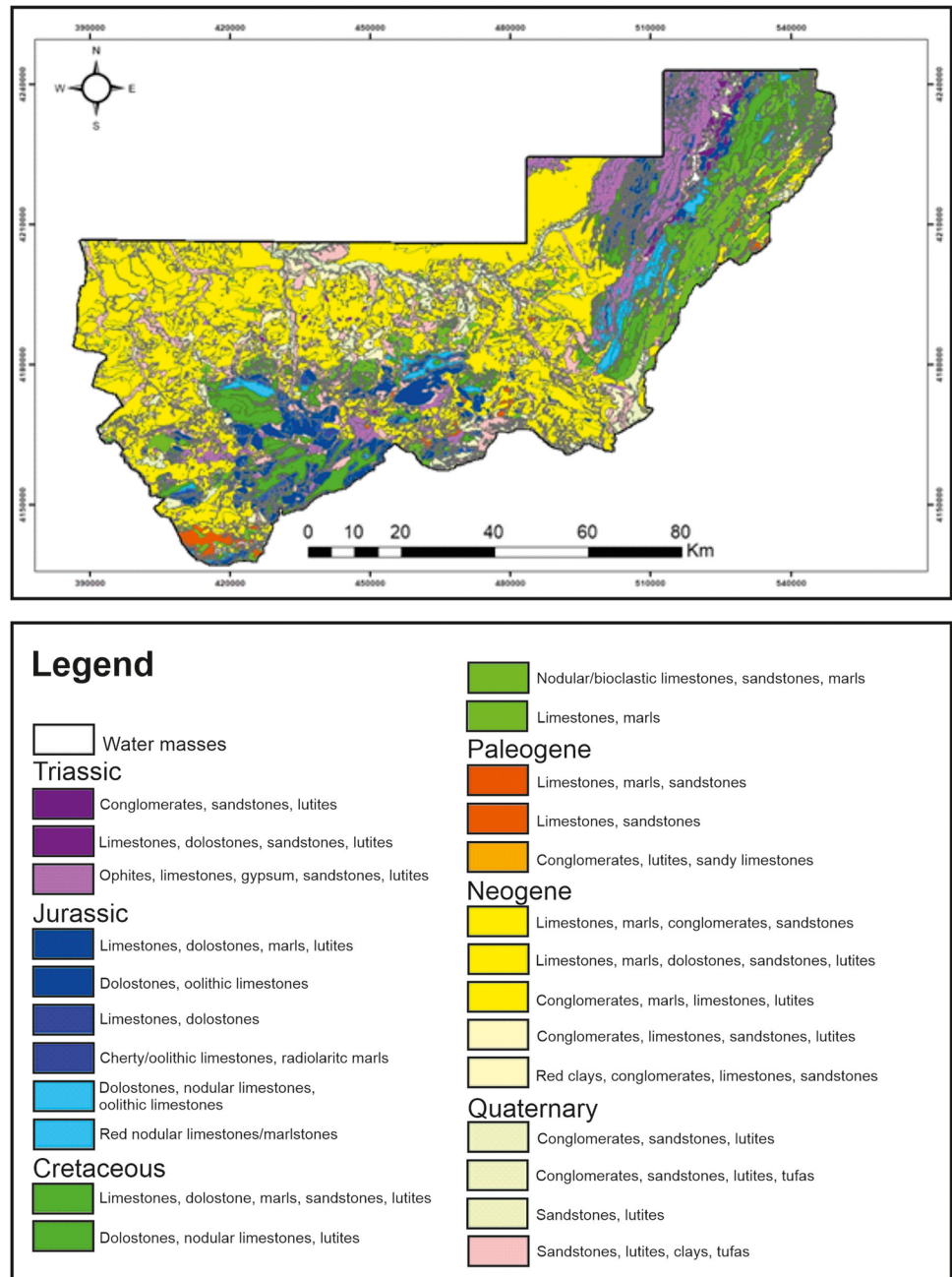
Geomorphologic Index The calculation of this index was based on the map of geomorphological and physiographic units of Andalusia at a scale of 1:400,000 (Table 1). This map has been made from the compilation of geomorphological maps of the MAGNA50, fit with LANDSAT images. The procedure followed is similar to that shown for the lithological index. Once the map is obtained, the defined grid is superimposed and the geomorphological units appearing in each square of the grid are counted. The numerical index per square is thus obtained (Fig. 4b). Finally, five grades are established for this index.

Pedologic Index The starting point was the soil map of Andalusia, at a scale of 1:400,000, published by the Regional Ministry of the Environment in 2005, which was designed based on the one made in 1989 by the Regional Ministry of Agriculture and the Spanish National Research Council (CSIC in Spanish) (Table 1). The soils were represented as cartographic units classified according to the 1974 FAO criteria and the 1985 European Union Soil Map. The index has been

calculated in a similar way as in previous indices, i.e. counting how many different soil units there are in each square of the grid (Fig. 4c) and then differentiating five relative orders.

Hydrology Index This index is defined as an indicator of the diversity of water resources in a territory (Fernández et al. 2020). This index results from the sum of three sub-indices: (a) hierarchy of river channels; (b) aquifers and (c) average annual precipitation, which are interconnected. Table 1 shows the URLs from which the data needed to calculate this index were obtained. The hierarchy of river channels is conditioned by the lithologies on which they develop (Gutiérrez-Elorza 2008; Araujo and Pereira 2018; Fernández et al. 2020). In consequence, river courses that run on lithologies that are very resistant to erosion, as limestones, dolostones and sandstones, will have a lower hierarchy than those that are arranged on materials that are not very resistant to erosion, as lutites, gypsum and sands. The aquifer sub-index is related to the permeability of the rocks and the average annual rainfall; the greater the permeability of the rocks, the greater the infiltration and, therefore, the scarcer and lower ranked the river channels. On the contrary, if the rocks are not very permeable, infiltration will be lower, which will mean less development of aquifers and greater hierarchy of the fluvial network. Finally, the precipitation sub-index allows us to estimate the available amount of water that will infiltrate into aquifers or be transported by surface runoff (Araujo and Pereira 2018; Fernández et al. 2020; Cameron

Fig. 3 Map of lithological units in the studied area. This map is composed from the MAGNA50 sheets shown in Fig. 2



2022). The three partial indices are also classified and then the hydrology index is calculated with the sum of the 3 sub-indices described above, considering as values the classification levels obtained in them; and finally, as in the rest of the indices, the hydrology index was also classified into 5 classes (Fig. 4d), according to Jenks' method.

Minerals Index The minerals index was calculated from the position of the different mineral deposits located in each of the MAGNA maps (Fig. 2, Table 2) and their location into the squares of the considered grid. For this purpose, a file was generated in SHP format of vector entities of points corresponding

to the mineral deposits. Once this file was created, the methodology described for previous indices was applied and the number of mineral deposits in each square was established (Fig. 4e). Finally, the Jenks classification is applied, establishing three orders: low (1), medium (2) and high (3).

Palaeontological Index The calculation of this index is based on considering the lithological units with presence of macrofossils (invertebrates and/or vertebrates) according to the descriptions that can be found in the explanatory reports of each of the maps of the MAGNA50 series (Fig. 2, Table 2). The number of genera and species described in these reports

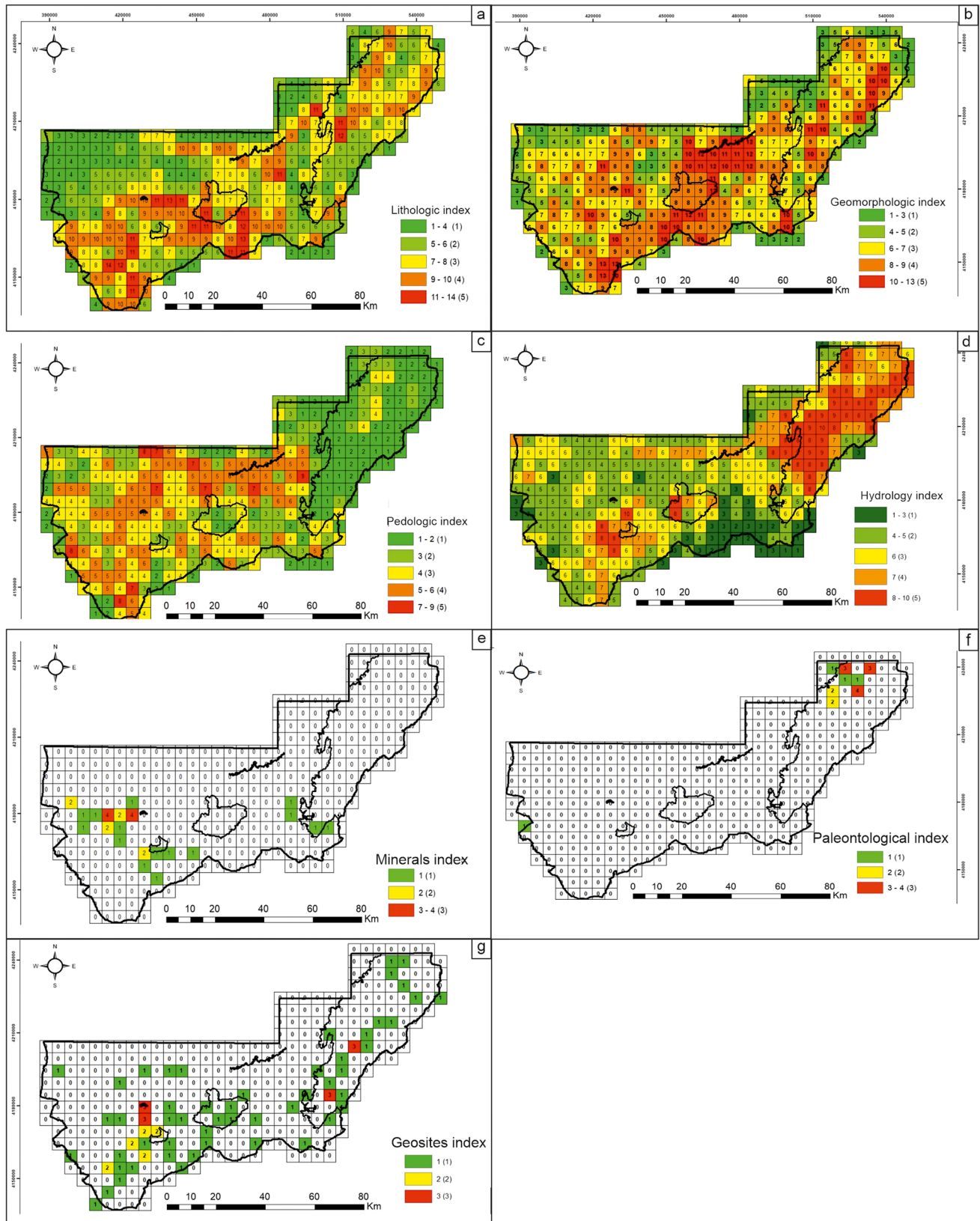
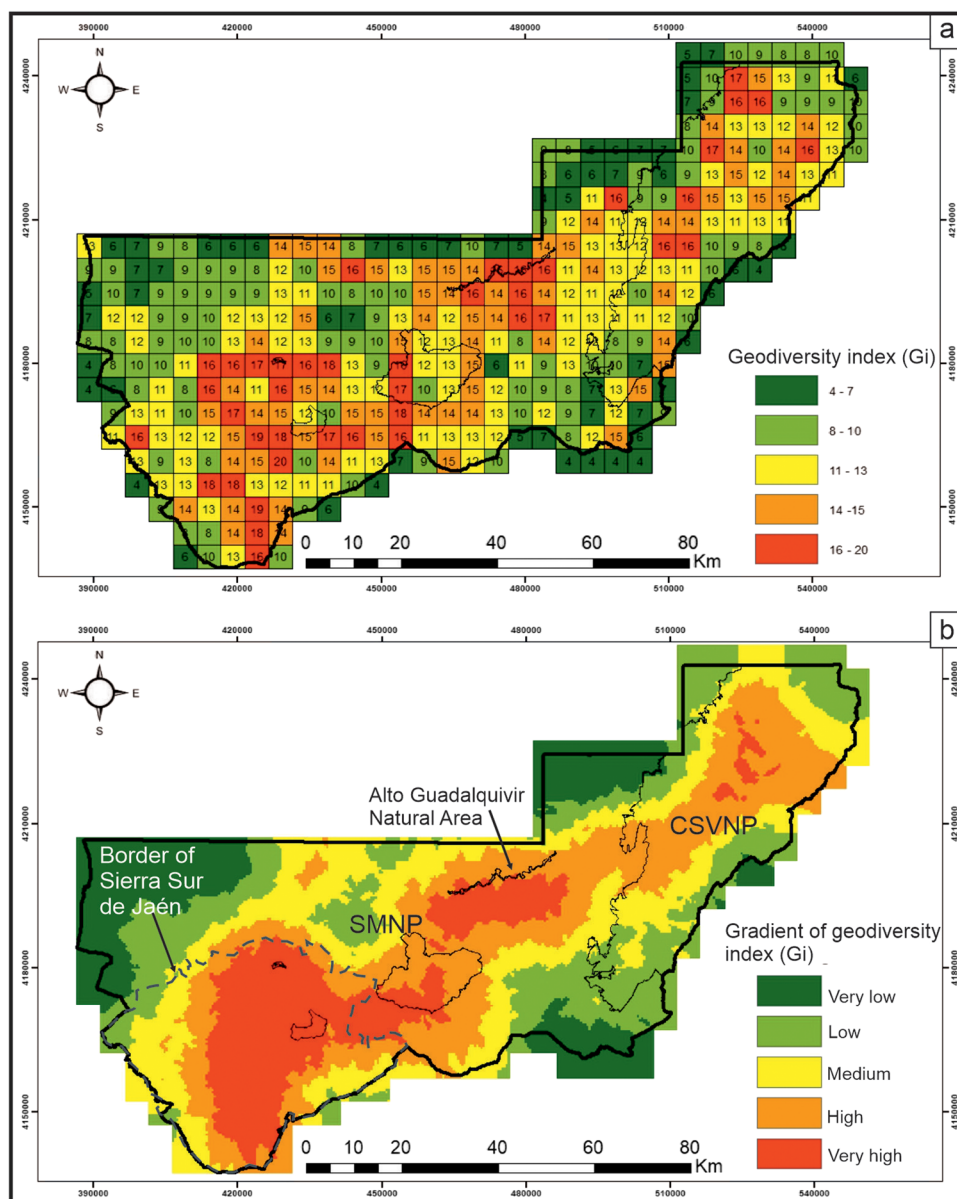


Fig. 4 Maps of partial geodiversity index: **a** lithologic index, **b** geomorphologic index, **c** pedologic index, **d** hydrology index, **e** minerals index, **f** palaeontological index, **g** geosites index

Fig. 5 Geodiversity maps. **a** Geodiversity index map according to the 5 km × 5 km grid. **b** Geodiversity gradient map deduced from the previous map applying kriging



has been considered and each site has been identified in the squares of the designed grid. Microfossils have not been contemplated since they are textural components of most of the sedimentary rocks that outcrop in the studied region and, therefore, are not very significant when evaluating them as singular geological elements. As in previous cases, the Jenks classification is applied, establishing 3 categories (Fig. 4f).

Geosites Index This index has been determined from the output vector layer, using as support the Areas of Geological Interest of Andalusia (REDIAM; <https://descargasrediam.cica.es/repo/s/RUR>; Table 1), updated in the Spanish Inventory of Geosites (IELIG in Spanish), developed by the IGME in 2016. The geosites can be consulted from the Google Earth © platform. A total of 100 geosites have been defined in the

province of Jaén. As in previous indices, the procedure to obtain the value of the geosites index is similar, counting the number of geosites per square of the 5 × 5 km² grid (Fig. 4g).

Geodiversity Index (Gi) The geodiversity index (Fig. 5a) is obtained from the sum of the preceding partial indices for each square of the considered grid. Like the partial indices, it will be classified into 5 geodiversity classes according Jenks classification (Fig. 5a). Since geodiversity is a continuous property of the territory, from the geodiversity index map (Fig. 5a) it is applied an interpolation by kriging (Araujo and Pereira 2018) of ordinary type and with Gaussian adjustment, resulting in the geodiversity gradient map (Fig. 5b). The latter shows the spatial and continuous variability of this property. As in previous cases, five classes are defined, very

low gradient, low gradient, medium gradient, high gradient and very high gradient (Fig. 5b).

Biodiversity Indices

In order to design the biodiversity index and the endangered species index (Fig. 6), the starting point was the biodiversity map and the endangered species map drawn up by the Regional Government of Andalusia (Junta de Andalucía) based on data on the biogeographical distribution of animal and plant species (Table 1). Therefore, these initial data have not been obtained by the authors of current research.

On the previous biodiversity and endangered species maps, a square grid of 25 km² has been superimposed. From there, the same methodology of counting biodiversity value/number of endangered species per grid square has been applied as was used to produce the partial geodiversity index maps.

Biodiversity Index The biodiversity map (Table 1) has an original scale of 1:400,000. It was prepared by the Regional Departments of Civil Engineering and Transport and the Environment (2005). It proposes a relative classification in six levels (very low, low, medium, high, very high and not evaluated, the latter coinciding with masses of water; Fig. 6a, c). In order to correlate the biodiversity index obtained with the other indices, the regular 5 × 5 km² grid was superimposed and the relative classification was adjusted to the five levels considered for other indices (Fig. 6a, c).

Endangered Species Index The map of endangered species was founded on the vector map representing the distribution of protected fauna and flora prepared by the Regional Department of Environment (Table 1). To make it alike to other maps, all species were counted and the square grid defined in this research was superimposed (Fig. 6b). From this, we proceeded similarly to that followed for other indices.

Correlation Analysis

The Pearson correlation coefficient (p) between indices has been calculated by means of the corresponding tool (covariance and correlation matrices) of ArcGIS, considering the values of the raster layers of the indices in each grid square. Thus, a population of 365 grid squares is obtained. Then, according to conventional classifications, the correlation coefficient is catalogued as strong (>0.75 in absolute terms); moderate (0.50–0.75); weak (0.25–0.50) and very weak (<0.25). Moreover, a significance analysis is performed by calculating the t -Student (for a two-tailed distribution) and the corresponding p values, considering the population size (Davis 2002; Legendre and Legendre 2012). Two levels of significance are considered depending on whether the p values are lower than 0.01 or 0.05.

Results

Lithologic Index

The values of this index range from 1 to 14, with the highest values located in the southern part of the considered region (Fig. 4a). Thus, values of this index between 8 and 13 have been obtained in an area that approximately coincides with the Sierra Mágina Natural Park (SMNP), with the Sierra Sur de Jaén (both Subbetic) and a little further north in the Cazorla range (Prebetic). The lowest values are concentrated in the northwest of the study area, belonging to the Autochthonous Units of the Guadalquivir Basin.

Geomorphologic Index

This index ranges from 1 to 13, with several areas with very high values. High values are found in the central zone of the studied region, that is to the north of SMNP, but also in the southern part of this natural park; in fact, the highest values are recorded in the southernmost part of the considered area, at the Sierra Sur (Fig. 4b). From the geological point of view, these areas of high or very high geomorphologic index are located in the Prebetic Zone (Prebetic of Jaén and Prebetic of Cazorla, Segura and Las Villas) and the Subbetic Zone (southern part of the province). Areas of high values of this index have also been detected in grids within the Accretionary Complex of Guadalquivir Basin (Fig. 4b).

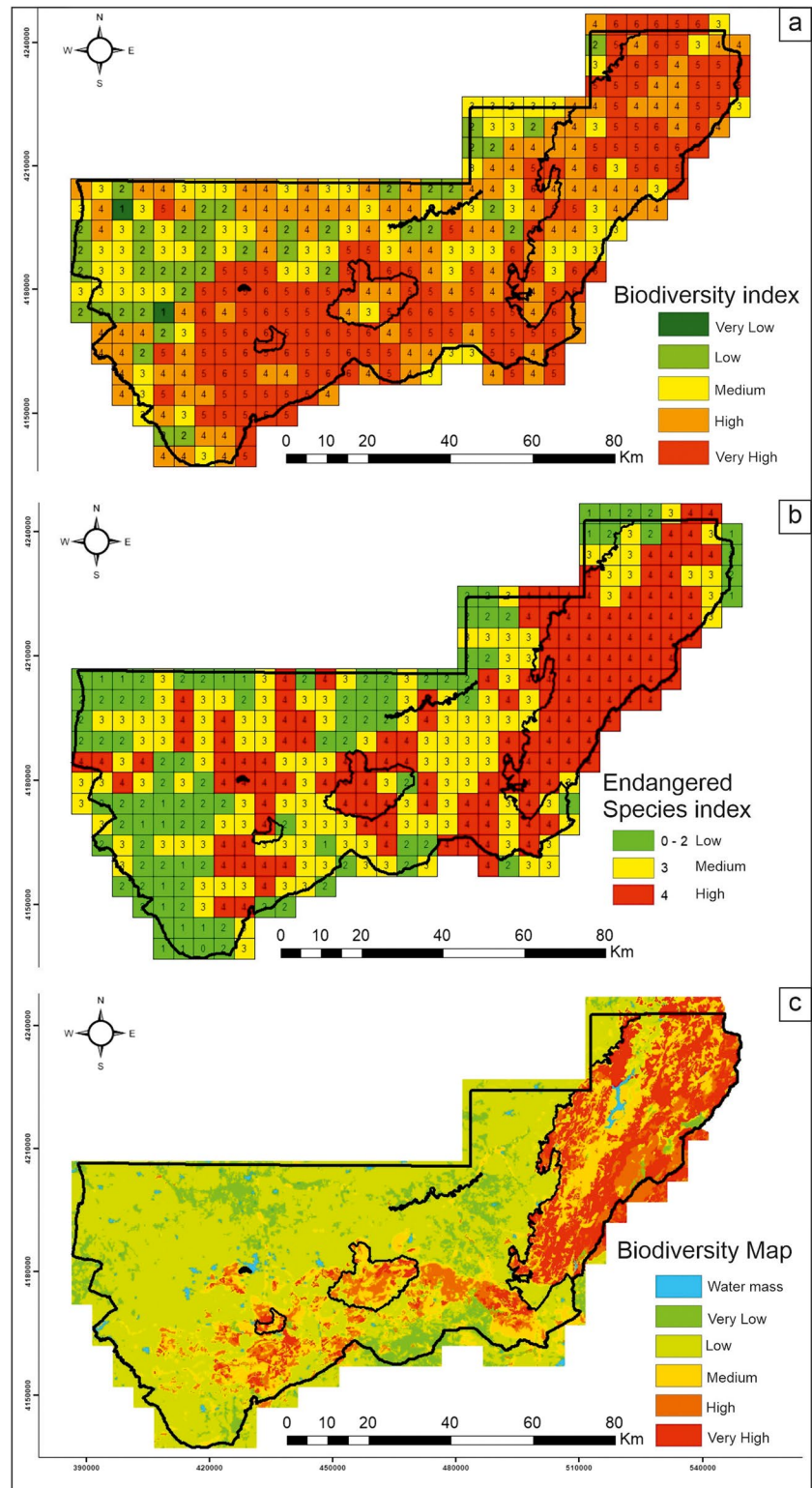
Pedologic Index

The values of this index are generally moderate in the centre of the study area (Fig. 4c), which geologically coincides with the Guadalquivir Basin. In the areas into the Prebetic of the CSVNP (Fig. 4c), the values of the pedologic index are low or very low; however, the highest value coincides with grids located at the limits of the mountain front, as well as with some areas where there is a confluence of geological domains with different types of rocks (carbonates, clastics, lutites).

Hydrology Index

This index has low and medium values in the centre of the studied area (Fig. 4d). The highest values are concentrated in the limits of the CSVNP (Fig. 4d), where there are karst systems belonging to Sierra de Cazorla aquifer that drain towards the Guadalquivir river, together with high precipitation. Also noteworthy is the high value found in the municipality of the provincial capital, where the Jaén and Jabalcuz-La Grana aquifers are located (Fig. 4d).

Fig. 6 Biodiversity maps. **a** Biodiversity index map. **b** Endangered species index map. **c** Biodiversity map from REDIAM (Table 1). From the previous maps **a** and **b**, the 5 km×5 km grid is used



Minerals Index

The values of this index vary from 0 to 4 (Fig. 4e). The highest values are found in the southern and eastern part, where MAGNA maps 946, 949 and 969 (Table 2; Fig. 2)

locate different mineralogical deposits. Besides, highest value of this index is also found in sheets 946 and 947 (Table 2; Fig. 2), related to the location of quarries in marly limestones and marls, which were exploited for concrete and which straddle both sheets, as well as a salt Triassic deposit,

exploited until the nineteenth century as a salt mine for domestic use and other very small exploitations of haematite and limonite also associated to Triassic rocks.

Palaeontological Index

The values of this index vary from 0 to 4 (Fig. 4f), they are relatively low, as for the mineralogical index. Macrofossil deposits are mostly found on sheet 887 (Table 2 and Fig. 2), where different deposits of ammonites, gastropods and other cephalopods are found in the Muschelkalk facies (Triassic).

Geosites Index

The values of this index are generally low, although with a relatively homogeneous distribution in those areas located in the Prebetic or Subbetic (Figs. 1d, 4g). Very high values are found in sheets 928 and 947 (Table 2 and Fig. 2), due to their geomorphological features, since large geological domains converge in them. Thus, close to Jaén city (sheet 947), there is the confluence of the Guadalquivir Basin, the Prebetic of Jaén and the Subbetic (Fig. 1d). In the sheet 928 (Fig. 2 and Table 2), there is the confluence between the Prebetic of the CSVNP and the Guadalquivir Basin (Fig. 1d). In both areas, at the border of the mountain front, several tectonic units are observed that produce lithological contrasts and steep forms, which strongly determine the relief and give the landscape an important scenic component (Guadiana Menor river peaks, Chorrogil tufas and waterfall, Tíscar fault). Normally, in these areas the geosites defined have didactic and touristic values.

Geodiversity Index (Gi)

The geodiversity index shown in the map of Fig. 5a results from the linear sum of the partial indices presented in Fig. 4, after overlaying the grids defined for each of them. The values obtained range from 4 to 20 (Fig. 5a). High or very high values are recorded in the centre and south of the area considered, coinciding with the Subbetic Zone, some parts in the Prebetic and the southern border of the Guadalquivir Basin (Figs. 1d and 5a). On the other hand, in the western and especially north-western part, low values are recorded, which is related to the homogeneity of the autochthonous materials of that part of the Guadalquivir Basin. The highest geodiversity values are found in 990 MAGNA map in the south of the province (Table 2, Fig. 2), where the lithologic, geomorphologic and pedologic indices show very high values.

By applying kriging to the map in Fig. 5a, resulted the geodiversity gradient map (Fig. 5b), which represents the continuous variation of this parameter. In this map, a band with very high geodiversity values can be seen in MAGNA maps 990, 947, 970 and 948 (geographically it includes

the Sierra Sur of Jaén and the SMNP). This band of very high geodiversity values also includes a good part of sheets 948, 927, 928, 949 and 950, that coincides with the Subbetic in the south of the province and its contact with the Guadalquivir Basin, specifically with the Accretionary Complex (Fig. 1d). In addition, in this area there are units of the Prebetic of Jaén, emplaced by thrusting, as is the case of the Bedmar-Jódar Unit or the Aznaitín Unit (sheet 948, Table 2; Figs. 1d and 2).

Biodiversity and Endangered Species Indices

The biodiversity of the area considered in this paper is generally low (Fig. 6a, b, c). Medium and high values are found mainly in relation to the SMNP and CSVNP. In addition, coinciding with the Sierra Sur of Jaén, some areas with a medium biodiversity index can be observed (Fig. 6a).

Endangered species index ranges from 0 to 4 (Fig. 6b). The highest values are concentrated in both natural parks. However, high values of this index show a considerable dispersion in the province, outside the protected natural areas mentioned above, such as in the Sierra Sur and the north-western of studied region.

Correlation Analysis

To analyse the independence of the partial indices, a correlation analysis will be performed (Table 3), as well as to establish the statistical relationship between the geodiversity, biodiversity and endangered species indices and determine if there is any type of dependence between them.

The correlation between the geomorphologic and geodiversity indices is the highest obtained (0.80). There is also a strong correlation between the geodiversity and lithologic indices (0.77), and a moderate correlation between the geodiversity index and the pedologic (0.55) and hydrology (0.54) indices (Table 3), all of them significant at a p value of 0.01. It should be noted that the geodiversity index is obtained linearly from the partial indices, some of which, due to their variability, acquire important weight within this. In addition, correlations appear between the geomorphologic and lithologic indices (0.55). With a weak level of correlation (coefficient lower than 0.5, but still significant at a p value of 0.01), some relationships between the lithologic and geomorphologic index with the pedologic and hydrology indices can be appreciated (Table 3).

It is striking the relatively high correlation value between the biodiversity index and the lithologic index (0.46) and, to a lesser extent, with the geomorphologic (0.26) and hydrology indices (0.27) (Table 3), all of them with a significant p value of 0.01. Along the same lines, the relationship between the biodiversity and the geodiversity indices, with a value of 0.37, should be noted. As for the endangered species index,

Table 3 Correlations between the partial geodiversity indices and between them and the geodiversity index, biodiversity and endangered species indices

Pearson correlation coefficient	Lithologic	Geomorphologic	Palaeontological	Pedologic	Minerals	Hydrology	Geosites	Geodiversity	Biodiversity	Endangered species
Geomorphologic	<i>0.55**</i>	1.00								
Palaeontological	0.03	0.02	1.00							
Pedologic	<i>0.27**</i>	<i>0.41**</i>	−0.09	1.00						
Minerals	0.09	0.09	−0.03	<i>0.18**</i>	1.00					
Hydrology	<i>0.31**</i>	<i>0.27**</i>	0.09	−0.13*	−0.01	1.00				
Geosites	<i>0.13*</i>	<i>0.12*</i>	0.01	0.00	0.06	<i>0.19**</i>	1.00			
Geodiversity	<i>0.77**</i>	<i>0.80**</i>	0.12	<i>0.55**</i>	<i>0.23**</i>	<i>0.54**</i>	<i>0.31**</i>	1.00		
Biodiversity	<i>0.46**</i>	<i>0.26**</i>	0.07	−0.04	0.05	<i>0.27**</i>	<i>0.21**</i>	<i>0.37**</i>	1.00	
Endangered species	0.09	<i>0.18*</i>	0.05	−0.16**	−0.01	<i>0.26**</i>	<i>0.13*</i>	<i>0.15**</i>	<i>0.24**</i>	1.00

The values in italics 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

the highest correlation was obtained with the hydrology index (0.26), slightly higher than the correlation between that index and the biodiversity index (0.24). The rest of the coefficients of this index have very low values (positive and negative) in absolute terms (Table 3).

Discussion

The geodiversity of the southern and eastern part of the province of Jaén shows high values looking that values near 20 points are reached in some squares of the grid, but it is lower than the maximum values obtained in the northern part of this province, about 24 points (Fernández et al. 2020). These results agree with those obtained by Benito-Calvo et al. (2009). According to them, the highest geodiversity values are found in areas composed of Palaeozoic materials affected by the Variscan Orogeny, similar to those studied by Fernández et al. (2020), followed by those areas within alpine range, such as the BEZ, studied in the present paper. Likewise, those authors indicate that the lowest geodiversity values are found in the Cenozoic basins, represented by the Guadalquivir Basin, especially by the Autochthonous Units. Thus, the lithologic index shows similar values in both areas, with maximum values of about 13–14, giving practically the same classification intervals. The same situation can be found in the pedologic index, with maximum values of 8–9. Meanwhile, the geomorphologic index presents higher values in this area, up to 13, than in the northern area, up to 9. Contrary, the hydrology index reaches values slightly lower (12) than in the north, probably due to a higher order of rivers in this part. However, the main difference is found in the minerals index, and especially the palaeontological index, which present values much higher in the northern than in the south-eastern part. Finally, the geosites are very similar between both areas (up to 3).

In the sections on the geological and geomorphological settings of the considered area, it was shown that the geomorphological features are strongly controlled by the lithology and tectonic structures. This is recorded in the high correlation between the geomorphologic and lithologic indices (Table 3), as well as between the hydrology and lithologic indices. In addition, the geodiversity index shows a high correlation with the previous partial indices (Table 3). The strong and significant correlation between these partial indices and with the geodiversity index was also detected by Fernández et al. (2020) in their analysis of the geodiversity in the Variscan Massif of the north of the province of Jaén. These authors explained it considering the lithological control of the geomorphological and hydrological features and the fact that these partial indices contributed a high value to the geodiversity index.

On the other hand, Table 3 also shows correlation coefficients with values close to 0, which, in general, can be explained as an absence of correlation between the different pairs of indices due to the fact that the genetic processes that have given rise to the features analysed with these indices have no influence on each other. Thus, between indices such as pedologic and palaeontological (correlation coefficient of −0.09; Table 3), the absence of a relationship can be explained by the fact that soil development does not influence the genesis of palaeontological deposits. The genetic processes that give rise to one and the other are different and are not interrelated. In any case, a negative relationship could be established between soil development and palaeontological sites, insofar as the pedologic processes can produce a deterioration and loss of palaeontological sites. The same can be considered between the palaeontological and minerals indices, which should also be understood as reflecting an absence of relationship; taphonomic processes do not necessarily cause the development of mineral deposits, nor the genesis of

special mineralisation associated with the palaeontological deposit. In this sense, it can be concluded that a good part of the indices, except for those more clearly determined by lithology, are in general quite independent.

A weak correlation but still significant (at the p value of 0.01) was also obtained between the biodiversity index and the lithologic, geomorphologic and hydrology indices (Table 3). This can be considered a record of the dependence between biodiversity and the nature of the rocks, the geomorphological features (largely conditioning the relief) and the hydrological characteristics of the region. This correlation between those partial indices of geodiversity and biodiversity is also detected between the geodiversity and biodiversity indices, which shows a potential dependence between both parameters.

This was already explained by Parks and Mulligan (2010), Tukiainen et al. (2016) or Crisp et al. (2022), all of them postulated that geological factors (lithology, geomorphology, hydrology, pedology processes) condition the development of ecosystems and thus the colonisation of new habitats. This relatively weak level of correlation could be explained by the fact that the region studied has a high degree of anthropisation, slightly lower in the NPAs. Geological dynamics, in general, and those related to the development of landscape and soils, condition to different extents the biotic features of the area considered, such as the distribution of habitats or the reproduction of species (e.g. Boothroyd and McHenry 2019; Chakraborty and Gray 2020).

Similarly, the weak correlation (0.26; Table 3) between the endangered species index and the hydrology index could be understood considering that living beings need water for their vital activity. Thus, where it is easier to acquire water, the greater the concentration of organisms will be. In fact, a correlation coefficient of 0.27 has been obtained between biodiversity and the hydrology index (Table 3), which shows this certain interrelation between both natural elements. Similarly, between the hydrology index and the endangered species index there is a correlation coefficient of 0.26 (Table 3), very similar to that shown above, so that it can also be considered that between these two natural elements (endangered species and hydrology) there is a mutual dependence. However, Fernández et al. (2020) did not find this relationship in their study of the northern part of the province of Jaén.

The practically null correlation (Table 3) between endangered species and pedologic and minerals indices could be a consequence of the lack of interrelation between the existence of endangered species, generally due to anthropogenic causes, and the development of soils or mineral deposits, the latter two resulting from geological processes over which the human being has no influence (mineralogical processes) or has little control (pedology origin).

The correlation between geodiversity and biodiversity, whose coefficient is of 0.37 (significant at p value of 0.01)

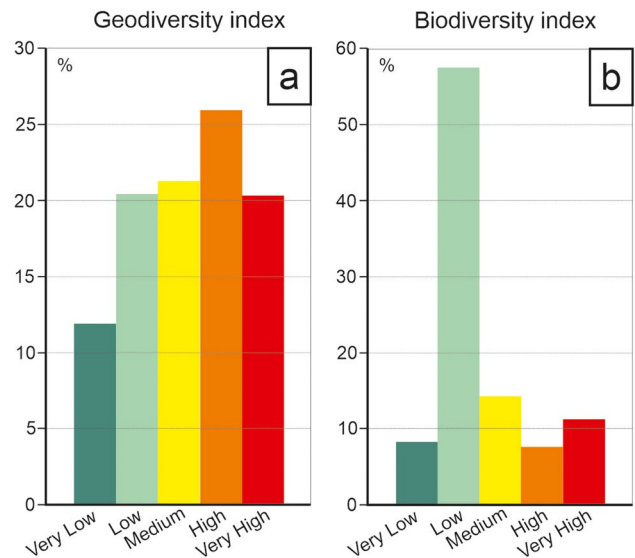


Fig. 7 Histograms of representativity of the **a** geodiversity index and **b** biodiversity index in the studied region

can be analysed from their distribution in the maps (Figs. 5 and 6). A noteworthy feature in the region is the existence of symmetry in the distribution of geodiversity index values. The geodiversity gradient map (Fig. 5b) shows a central part, extending from the SW to the NE, wider in the southern part than in the northern one, with high and very high geodiversity values. On both sides of this central zone, the geodiversity index values decrease towards the NW and SE. The histogram in Fig. 7a shows the surface distribution of the different values of the geodiversity index, in which high values predominate (slightly more than 25% of the area considered). This area with very high geodiversity (Fig. 7a) could be defined as a geodiversity hot-spot in the sense of Gray (2013, 2018) or Brilha et al. (2018), who associate this concept with areas with a significantly high value of geodiversity. To define it in the sense of Bétard and Peulvast (2019), it would be necessary to link the hot-spot with geological elements that show degradation risk and therefore require conservation procedures. Currently, there are no studies highlighting deterioration and, therefore, the need for specific conservation actions.

Much of the area covered by the geodiversity band of high and very high values coincides with the orogenic front and the confluence of disparate geological domains, both in lithology and geoforms and in the development of soils and hydrology parameters, which favour these high and very high geodiversity values (Figs. 1 and 5b). However, this distribution of geodiversity has not a clear relationship with that of biodiversity, as the weak correlation coefficient showed. Thus, unlike geodiversity, the biodiversity index is low in most of the territory (approximately 60% of it, Figs. 6, 7b). This could reflect the level of anthropisation

of the territory, as well as the low values of the pedologic index, especially in the natural parks considered in this research. The fact that the predominant rocks in both NPAs are carbonates favours that soil diversity is limited, being lithological factors the main drivers of the low pedologic diversity, which would be in line with the ideas proposed by Antonelli et al. (2018).

Geodiversity and Biodiversity in the NPA

Cazorla, Segura and Las Villas Natural Park (CSVNP)

When overlapping the borders of the NPA in the considered region with the geodiversity gradient map (Fig. 5b), it is noticeable that this natural park is located in a region where the high geodiversity index is located in the central and northern part of it, while the other NPA, which will be discussed later, belongs to areas with high and very high values of the geodiversity index (Fig. 5b). This lack of concordance between high/very high geodiversity index value and NPA was also found in the natural parks of Sierra de Andújar or Despeñaperros in the north of the province (Fernández et al. 2020). An analysis of the lithological index value in the CSVNP (Fig. 4a) shows that low (2) and medium (3) values predominate. This is closely related to the lithologies considered in this area, belonging to the Prebetic. In the map of Fig. 3, four lithological groups have been distinguished which, in general, are quite homogeneous, since they are different types of limestones, marls and dolostones, with occasional presence of shales and sandstones.

In addition, although the tectonic structures of this geological domain are made up of some thrust units towards the NW, large folds predominate, being responsible for the topography of the natural park. This means that the geomorphological structures are basically of the slope or ramp type with the development of large valleys through which watercourses of varying size flow. This would justify that the main value of geomorphologic index is also medium or high value (Fig. 4b), although there are areas with very high values, especially towards the NE of the NPA.

The tectonic and geomorphological structures favour the development of valleys occupied by watercourses of varying rank which collect surface runoff water when there is precipitation and, besides, can be courses fed by the groundwaters themselves. Both the lithological homogeneity and the simplicity of the geomorphological structures would justify that the pedologic index (Fig. 4c) of this NPA is predominantly very low, although there are some grids with low and medium values. Considering the dominant lithologies in the CSVNP (limestones and dolostones) and its geomorphology, the hydrology index value is predominantly high and very high (Fig. 4d). In addition, limestones and dolostones are good aquifers, so, there is groundwater, regardless of the

level of precipitation. On the other hand, according to the data provided by the minerals (Fig. 4e), palaeontological (Fig. 4f) and geosites (Fig. 4g) indices, they have little influence on the geodiversity value of this natural park.

The high value of the geodiversity index reaches 40% of the surface of the NPA (Fig. 8a), while the medium and low values are close to 30%. Overall, more than 95% of the territory occupied by the CSVNP has a geodiversity ranging from low to high, while the very low and very high values hardly reach 2% of the territory (Fig. 8a).

The predominant value of the biodiversity index in the CSVNP (Fig. 8b) is very high, followed by medium and high values. Only in the northern zone and in the southern border of the NPA, low values have been detected. An analysis of the spatial distribution of the biodiversity index values in this NPA (Fig. 6) shows that the very high value of this index occupies a surface close to 40% of the natural park, followed by the medium value (close to 35% surface). The high biodiversity index value is close to 15% of the park area (Fig. 8b). Finally, the low and very low values occupy less than 10% and 5% of the park surface, respectively. It should be noted that the high value of the endangered species index (Fig. 6b) is clearly dominant in the CSVNP, although there are some grids with medium values in the northern of the park.

The concordance between the biodiversity index and the endangered species index (Table 3) could be due to a close relationship between both, which could be interpreted as the basic factors that prevailed in the definition of this NPA. Thus, if the sum of the surface with low and medium values of the geodiversity index is considered, it is close to 60% of the park area (Fig. 8a), while the medium, high and very high values of the biodiversity index of this NPA are close to 90% (Fig. 8b).

Further to the analysis of previous data, it should be understood that geodiversity has not been sufficiently considered in the delimitation of the area of this natural park.

Sierra Mágina Natural Park (SMNP)

From the location of the SMNP on the geodiversity gradient map (Fig. 5b), it shows that the values of the geodiversity index vary from high to very high. Figure 8c shows that approximately 60% of the area covered by the NPA has a very high geodiversity index, while practically the other 40% is high (Fig. 8c).

The lithologic index (Fig. 4a) in this NPA shows medium values as dominant, followed by high and very high values, which is consistent with the considered lithological groups (Fig. 3); these are mainly limestones of several types and dolostones, both of Jurassic age, although there are also Triassic, Cretaceous, Neogene and Quaternary lithologies, the latter three being less representative. This is in accordance with the fact that in the SMNP there is a predominance of

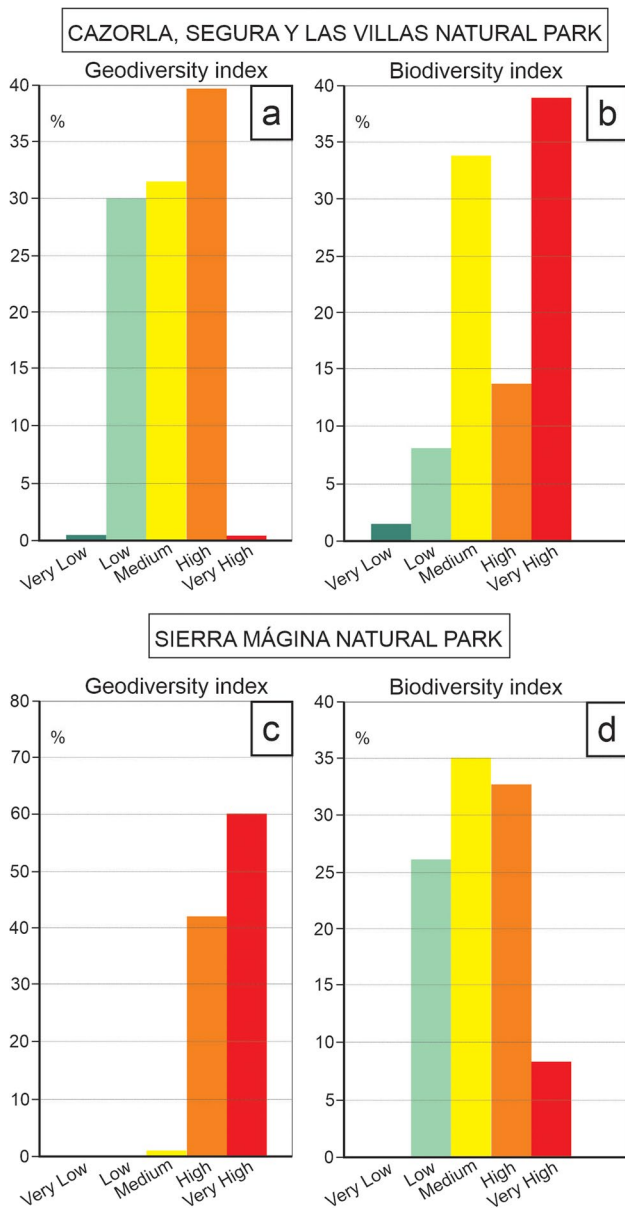


Fig. 8 Histograms of the representativity in the Cazorla, Segura and Las Villas Natural Park (CSVNP) of the **a** geodiversity index and **b** biodiversity index; and in the Sierra Mágina Natural Park (SMNP), of the **c** geodiversity index and **d** biodiversity index

Subbetic units, which are thrusting, at the base of which, Triassic materials usually appear.

Only in the north of the natural park there are small tectonic units (Sierra de Bedmar-Jódar, Aznaitín, Sierra de la Golondrina) attributed to the Prebetic of Jaén, made up of Cretaceous limestones and dolostones. This lithologic homogeneity means that the pedologic index is dominated by very low values, although it can reach high values in the north-western area of the natural park. The geomorphologic

index (Fig. 4b) in this NPA has predominantly high values, although there is also a grid in the eastern zone with a very high value. This could be related to the complex tectonic structure mentioned above, together with the presence of large folds and an important development of an exo- and endo-karst controlled by post-orogenic fractures, which favoured the infiltration of rainfall. To this, it must be added that the structure in stacked thrust units and the large folds favour the development of geomorphological forms controlled by these tectonic structures. This could condition the disparate values of the hydrology index (Fig. 4d), which vary from low to very high, without being able to establish a predominant value. As in the case of the CSVNP, the minerals (Fig. 4e), palaeontological (Fig. 4f) and geosites (Fig. 4g) indices have little or no influence on the value of the geodiversity index.

The biodiversity index in the SMNP (Fig. 6a, c) has low, medium, high and very high values (also scarce). The surface distribution of these values in this natural park is shown in Fig. 8d; around 35% of the park surface has a medium biodiversity value, followed by the high value, which is distributed over 30% of the surface. Areas with a low biodiversity index occupy approximately 25%, while those with very high biodiversity represent less than 10% of the area of this NPA.

Outside the boundaries of the natural park, low and very low biodiversity index values predominate. This would also be supported by the fact that the endangered species index (Fig. 6b) shows the high value as dominant in the SMNP. The fact that the natural park shows high and very high geodiversity index values (Fig. 8c) can be explained by geological features, such as the NPA position at the front of the Betic Orogen, where there is a confluence between units of the BEZ, Accretionary Complex and materials from the Autochthonous of the Guadalquivir Basin.

From the previous analysis, it can be interpreted that the geodiversity present in the territory was considered for the delimitation of this natural park.

Other Natural Areas

In this section, other natural areas (protected or not) are analysed; they deserve special consideration due to their relevance among the population. These are Sierra Sur de Jaén and Alto Guadalquivir Natural Area.

In the territory known as Sierra Sur (located between the city of Jaén and the southern border of the province; Figs. 1d, 5b) the maximum values of geodiversity index of the whole area studied in this paper are reached (Fig. 5b). There is no declared natural protection figure, but there are two peri-urban parks, Santa Catalina and Monte la Sierra, although the highest values are found somewhat further south (Fig. 5). In this case, the geological context, which

conditions the lithologic, geomorphologic, pedologic and even hydrology indices are very similar to those found in the SMNP, with Subbetic units stacked by thrusts, at the base of which Triassic materials usually appear, together with Jurassic limestones and dolostones, and more Cretaceous marly rocks, giving truly spectacular shapes and colorations to the territory.

There are also interesting morphologies in favour of the tectonic structure with the development of a karst that allows the infiltration of rainfall. There are medium–high values of the biodiversity index (Fig. 6a, c) and of the endangered species index (Fig. 6b). This leads us to think that, in this sector, as shown in the geodiversity gradient map (Fig. 5b), a larger NPA could be delimited, considering both biodiversity and geodiversity criteria. According to the geodiversity gradient map (Fig. 5b), the area would be mostly a geodiversity hot-spot in the sense of Gray (2013), although there are parts with high and medium geodiversity gradients. From the values of the biodiversity index (Fig. 6a) in this area, they would have predominantly high or very high values of this index. When compared the values of the lithologic, geomorphologic, pedologic and hydrology indices, it can be seen that medium and high values predominate in this area (Fig. 4a, b, c, d). This correlation between different indices of geodiversity and biodiversity would allow to define this area as an Omniversity, according to Crisp et al. (2022), in which the diversity of species would be closely related to the heterogeneity of geological features, especially lithological, geomorphological and pedological ones. The hydrology index shows medium and low values as predominant, given that in this area the hydrographic network is scarcely developed and, therefore, there is no associated diversity of organisms.

In the Alto Guadalquivir Natural Area, named as special conservation zone (ZEC in Spanish), a high geodiversity was found (Fig. 5), especially due to its high lithological, geomorphological and hydrological index values. In this case, geologically it is located where the mountain front is more diffuse, but in which there are units of the Guadalquivir Accretionary Complex, where materials of different origins are tectonically intercalated, in transition to the autochthonous rocks of the Guadalquivir Basin and with the presence of Quaternary sediments. This lithological diversity influences the variety of morphologies, and from the hydrological perspective, there are orders of high channels and detrital aquifers in the Quaternary materials around the Guadalquivir river. In view of the geodiversity of the area, this natural space could be extended a little further, especially to the southwest of the zone, in areas close to SMNP, so that the very high values of geodiversity that have been detected would be included in the delimitation of the NAP (Fig. 5).

Conclusions

The consideration of the partial geodiversity indices (lithologic, geomorphologic, pedologic, hydrology, palaeontological, minerals and geosites) has allowed to compile a geodiversity map of the area of the province of Jaén represented by the Guadalquivir Basin, and the Betic External Zone (Prebetic and Subbetic), where several natural protected areas are located, among which the Natural Park of Cazorla, Segura and Las Villas and the Natural Park of Sierra Mágina stand out. From the geodiversity index map, a geodiversity gradient map has been obtained showing that a large part of the area considered has a very high geodiversity value.

The high value of the geodiversity index is in accordance with the fact that in the central part of the studied area there is the Betic mountain front and its contact with the Guadalquivir Basin, which implies a high diversity of lithologies, geomorphological structures, hydrological and hydrogeological features and pedology development. All of these have a positive influence on the value of the geodiversity index. By contrast, the presence of palaeontological, minerals and geosite does not add significantly to the geodiversity index, unlike what happens in the north part of the province.

While the geodiversity index of the Sierra Mágina Natural Park fits very well with the pattern described in the previous paragraph, this is not the case for the Cazorla, Segura and Las Villas Natural Park, where the geodiversity index only reaches high values. This may reflect a greater lithological homogeneity in the natural park, as well as a simpler geological structure, which results in few geomorphological forms, however, this index is the most interesting in this NPA.

Maps of the corresponding indices have been prepared based on biodiversity and endangered species maps, following the methodology used with the different partial geodiversity indices. Comparison of these maps with the geodiversity gradient map shows that there is no clear correlation between the three indices, at least at the scale of the territory studied.

If we consider the different NPA existing in the study area, we find that in the Cazorla, Segura and Las Villas Natural Park there is a low or very low correlation between the biodiversity and endangered species indices and the geodiversity index. This can be explained assuming that, for the definition of the NPA, the geological features of the area covered by it have not been considered. On the contrary, in the Sierra Mágina Natural Park, there is a good correlation between the biological indices and the geodiversity index, which indicates that the geological features of the area covered by the natural park have been contemplated, either consciously or due to the need to explain the biological diversity in view of the pedologic development.

The remaining natural areas (Sierra Sur and Alto Guadalquivir Natural Area) are located in a zone of very high geodiversity. It is understood that this coincidence may be the result of the consideration of areas with landscape value, this being the basic criteria for delimitation of the NPA, coinciding with a wealth of geological elements. In any case, they are located on the orogenic front, which ensures geological diversity.

The results of this analysis, following a methodology already tested internationally and even in the north of the province of Jaén, reach similar conclusions to the latter regarding the non-concordance of geodiversity with the current limits of natural protected areas, defined with previous laws (now revoked) on nature conservation. Thus, a revision of the boundaries of the NPAs should be undertaken, considering geodiversity where appropriate.

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Declarations

Conflict of Interest The authors declare no competing interests.

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