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Assessment of the visual fragility of geomorphological landscapes and geodiversity sites in the Sierras Subbéticas UNESCO Global Geopark (southern Spain)☆

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ABSTRACT

UNESCO Global Geoparks are unified geographical areas that manage sites and landscapes of international geological significance through an integrated approach encompassing conservation, education, and sustainable development, with active involvement of local communities. The Sierras Subbéticas Geopark is among the 213 UNESCO Global Geoparks, recognized for its outstanding ammonite fossil deposits and distinctive geomorphological landscapes, particularly those associated with karst landforms. Given their undeniable aesthetic value for both visitors and local residents, assessing the visual fragility of the landscapes in which these features are embedded is crucial for effective management, especially in the face of sudden territorial changes (e.g., forest fires or land-use transformations). To address this, the study applied a multi-step methodology: i) mapping and inventory of geomorphological landscapes; ii) selection of geodiversity sites associated with landforms; iii) spatial analysis of the visual fragility of geomorphological landscapes and selected geodiversity sites based on observation points along road and trail networks; and iv) simulation of the impact of a sudden landscape change (e.g., forest fire). The results revealed: i) the presence of six geomorphological domains within the Geopark, primarily shaped by exokarstic and fluvial processes, with structural geology playing a significant role in the southern sector; and ii) several geodiversity sites exhibited high vulnerability to abrupt landscape alterations, particularly those located at higher elevations, on steep slopes, or in highly visible locations. Overall, the study offers valuable insights for land managers to design and implement mitigation strategies aimed at preserving the visual and geological integrity of geodiversity sites under the pressures of global change.

1. Introduction

The concept of geoparks was first introduced in the late 1980s (Henriques and Brilha, 2017). This initiative gained institutional support when the United Nations Educational, Scientific and Cultural Organization (UNESCO) promoted the development of geoparks by launching the UNESCO Geoparks Programme in 1997. Subsequently, UNESCO signed a cooperation agreement with the European Geoparks Network in 2001 and supported the creation of the Global Geoparks Network in 2004 (Jones, 2008). More recently, the programme was ratified in 2015 (UNESCO, 2024).

Many UNESCO Global Geoparks are characterized by a high diversity of rocks, tectonic structures, and landforms, reflecting complex geological and geomorphological histories (Brilha, 2018). These geoparks are defined as single, unified geographical areas that contain sites and landscapes of international geological significance. They are managed with a holistic approach that integrates conservation, education, and sustainable development, following a bottom-up model that actively involves local communities (UNESCO, 2024). Currently, there are 213 UNESCO Global Geoparks in 49 countries, all of which play a vital role in the characterization, conservation, and interpretation of geoheritage and other natural and cultural assets. These elements are essential to geoconservation strategies and form the basis of educational and geotourism initiatives (Brilha, 2016).

Geoparks encompass a broad range of geodiversity elements of local, regional, or global significance (Reynard et al., 2016; Brilha, 2018).

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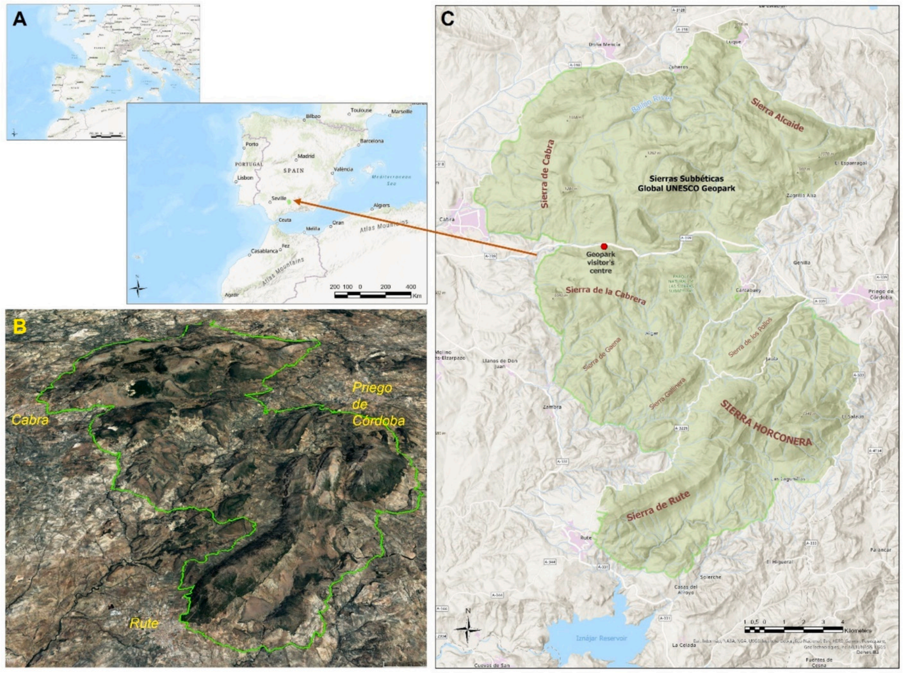

Fig. 1. Location (A), boundaries (B), and geographical context (C) of the Sierras Subbéticas UNESCO Global Geopark.

According to Brilha (2016), these elements can be categorized as follows: i) geosites, in situ occurrences of geodiversity with high scientific value; ii) geoheritage elements, ex situ geological elements (e.g., minerals, fossils, and rocks) that, despite being removed from their original context, retain scientific significance, such as those preserved in museum collections; and iii) geodiversity sites: sites of educational, aesthetic, or cultural value for society (e.g., for teaching, tourism, or recreation), which may or may not also have scientific relevance.

The assessment of these geodiversity features has received considerable attention over recent decades, resulting in the development of diverse methodological approaches. These include quantitative frameworks (Reynard et al., 2007a, 2007b, 2016; Brilha, 2016), qualitative models (Migoń, 2018), and hybrid approaches that integrate both (Bruschi and Cendrero, 2009; Pereira and Pereira, 2010; Kubalíková, 2013).

Due to anthropogenic and natural influences, such as geomorphological processes, geosites and geodiversity sites must be periodically monitored and re-evaluated to assess changes in their geotourism and educational potential (Brilha, 2016; Pal and Albert, 2021). This is increasingly relevant in the current context of global environmental change, particularly for nature-based tourism (Scott and Konopek, 2007; Berred and Berred, 2021).

Geodiversity sites can derive their value either from the integration of abiotic, biotic, and human landscape elements (as defined by the European Landscape Convention; European Council, 2000) or from the predominance of geological features with outstanding value at various spatial scales. In the former case, evaluating landscape quality can provide essential complementary data to scientific, cultural, and touristic assessments of geodiversity (Reynard and Giusti, 2018).

In this holistic view, landscape is no longer regarded merely as a multidisciplinary construct but rather as a universal framework for environmental perception—particularly in geoparks, where landscape plays a key role in shaping the geotourism experience (Newsom and Dowling, 2018). The European Landscape Convention encouraged a methodological redefinition of the relationship between land components and their spatial and temporal arrangements, as perceived by non-expert observers.

Given its inherently visual nature, landscape analysis should consider the aesthetic impressions and emotional responses of observers. In this context, the concept of landscape quality includes both an evaluation of the landscape's intrinsic value and its visual fragility (Bolós, 1992). In the present study, only visual fragility is examined, defined as the susceptibility of a landscape to degradation due to human-induced visual impacts (Martínez-Béjar et al., 2001; Arias-Orozco et al., 2015; Delgado Peña et al., 2017).

It is important to clarify that the notion of visual fragility adopted in this study diverges from other interpretations of landscape or site fragility. For example, García-Ortiz et al. (2014) define fragility as the vulnerability of a geosite to intrinsic damage or destruction; Fuertes-Gutiérrez and Fernández-Martínez (2010) focus on sensitivity to degradation under natural conditions; and Rocha et al. (2013) emphasize the negative impacts of anthropogenic activities, which may result in varying degrees of damage or even complete destruction.

Conversely, in line with holistic landscape approaches (Martínez-Béjar et al., 2001; Arias-Orozco et al., 2015; Delgado Peña et al., 2017), the present study interprets landscape fragility from a visual perspective—that is, from the viewpoint of an observer at a certain distance—directly tied to the aesthetic character of the landscape in which geodiversity sites are embedded.

Therefore, the aim of this study is to characterize the visual fragility of geomorphological landscapes in the Sierras Subbéticas UNESCO Global Geopark (SSG), as well as selected geodiversity sites. Sites associated with fossils and endokarst landforms are excluded, as these features are either not visible or not easily observable from the surface or at a distance. The specific objectives are: i) to map and catalogue the geomorphological landscapes, and ii) to assess their visual fragility, along with that of the selected geodiversity sites, in order to support improved management of geotourism and geoeducation activities within the Geopark.

2. Regional settings

Located in the southern Iberian Peninsula, the Sierras Subbéticas Geopark (SSG) is included on the list of UNESCO Global Geoparks (Fig. 1). Initially designated as a natural park in 1988 by the regional government of Andalusia, SSG joined both the Global and European

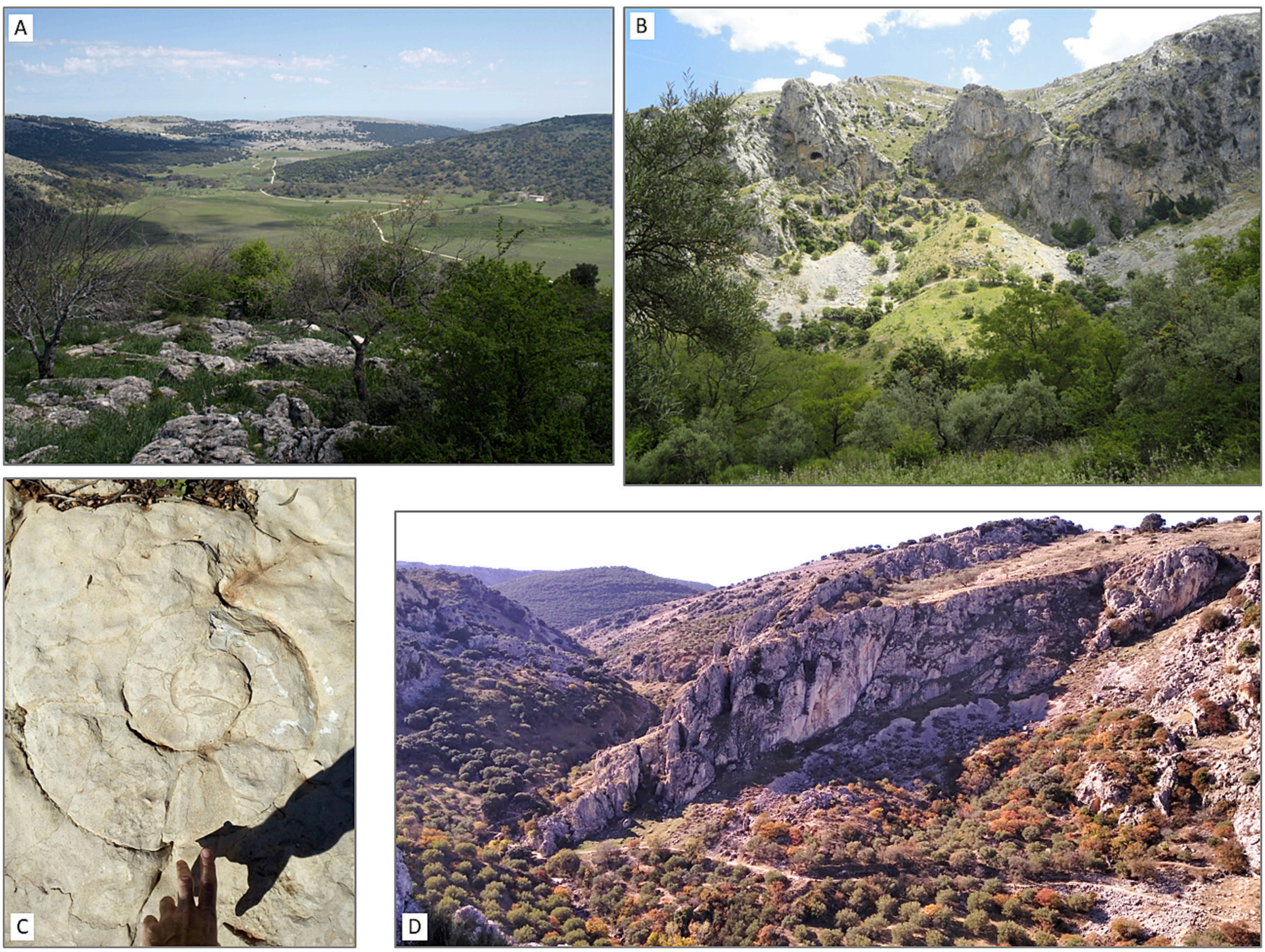

Fig. 2. Examples of geodiversity sites in the Sierras Subbéticas UNESCO Global Geopark: A) paleo-polje of La Nava de Cabra; B) rockfall scarps and deposits resulting from gravitational and periglacial processes; C) ammonite fossil; D) fluvio-karst canyon of the Bailón River. Photos: Authors.

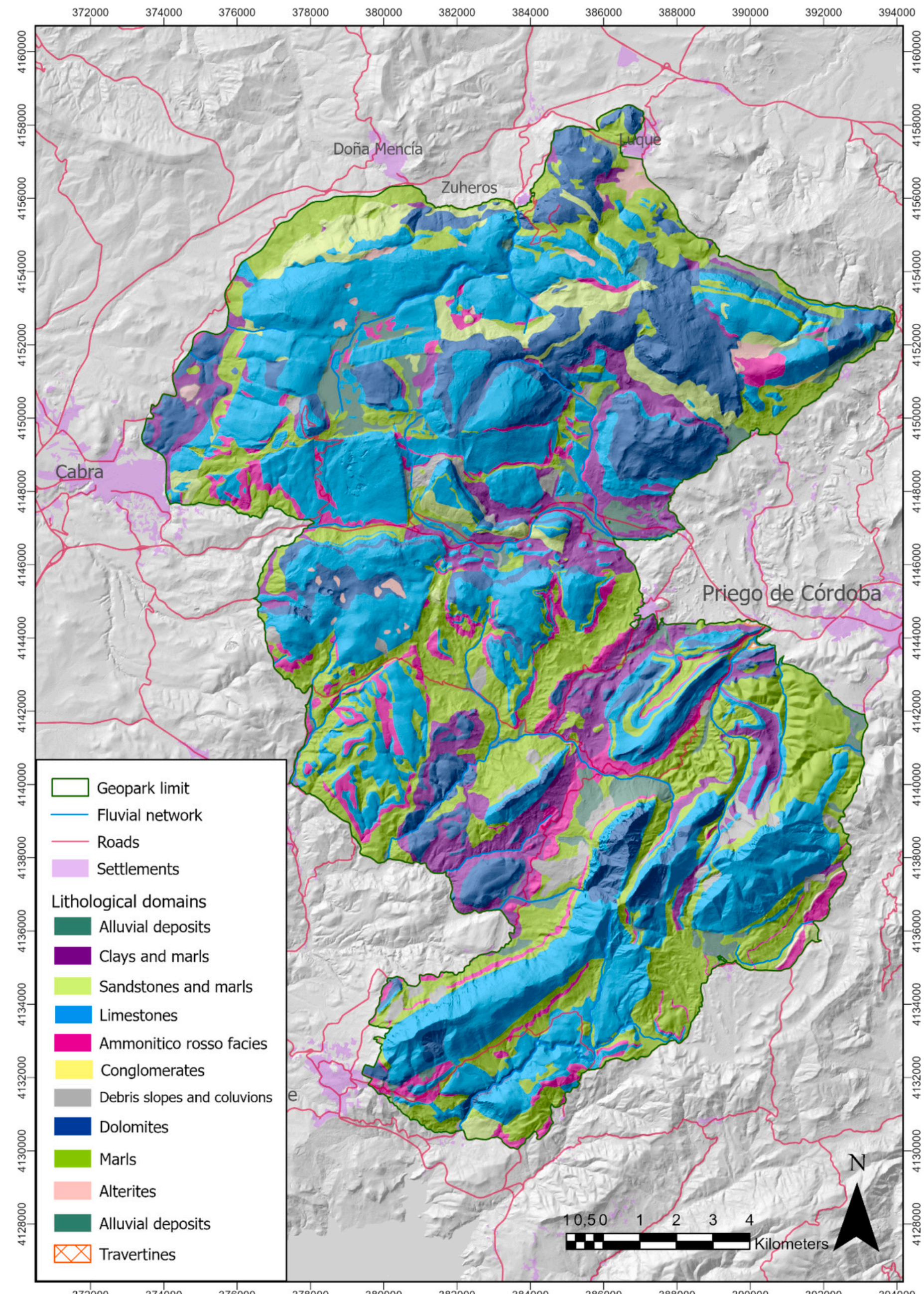

Fig. 3. Spatial distribution of lithological domains in the Sierras Subbéticas UNESCO Global Geopark.

Geoparks Networks in 2006 and was officially recognized as a UNESCO Global Geopark in 2015. The geopark covers an area of 32,056 ha and encompasses eight municipalities, all situated within the province of Córdoba.

The landscape of SSG is heavily influenced by its geological characteristics. Steep mountain ranges composed of highly resistant limestone dominate the topography and include the highest elevation—La Tiñosa Peak, reaching 1570 m above sea level. These mountainous areas host the majority of natural vegetation, including oak and pine forests, Mediterranean shrublands, and pastures. In contrast, lower-altitude zones, underlain by marly, clayey, and alluvial substrates, are primarily used for agricultural activities. According to Gómez-Zotano et al. (2015), the climate of SSG is characterized by two distinct domains: a semi-oceanic Mediterranean (sub-humid) climate in the north western mountainous sector, and a typical Mediterranean climate throughout the remaining mountainous and lowland areas.

One of the key geological features that contributed to the geopark's designation is the presence of the Rosso Aaliense ammonite facies (Jurassic), found within nodular limestones up to 40 m thick in the central sector (Fig. 2). The geopark also contains an abundance of both exokarst and endokarst features developed in carbonate rocks, which hold significant scientific and educational value. These include paleopoljes, dolines, caves, and vertical shafts (simas). Additionally, notable structural features such as thrust fronts and klippes are of regional geological interest. Carruana-Herrera and Martínez-Murillo (2020) assessed the geodiversity of the area using three established mapping methodologies and found consistently high levels of geodiversity across large sectors of the geopark.

2.1. Geological features

SSG is situated within the central sector of the Alpine Subbetic Zone

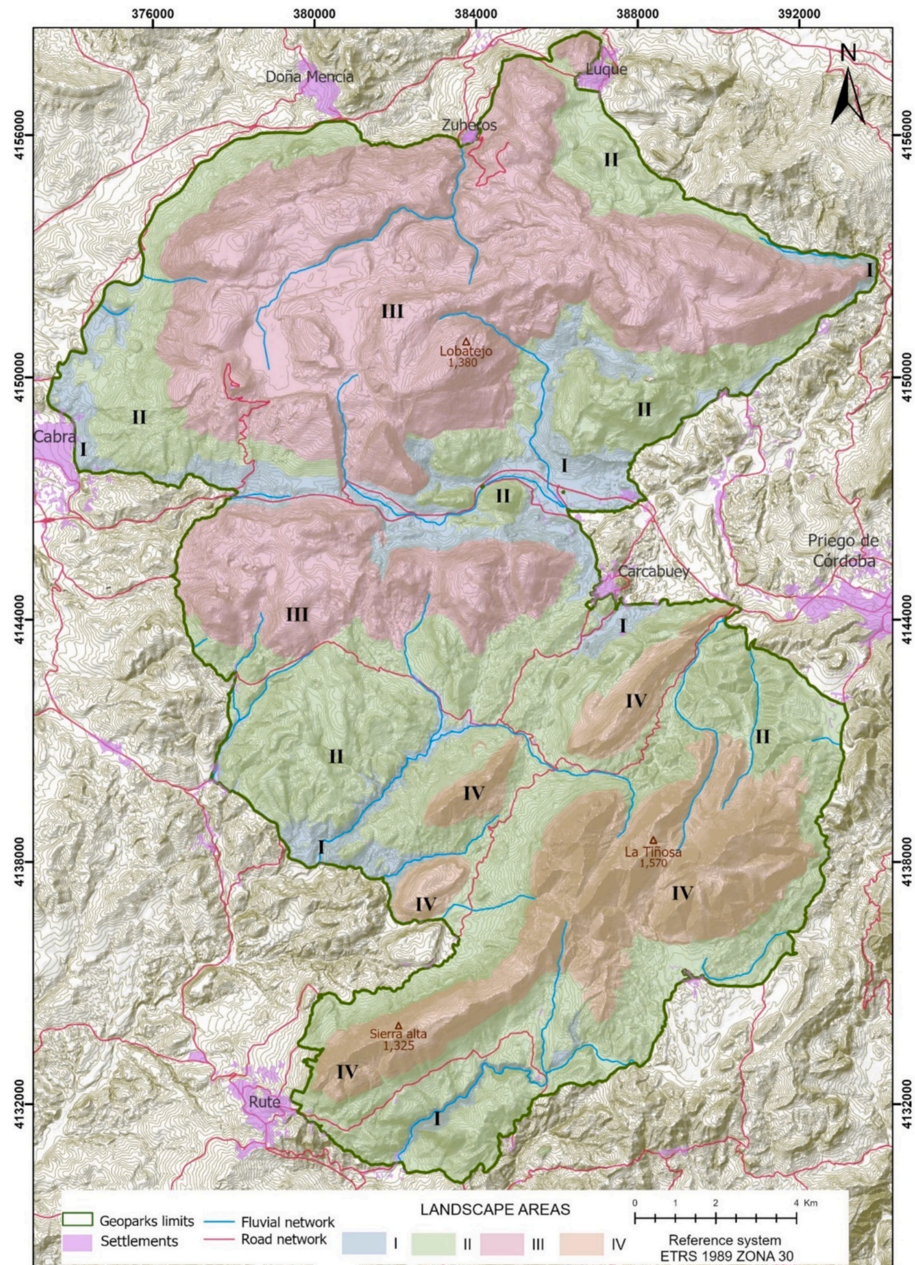

Fig. 4. Map of landscape areas in the Sierras Subbéticas UNESCO Global Geopark.

(Sanz de Galdeano, 1973). The predominant geological units are composed of Jurassic and Cretaceous sedimentary rocks, although minor outcrops of Triassic and Cenozoic materials also occur (Molina et al., 1999) (Fig. 3). According to Díaz de Neira et al. (1991), the area includes three major Alpine units: the External Subbetic, the Middle Subbetic, and an Intermediate Jurassic-Cretaceous unit.

The lowland regions are mainly composed of Triassic materials, including variegated clays and gypsum, locally associated with red quartzitic sandstones, black laminated dolomites, ophiolites, ochre limestones, and carniolas. Overlying the Triassic, four allochthonous tectonic units can be distinguished in the mountainous zones, comprising rocks from the Triassic to the Middle Miocene. These include marly limestones, marls, nodular limestones, flint-bearing limestones, radiolaritic marls, and dolerites. An intermediate geological unit is mostly exposed in the northwestern sector of SSG. It consists of gray and ochre marls, accompanied by Cretaceous turbiditic sequences and Paleocene–Eocene marls and marly limestones.

Neogene and Quaternary deposits are mainly restricted to valley floors, foothills, and some slope areas—especially on north-facing slopes. These deposits include: Miocene, white and green silts, algal limestones, biocalcarenites, yellowish sandy loams, breccias and conglomerates, nummulitic limestones, and white loams with microbreccia levels; Pliocene, highly cemented breccias and conglomerates; Pleistocene, clay and silt deposits with embedded pebbles, forming glacis; and Holocene, colluvial, alluvial, and alluvial fan sediments.

The structural geology of the area is characterized by several thrust fault systems, with detachment levels located in clayey and marly Triassic strata. Two main structural groups can be distinguished: a northern massif composed of two superimposed tectonic blocks, separated by impermeable marly formations of Cretaceous and Paleogene age; and a southern sector dominated by tight, sub-vertical folds that give rise to rugged topography with extremely steep slopes.

Table 1
Sources and data used in the study.

Source	Data format / type	Data
Spanish National Geographic Institute (IGN)	Vector and raster layers	DEM (spatial resolution, 25 m) 2022-aerial photo
Geological and Mining Institute of Spain (IGME)	Vector layer	Lithology
Environmental Data Network of Andalusia (REDIAM)	Vector layers	Limit of protected natural area Geodiversity sites[a] Hydrographic network Land use (2018-SIPNA) Geomorphological units Road, unpaved road, and trail networks
Online bibliography repositories	Scientific publications	Publications dealing with the study topics
Field work	Inventory and mapping	Validation of maps

[a] Only those geodiversity sites visible on the surface at a certain distance were considered in the study (geodiversity sites related to fossils or endokarst morphologies were not included).

2.2. The landscape of the Sierras Subbéticas UNESCO Global Geopark

The Sierras Subbéticas Geopark (SSG) is divided into four main landscape areas, delineated at a scale of 1:100,000 (Fig. 4). The geo-ecological characteristics of each area are summarized below:

2.2.1. Area I: valley bottoms and denudational hills

This unit consists of low-altitude terrain (300–600 m a.s.l.) developed on sedimentary substrates such as alluvial deposits, clays, and marls. The landscape includes fluvial terraces, gently sloping glacis, and low-relief hillsides shaped predominantly by water erosion. According to Gómez-Zotano et al. (2015), the climatic regime varies from a dry–semi-arid continental Mediterranean climate in the eastern piedmont (southern sector of the geopark) to a sub-humid, semi-oceanic Mediterranean climate in the western piedmont. Land use is mainly agricultural, characterized by traditional olive groves, irrigated olive plantations, and fruit orchards, as well as riparian vegetation along river courses.

2.2.2. Area II: denudated hilly landscapes

This unit features medium-elevation terrain (600–900 m a.s.l.) with generally moderate to steep slopes and rounded summits. It is dominated by denudational processes, with clayey and loamy substrates that experience severe to extreme water erosion. The prevailing climate is sub-humid semi-oceanic Mediterranean, particularly in the western foothills. The main land use is agricultural, primarily traditional olive groves and other irrigated crops.

2.2.3. Area III: mid-elevation denudational mountain landscapes

This unit includes terrain between 900 and 1200 m a.s.l., characterized by moderate to steep slopes. The geological substratum is predominantly calcareous, although clayey outcrops are also present. Karst dissolution is the dominant geomorphic process. Climatic conditions range from sub-humid semi-oceanic Mediterranean in the western foothills to continental Mediterranean in the central depressions and mountain corridors. Land use is mainly pre-forestry, including shrublands and pasturelands, with extensive grazing and scattered traditional olive groves.

2.2.4. Area IV: structural mountainous landscapes

This unit comprises structure-controlled terrain ranging from 900 to 1500 m a.s.l., featuring steep slopes, rocky peaks, ridges, and escarpments. The substratum is largely calcareous, interspersed with clayey-marly formations. The prevailing climate is continental Mediterranean, with a gradient of decreasing precipitation from the northern to the southern slopes and lower elevations (Gómez-Zotano et al., 2015). Land use combines pre-forest areas (shrubland and pastures) and forested zones, mainly oak and pine woodlands, with widespread extensive grazing.

In addition to their physical characteristics, the landscapes of the SSG are marked by a strong cultural component stemming from centuries of human activity. Particularly significant are the traditional mountain olive groves, which are increasingly threatened by the intensification of modern agricultural practices. Another noteworthy feature is the spatial correlation between human settlements—many of which have evolved into town centres—and karst landforms associated with natural springs and/or travertine platforms. This interplay between physical and human geography results in a pronounced overlap of geodiversity, landscape, and cultural heritage across the geopark, underscoring the need for integrated management approaches that recognize both natural and anthropogenic values.

3. Methodology

3.1. Sources and data

Table 1 summarizes the datasets used for the visual fragility assessment of geomorphological landscapes and geodiversity sites within the Sierras Subbéticas Geopark (SSG). For the mapping procedures, both vector and raster layers related to topography, geology, climate, and land use were obtained from open-access cartographic databases. These geospatial datasets were supplemented with information from peer-reviewed scientific publications and data collected during field campaigns.

3.2. Delimitation of landscape areas and spatial analysis of visual fragility

Following the approach proposed by Simensen et al. (2018), this study inventoried and mapped the landscape using a method based on the a priori selection of geo-ecological attributes. This approach was carefully chosen due to: i) the high spatial variability of geo-ecological variables in the study area (e.g., topography, geology, climate, hydrography, land use, and vegetation cover); ii) the availability of freely accessible spatial data from public online repositories; and iii) the high level of objectivity inherent in the mapping procedure.

Landscape areas were mapped using a procedure previously applied in similar studies (Quintela, 1996; Priego-Santander et al., 2003; Ramón et al., 2009; Menjíbar-Romero et al., 2024). The method was based on the superimposition of selected variables in vector format (Fig. 5). The resulting composite map was refined according to two criteria: i) a minimum mappable area, considering the reference scale of 1:100,000 used in this study, and ii) expert judgement to spatially regroup the mapped polygons. Once the final landscape units were delineated, their geo-ecological characteristics were inventoried and verified through fieldwork.

3.3. Geomorphological mapping and geodiversity site inventory

The landscape was characterized from a geomorphological perspective through the following procedures: i) a geomorphological survey aimed at inventorying and mapping the main landforms, following the methodology proposed by the Spanish Geological Survey (IGME, 2004), which considers morphogenetic and morphochronological criteria, at a spatial scale of 1:100,000; and ii) based on the previous step, the delimitation of geomorphological domains. The resulting geomorphological inventory and mapping also contributed to the characterization of the defined landscape areas within the SSG. To further complement this geomorphological approach to landscape

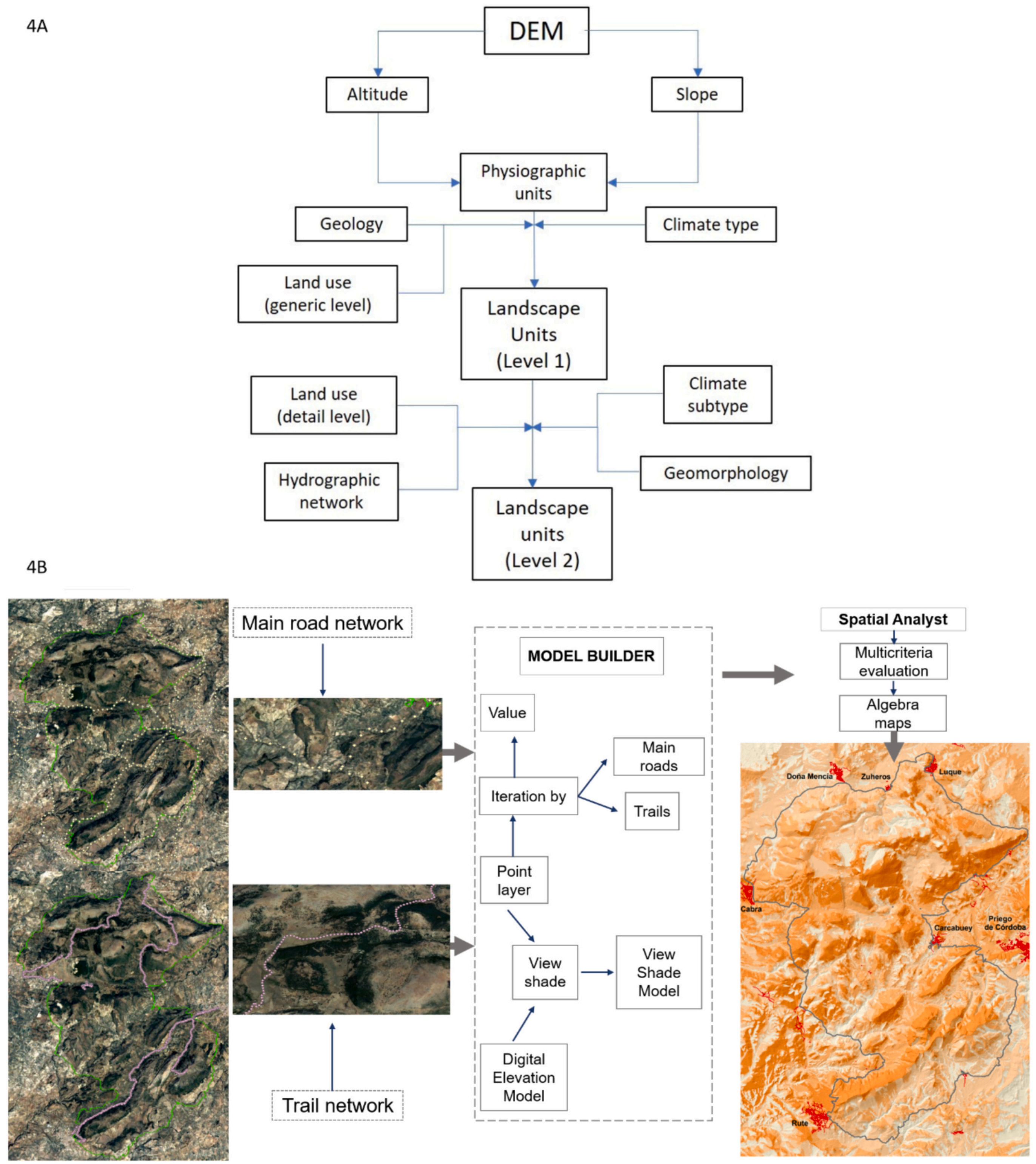

Fig. 5. Flow chart applied to map the landscape areas (4 A) and model builder to analyse the spatial variability of visual fragility (4B).

analysis, the geodiversity sites previously inventoried by the Regional Government of Andalusia were integrated into the study. These sites were assessed following a methodology proposed by IGME (2014), which is closely aligned with the approaches developed by Reynard et al. (2007a, 2007b, 2016).

3.4. Spatial analysis of visual fragility

The spatial analysis of visual fragility was carried out following the methodology applied by Menjíbar-Romero et al. (2023), as illustrated in Fig. 4B. The procedure was implemented using the 3D Analyst and ModelBuilder toolsets in ArcGIS Pro, and consisted of the following steps:

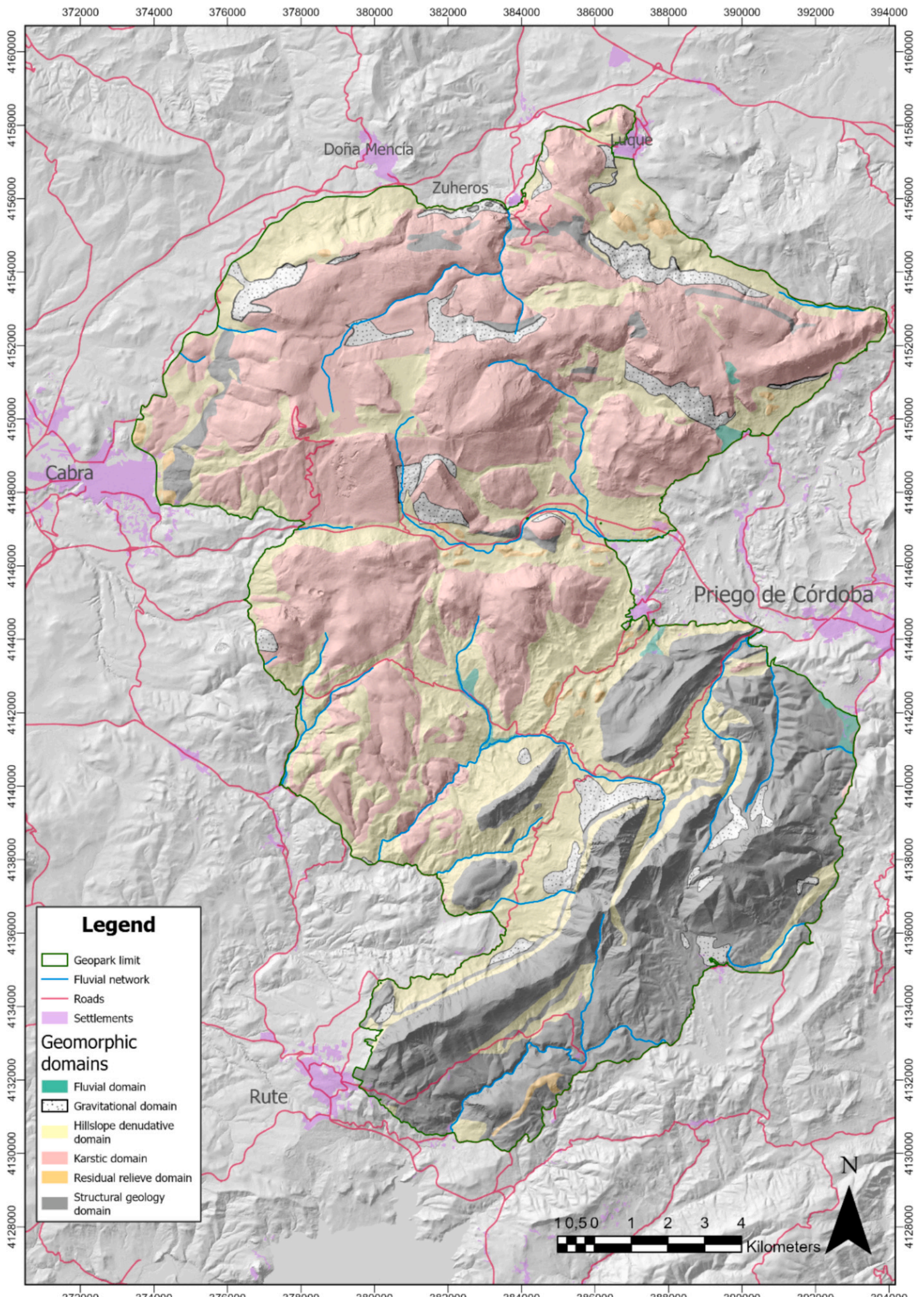

Fig. 6. Geomorphological domains in the Sierras Subbéticas UNESCO Global Geopark (based on Carruana-Herrera and Martínez-Murillo, 2020).

i) Data Preparation: The spatial layers used for the analysis included: the network of main roads and trails; a 5 × 5 m resolution digital elevation model (DEM); the geomorphological landscape units; and the boundaries of geodiversity sites, as defined in the official inventory by the Regional Government of Andalusia. As previously mentioned, geodiversity sites of fossil or endokarst nature were excluded from the analysis, due to their limited surface visibility.

ii) Generation of Observation Points: The 'Generate Points Along Lines' tool (Data Management toolbox, ArcGIS Pro) was used to create observation points at 100-meter intervals along the road and trail networks. This approach ensured broad spatial coverage by simulating potential viewpoints accessible to observers. In total, 6291 observation points were generated—5481 along roads and 810 along trails.

iii) Visibility Mapping: Using the DEM, viewshed analyses were performed from each of the 6291 observation points to delineate individual visual basins, producing one raster map per viewpoint. These maps were subsequently summed to create a cumulative visibility map in raster format. The computational challenge posed by the large number of iterations was addressed using the ModelBuilder tool in ArcGIS Pro, which automated the visibility analysis workflow.

iv) Reclassification of Visibility Values: Each cell in the resulting cumulative visibility map was assigned a value corresponding to the number of observation points from which it was visible. These values were reclassified into four categories using Jenks natural breaks: 0–1 = null or low, 2 = medium, 3 = high, and 4 = very high visibility.

v) Calculation of Visual Fragility for Geodiversity Sites: To determine the visual fragility of each geodiversity site, the 'Extract

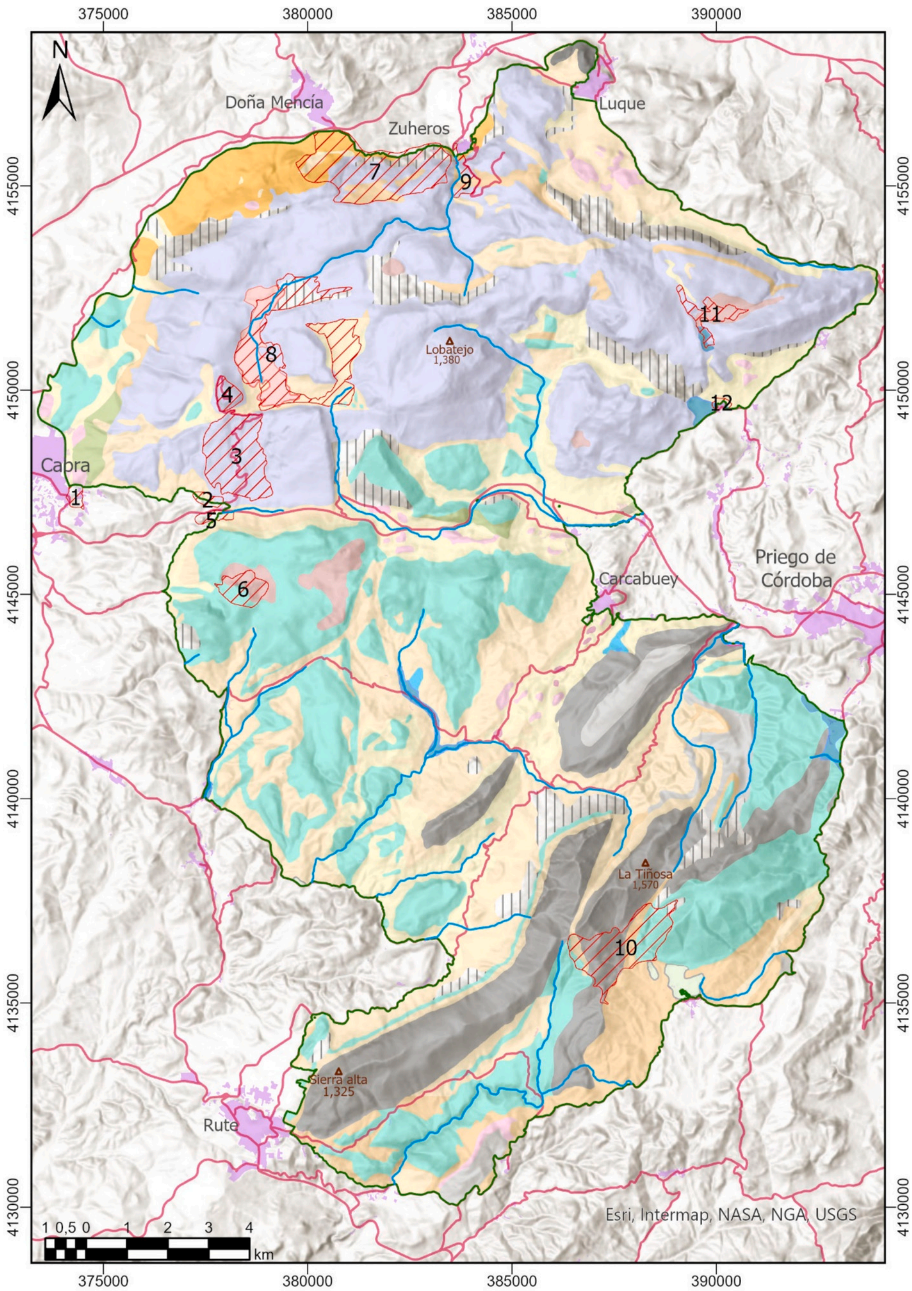

Fig. 7. Map and legend of landforms and location of the selected geodiversity sites in the Sierras Subbéticas UNESCO Global Geopark: 1, spring of Fuente del Río; 2, Jurassic series of Fuente de los Frailes; 3, karren of Lanchares; 4, klippe of Sierra de Cabra; 5, paleokarst of Venta Los Pelaos; 6, doline field of Los Hoyones; 7, thrust front of Zuheros; 8, polje of Nava de Cabra; 9, fluvio-karst canyon of Bailón river; 10, Lagunillas Cliffs (ruz morphologies); 11, polje of Nava de Luque; 12, spring of Zagrilla Alta.

Values to Points' tool (Spatial Analyst toolbox, ArcGIS Pro) was used to overlay site boundaries onto the reclassified visibility map. The visual fragility value for each site was calculated as the average visibility value of all raster cells intersecting the site's extent.

4. Results and discussion

4.1. The geomorphological landscapes in the Sierras Subbéticas UNESCO Global Geopark: domains and landforms

The geomorphological landscape of the Sierras Subbéticas UNESCO Global Geopark (SSG) is primarily shaped by the calcareous nature of the bedrock, the intensity of karstification processes, and the influence of geological structures. According to Carruana-Herrera and Martínez-Murillo (2020), the spatial distribution of geomorphological domains is illustrated in Fig. 6. Based on the dominant landforms and geomorphic processes, the SSG territory was subdivided into six geomorphological domains (Fig. 7): four domains primarily associated with hillslope, fluvial, karstic, and gravitational processes, respectively; one domain controlled mainly by geological structures; and another comprising residual landforms, which is notably less extensive in area. While each landscape area is generally dominated by a particular geomorphological domain, overlaps and transitional zones are also present. For instance, the fluvial domain appears in both Landscape Areas I and II, whereas the karstic domain is predominantly mapped within Landscape Area III,

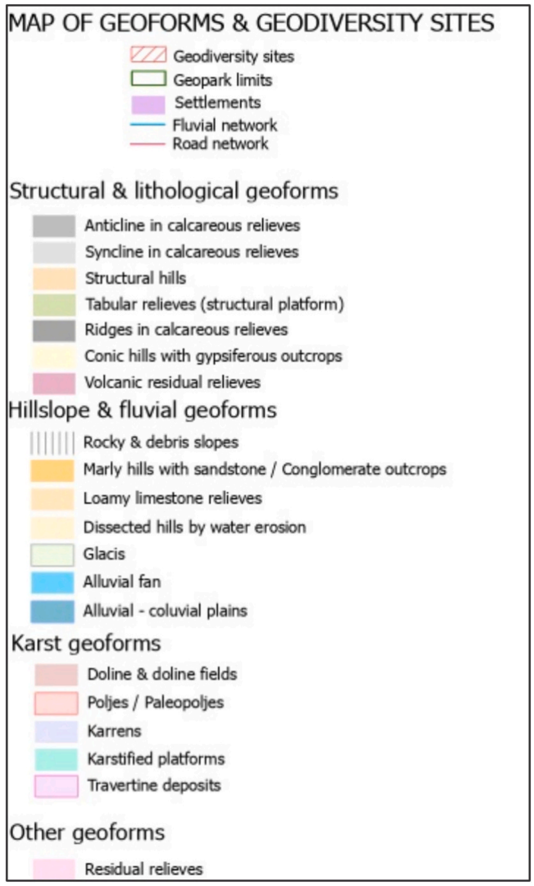

Fig. 7. (*continued*).

though not exclusively. The only geomorphological domain that corresponds almost entirely to a single landscape area is the structural domain, which is largely confined to Landscape Area IV. In contrast, the gravitational and residual domains are dispersed across multiple landscape areas.

In the northern sector of the Sierras Subbéticas Geopark (SSG), the topography is characterized primarily by a series of gently sloping reliefs and summits, which are relatively flat in some upper areas. According to Lhenaff (1999) and Durán-Valsero and López-Martínez (1999), this area exhibits a diverse array of exokarstic landforms, including poljes, isolated and clustered dolines, exhumed karren fields, and remnants of pre-Quaternary erosion surfaces (Torres and Recio, 1994). These features are bounded by sharp escarpments with very steep slopes, where the calcareous massif interfaces with the adjacent clayey and marly lowlands. On these steep slopes, rocky and debris deposits—originating from both gravitational and periglacial processes—are predominantly concentrated on the northeastern slopes above 1000 m a.s.l. The northern calcareous massif and the lowlands are linked by the incision of the drainage network, with the Bailón River fluvio-karst canyon serving as a prominent example of this geomorphological connection.

Conversely, in the southern sector of the SSG, the geomorphological landscape is essentially controlled by geological structure. This area is characterized by a succession of sharply defined SW-NE trending anticlines, predominantly composed of resistant calcareous rocks, alternating with synclines that coincide with softer lithologies such as marls and clays. The highest elevations correspond mainly to anticlines, whereas synclines generally underlie the lower altitudinal zones. A notable geological feature, located in the northern sector, is the Sierra de Cabra klippe (Fig. 8C)—an isolated calcareous peak surrounded by lower-altitude areas formed by ancient erosive karstic platforms.

Torres and Recio (1994) interpret the current geomorphological landscape of the SSG as the product of Quaternary evolution of an ancient paleo-topography, presently situated between 750 and 800 m a.s.l. This paleo-relief is particularly well preserved in the northern area and along the piedmont, linking summit areas at approximately 1100–1200 m a.s.l. The extensive erosion surfaces of this paleo-topography were dissected by incision from a former northward-flowing fluvial system, which caused the detachment of the calcareous massif from adjacent lowlands at around 600 m a.s.l. As a result, paleo-fluvial deposits are found above 500 m a.s.l. According to these authors, the Quaternary base-level evolution can be divided into two stages: (i) an initial phase characterized by a paleo-fluvial network draining northwards, and (ii) a subsequent phase corresponding to the present-day fluvial system, with associated terraces and channels—the highest terrace being situated 70–80 m above the current channel level. During this latter stage, rivers incised into the calcareous massifs, connecting upland areas to lowland piedmonts, draining poljes, and facilitating the formation of the Bailón River fluvio-karst canyon.

Additionally, periglacial morphologies formed during colder Quaternary periods are evident, primarily as heterogeneous rocky deposits at the base of scarps and steep calcareous slopes. These are especially prominent on northwestern exposures above 1000 m a.s.l. The cryoclastic processes led to the accumulation of rock and debris deposits at the foot of these slopes (Torres-Girón and Recio-Espejo, 1997). Furthermore, in marly terrains above this altitude, active solifluction processes are responsible for the development of irregular and convex landforms.

4.2. The selected geodiversity sites from Sierras Subbéticas UNESCO Global Geopark

This study considered geodiversity sites observable at the surface

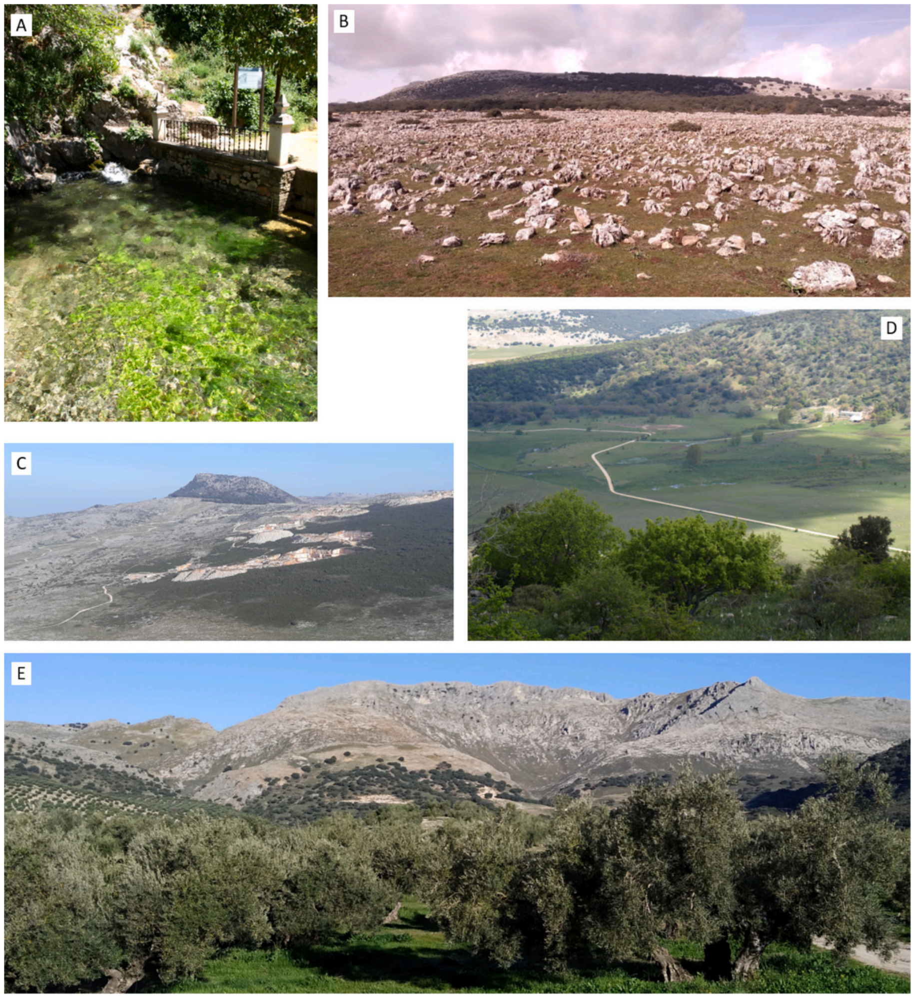

Fig. 8. Views of some selected geodiversity sites located in the Sierras Subbéticas UNESCO Global Geopark: A, spring of Fuente del Río; B, karren of Lanchares; C, klippe of Sierra de Cabra; D, polje of Nava de Cabra; and E, Scarps of Lagunillas (ruz). Photos: authors.

Table 2
List of geo-resources in the Sierras Subbéticas Global UNESCO Geopark. Source: Inventory of Andalusian Geo-resources by the Regional Government of Andalusia.

N	Geodiversity site	Latitude (X)	Longitude (Y)	Area (ha)	Geological unit	Type
1	Spring of Fuente del Río	374,423.0	4,147,609.5	18.6	External Zone, Cordillera Bética	Hydrogeology, Geormophology (karst)
2	Jurassic series of Fuente de los Frailes	377,636.9	4,147,543.8	18.5	External Zone, Cordillera Bética	Sedimentary
3	Karren Los Lanchares	378,364.5	4,148,629.0	267.6	External Zone, Cordillera Bética	Geormophology (karst)
4	Klippe of Sierra de Cabra	378,156.6	4,150,089.0	36.7	External Zone, Cordillera Bética	Structural geology
5	Paleokarst Los Pelaos	377,888.2	4,147,119.6	20.9	External Zone, Cordillera Bética	Geormophology (karst)
6	Doline field of Los Hoyones	378,564.4	4,145,310.8	73.7	External Zone, Cordillera Bética	Geormophology (karst)
7	Thrust front of Zuheros	381,548.8	4,155,625.8	424.0	Neogene/Quaternary basin, Guadalquivir Basin	Structural geology
8	Polje of Nava de Cabra	380,953.8	4,151,445.1	418.1	External Zone, Cordillera Bética	Geormophology (karst)
9	Canyon of Bailón River	384,010.5	4,155,295.6	40.5	External Zone, Cordillera Bética	Geormophology (karst, fluvial)
10	Scarps of Lagunillas (Ruz)	387,794.7	4,136,519.5	275.8	External Zone, Cordillera Bética	Structural geology
11	Polje of Nava de Luque	390,062.8	4,152,110.6	63.0	External Zone, Cordillera Bética	Geormophology (karst)
12	Spring of Fuente de Zagrilla	390,181.1	4,149,947.9	6.8	External Zone, Cordillera Bética	Hydrogeology, Geormophology (karst)

within defined viewing distances, as detailed in the methodology section. These sites were selected from the inventory compiled by the Regional Government of Andalusia, which aims to promote geo-conservation and geotourism (Junta de Andalucía, 2024). The inventory methodology closely follows the approach proposed by Reynard et al. (2007a, 2007b, 2016). From the comprehensive list of geodiversity sites located within the Sierras Subbéticas Geopark, twelve sites were ultimately selected for detailed assessment (Table 2). Several of these sites are illustrated in Fig. 8. Most of the selected geodiversity sites are either readily accessible or easily visible and identifiable from a distance. The only exception is the doline field of Hoyones, which is situated on private land and is therefore not easily accessible.

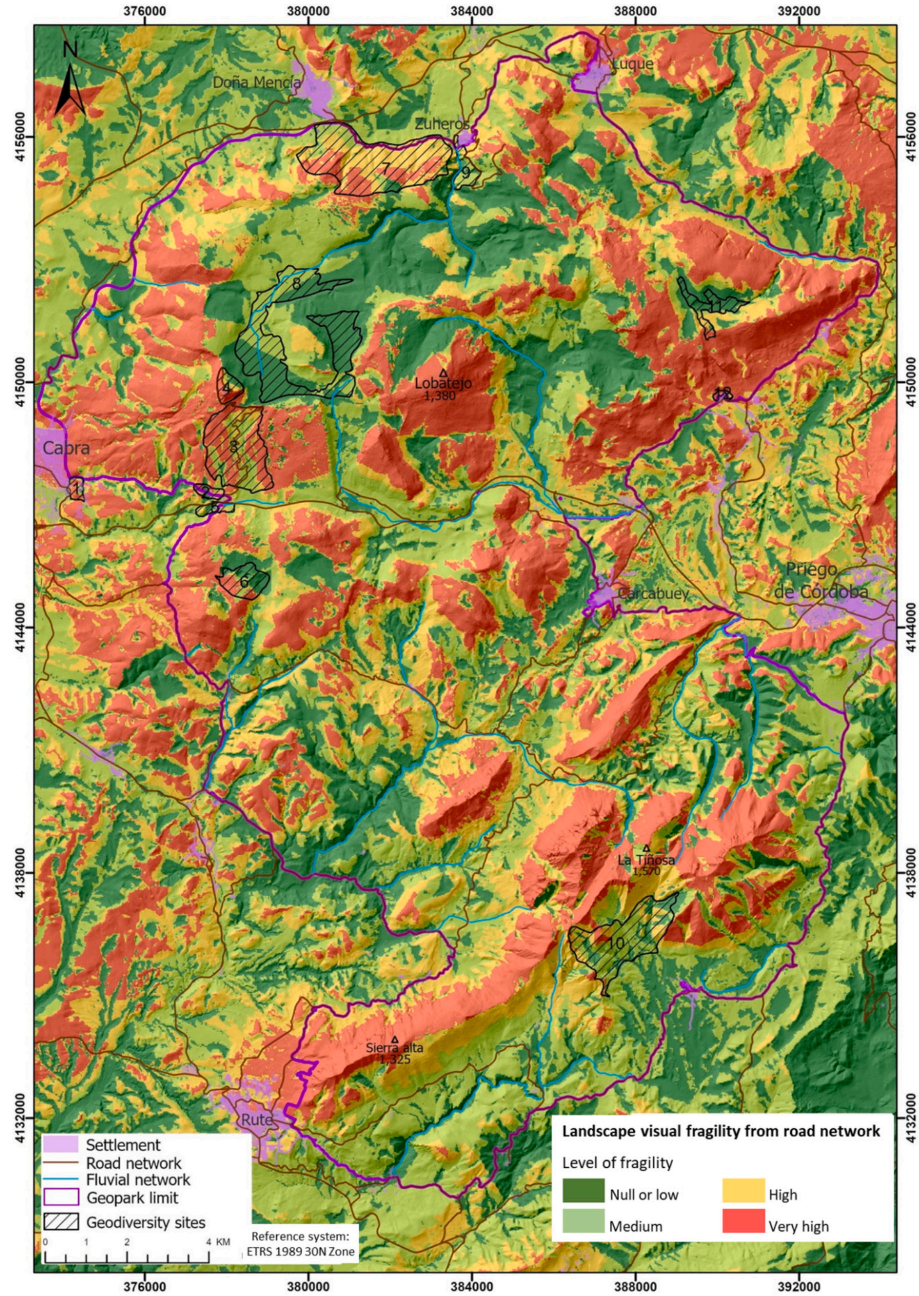

Fig. 9. Spatial variability of visual fragility from road network in the Sierras Subbéticas UNESCO Global Geopark and including the regional inventory of geo-resources.

The selected geodiversity sites exhibit the following characteristics:

1) Springs of Fuente del Río and Fuente de Zagrilla: Both sites are associated with water springs linked to travertine platforms, which have historically influenced the settlement patterns of local populations within the SSG.
2) Jurassic Series of Fuente Los Frailes: This site is characterized by Jurassic calcareous rocks and contains notable stepped quarries of Roman origin, highlighting its cultural significance. It is fed by a small spring connected to an important aquifer that supplies nearby communities, and the area is renowned for its paleontological heritage.
3) Karren Los Lanchares: This geodiversity site consists of an exhumed karren located on a thrust formed by oolitic limestones of the sub-Baetic Dogger. It represents one of the largest karren fields in southern Spain and is easily visible from the road that leads to the subsequent geodiversity site.
4) Klippe of Sierra de Cabra: This klippe is composed of Middle and Upper Miocene limestones and dolomites, with very steep topography culminating at a peak of 1217 m a.s.l. Besides offering exceptional panoramic views of the geopark, it holds considerable cultural value due to the presence of religious buildings significant to local communities.

5) Paleokarst Los Pelaos: Formed during the Mesozoic era (Middle-Upper Jurassic), this paleokarst is now overlain by Tertiary sediments. Its internal structure reveals neptunic dykes within oolitic limestones (Lower Dogger), which are filled with nodular limestones (Malm).

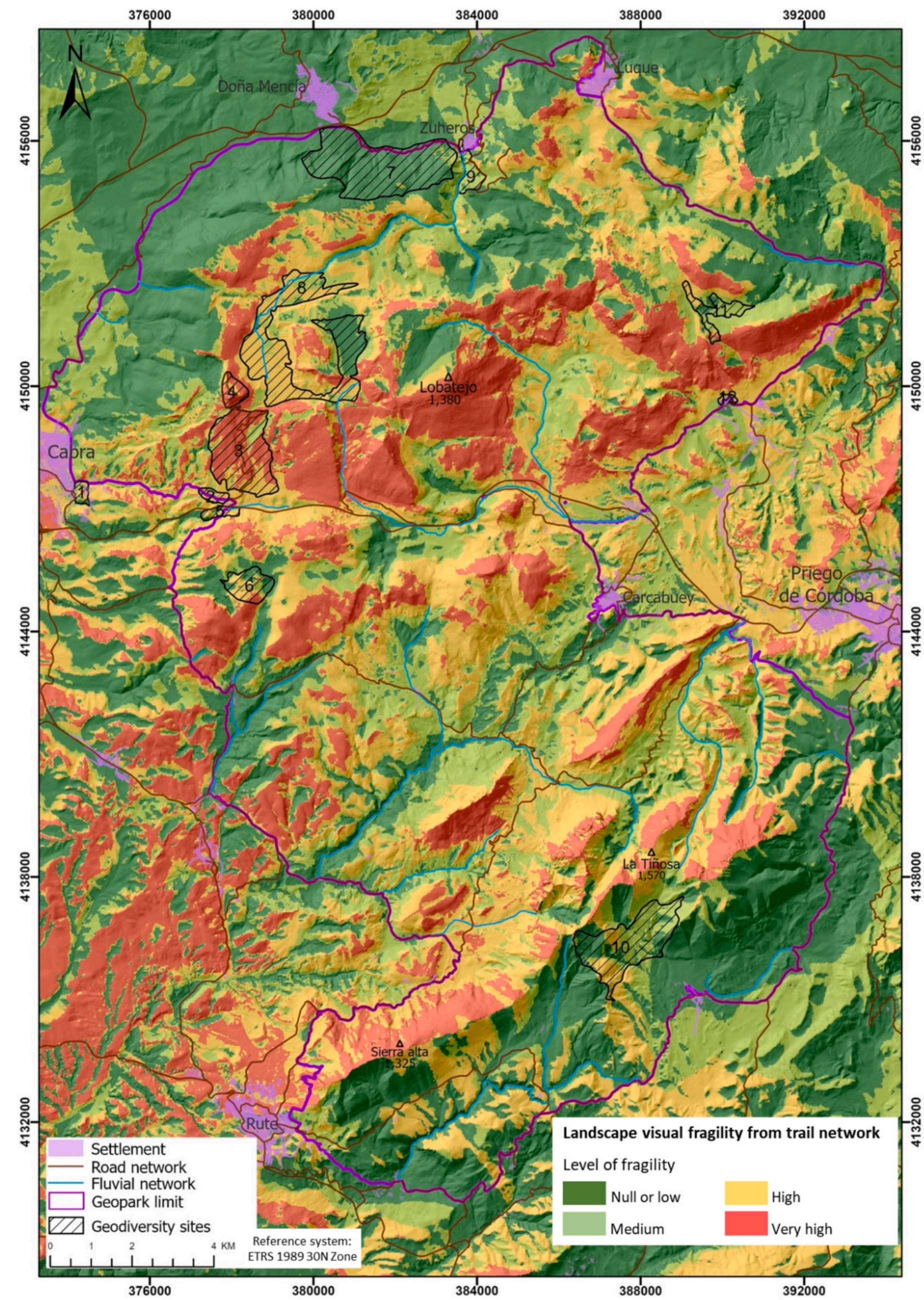

Fig. 10. Spatial variability of visual fragility from trail network in the Sierras Subbéticas UNESCO Global Geopark and including the regional inventory of geo-resources.

6) Doline Field of Los Hoyones: Comprising circular depressions exceeding 300 m in diameter, these dolines were formed by dissolution processes. Located centrally within the SSG at approximately 800 m a.s.l., this site is notable for its karstic features.
7) Thrust Front of Zuheros: This sloping ridge delineates two major geological domains: the Betic Cordillera (sub-Baetic domain) and the Guadalquivir sedimentary basin. It is characterized by the disarticulation of Triassic, Jurassic, and Tertiary materials, with frequent olistoliths. The thrust front results in an approximate 500 m elevation drop from the calcareous summits to the clayey valley below.
8) Polje of Nava de Cabra: Located primarily on loamy substrates from the Middle-Upper Miocene, this elevated plain at about 950 m a.s.l. features large depressions formed by differential limestone dissolution during the Quaternary. These depressions drain through sinkholes into the Bailón River.
9) Bailón River Canyon: The Bailón River has incised into limestone bedrock, forming a fluvio-karst canyon with a vertical drop exceeding 300 m. Along the canyon walls, faults and caves related to karstic processes are prominent.
10) Scarps of Lagunillas: This site consists of a depression with steep slopes formed through dissolution and water erosion acting on limestone and dolomites. It corresponds to a ruz developed on the southeastern slope of Sierra Horconera.
11) Polje of Nava de Luque: Situated in the eastern sector of the SSG at 900 m a.s.l., this flat-bottomed depression originated from Quaternary limestone dissolution and is currently overlain by Tertiary loamy deposits, confined between Jurassic thrust faults.

Table 3
Mean values of visual fragility in the inventoried geodiversity sites in the UNESCO Sierras Subbéticas Geopark. The visual fragility ranges from 0 to 4. Source: Inventory of Andalusian Geo-resources by the Regional Government of Andalusia.

N	Geodiversity site	Roads	Trails	Total
1	Spring Fuente del Río	3.1	2.2	2.9
2	Jurassic series of Fuente de los Frailes	2.4	2.8	2.8
3	Karren Los Lanchares	3.1	3.6	3.5
4	Klippe Sierra de Cabra	3.0	3.7	3.6
5	Paleokarst Los Pelaos	2.0	2.4	2.6
6	Doline field Hoyones	2.2	2.2	2.5
7	Thrust front of Zuheros	3.0	1.0	2.3
8	Polje of Nava de Cabra	1.3	2.4	2.0
9	Canyon of Bailón River	1.8	1.9	2.1
10	Scarps of Lagunillas	2.1	1.8	2.2
11	Polje of Nava de Luque	1.5	2.1	2.1
12	Spring Fuente de Zagrilla	3.5	2.5	3.3

4.3. The visual fragility of the geomorphological landscapes and the selected geodiversity sites in the Sierras Subbéticas UNESCO Global Geopark

This study focused on the visual fragility of the geomorphological landscapes and selected geodiversity sites within the SSG. Following previous research (Antrop, 2000; Bastian, 2008; Brabyn, 2009; Sarlöv Herlin, 2016; Antrop and Van Eetvelde, 2017), landscape studies can be broadly categorized into two types: i) those based on biophysical features, which define landscapes as tangible, physically delineated areas and are typically employed by physical geographers and landscape ecologists; and ii) those concerned with assessing the character of landscape units, which, in addition to biophysical attributes, depend on human perception and sociocultural relationships with geographic areas, as emphasized by the European Landscape Convention (European Council, 2000). A thorough characterization of landscape character necessitates prior inventories and mapping of biophysical features, facilitating a comprehensive landscape assessment that commonly includes evaluations of landscape quality and visual fragility. Visual fragility has been defined by Martínez-Béjar et al. (2001) as the susceptibility of landscapes to alteration by human activity. Evaluating these landscape properties can guide the selection of development paths that minimize environmental impacts (Martínez-Graña et al., 2019).

The analysis of the road and trail network is essential for the effective management of the geopark and its geodiversity sites due to a critical consideration: these sites are located in areas where potential threats may be exacerbated by high visual fragility, thereby risking damage to their aesthetic and intrinsic values, which are of paramount importance to local communities and geotourists alike (Reynard, 2009; Coratza and Hobléa, 2018; Bussard and Reynard, 2022).

Visual fragility was quantified based on modelled observation points distributed along the road and trail networks, as well as their combined dataset. The resulting values were classified into four categories, ranging from low to very high visual fragility. Overall, the SSG landscape is predominantly characterized by high to very high levels of visual fragility, affecting approximately two-thirds of its area. Consistent with findings from Menjíbar-Romero et al. (2023) in the Sierra de las Nieves National Park—an area exhibiting similar geomorphological features—and in line with Scarfò et al. (2013), three physical factors were identified as primary determinants of visibility in the study area: (i) the slope of the visible terrain relative to observation points, (ii) the altitude difference between observation points and visible areas, and (iii) the distance between observation points and visible terrain.

It is important to note that the observation points utilized in this visual fragility analysis differ from the 'viewpoint geosites' defined by Migoń and Pijet-Migon (2017), which are specific locations offering particularly panoramic views and are suitable for scenic interpretation. While some observation points modelled in this study may correspond to such geosites, the intent here was to comprehensively assess the overall visual fragility of the landscape encompassing the selected geodiversity sites by maximizing the number of observation points considered.

Areas exhibiting the highest visual fragility corresponded predominantly to elevated terrains or zones highly visible from multiple points along the primary roads and trails (Figs. 9 and 10).

Consequently, geomorphological landscapes characterized by karstic and structurally controlled landforms exhibited the greatest visual fragility values. With respect to the geodiversity sites, Table 3 summarizes their visual fragility scores derived from the road network, the trail network, and the combined total (Fig. 11). Sites situated in the most visible locations within the SSG—such as the klippe of Sierra de Cabra and the karren of Los Lanchares—were associated with the highest visual fragility. Other sites displayed variable visual fragility values depending on their relative visibility from roads or trails.

According to Newsom and Ladd (2022), the degree of landscape relief significantly influences human perceptions of terrain regarding its utility for land use, aesthetic value, and even religious or cultural significance. Furthermore, highly rugged reliefs tend to exhibit greater visual fragility, as they stand out prominently, particularly when surrounded by lower or flatter areas (Menjíbar-Romero et al., 2023). Consequently, any visible alterations in the landscape—such as sudden changes in land use or vegetation cover due to forest fires, large landslides, shifts in cultivation types, or new constructions like roads—can impact human perception and the aesthetic character of the landscape, potentially affecting nearby geodiversity sites. For illustration, we overlaid the boundary of a 2021 forest fire with the closest geodiversity sites and the modelled visual fragility levels to assess its impact (Fig. 12).

In geoparks, the impact on geodiversity sites can be significant from both geotourism and local development perspectives, as geotourism activities and the development of local products often constitute the economic foundation of surrounding communities (Rubam et al., 2023). Geoconservation involves protecting elements of geodiversity with geoheritage value not only for scientific purposes but also due to their educational, cultural, aesthetic, spiritual, and ecological significance (Crofts and Gordon, 2015; Gray, 2013; Gordon, 2019). Therefore, analyzing the visual fragility of the landscapes that encompass geodiversity sites adds an important dimension to the assessment of their scientific, cultural, educational, and aesthetic values, while providing practical cartographic tools for geopark management.

Our findings emphasize that local authorities responsible for managing geodiversity sites should pay particular attention to those located in highly visible and thus visually fragile areas, since visual fragility is a critical evaluation criterion. These results do not discourage the promotion of the analysed geodiversity sites but rather advocate for enhanced preventive measures, as any adverse impact on these locations could degrade landscape quality.

Moreover, the spatial analysis methodology applied herein has proven effective in identifying visually fragile hotspots within the geomorphological landscape and among geodiversity sites. Nonetheless, there is scope for methodological improvement in future studies, particularly concerning: i) incorporating traffic intensity data for vehicles and hikers on roads and trails to weight visual fragility accordingly, and ii) implementing monitoring protocols to detect sudden landscape changes, thereby enabling validation and recalibration of the visual fragility spatial analysis.

5. Conclusions

This study, conducted within the Sierras Subbéticas UNESCO Global Geopark, aimed to characterize the visual fragility of geomorphological landscapes and a selected set of geodiversity sites. The key conclusions are as follows:

i) The SSG encompasses five geomorphological landscape areas defined by dominant geomorphic processes. The most prominent

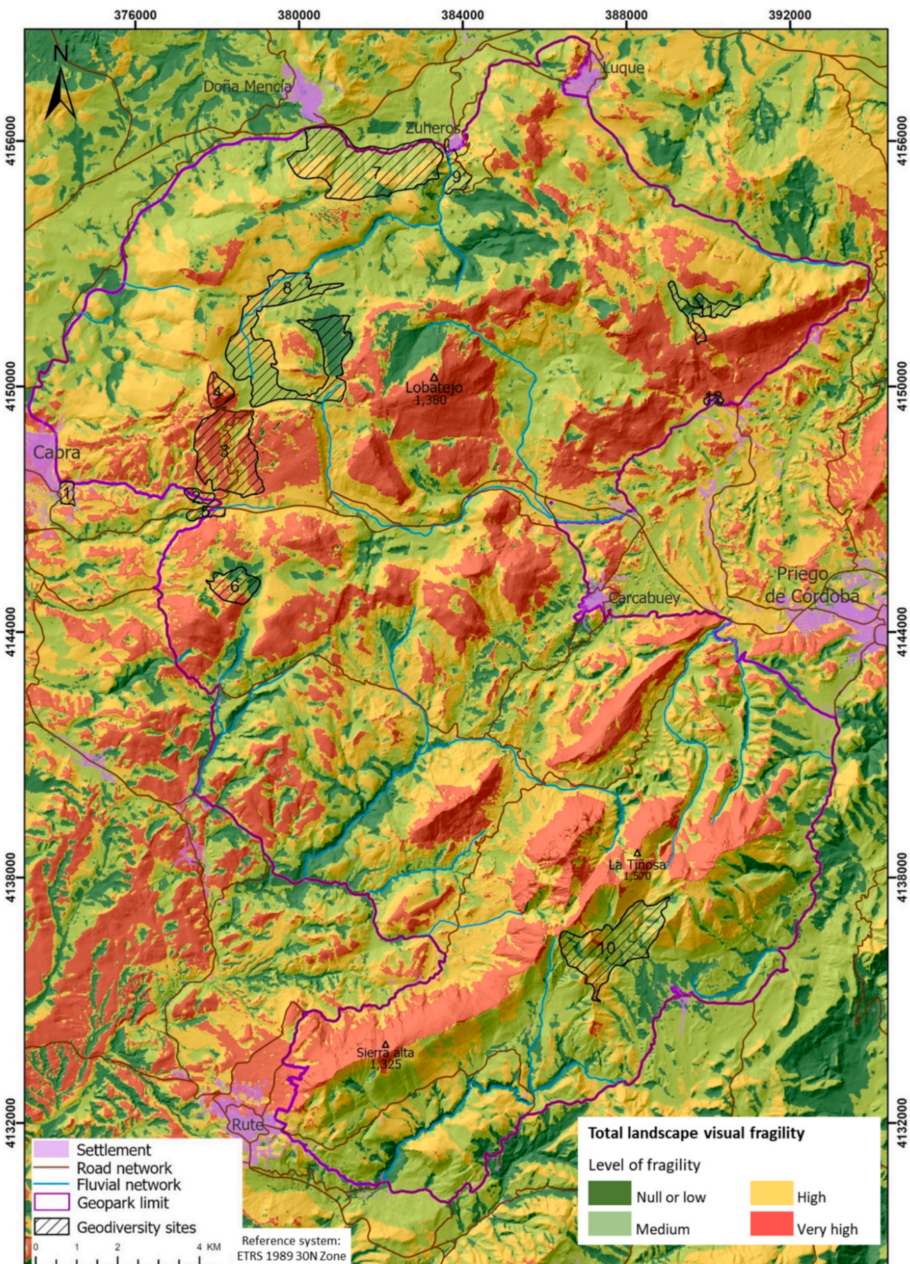

Fig. 11. Spatial variability of total visual fragility in the Sierras Subbéticas UNESCO Global Geopark and including the regional inventory of geo-resources.

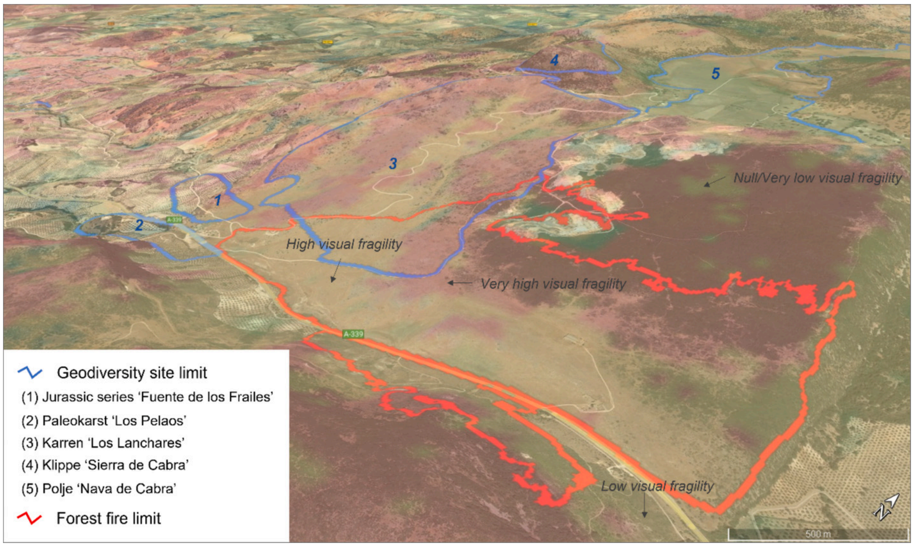

Fig. 12. Example of the affection of one sudden change in the landscape as it was the forest fire occurred in 2021 very close to some of the selected geodiversity. It can be observed in transparency the different degrees of the landscape visual fragility modelled in the area (the terms and arrows indicate each level of visual fragility to facilitate the readability of the figure). Source: authors based on own cartographic database and Google Earth Pro.

geomorphological domains are karstic and fluvial. Notably, exokarstic landforms and hillslopes shaped by fluvial erosion dominate the geopark. Structural geological elements also significantly influence landscape formation, especially in the southern region.

ii) Most geodiversity sites are associated with exokarstic landforms, although several are linked to prominent structural geological features that actively shape the landscape and are highly visible. Many sites hold considerable cultural importance to local communities as ancient water sources, construction material quarries, or sites of religious significance.

iii) The spatial analysis of visual fragility reveals that several geodiversity sites are vulnerable to sudden landscape changes (e.g., forest fires). This vulnerability is especially pronounced for sites located at higher altitudes, on steep slopes relative to surrounding terrain, or in areas highly visible from a distance.

Future research should focus on refining spatial analyses of visual vulnerability by incorporating additional spatial variables, such as the proximity of roads and trails to geodiversity sites and corresponding traffic intensities. Ultimately, this study demonstrates that key spatial datasets can inform better management practices for geoparks and geodiversity sites, providing a foundation for mitigation strategies and raising awareness among land managers, local communities, and geotourists.

CRediT authorship contribution statement

Juan F. Martínez-Murillo: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mario Menjíbar-Romero:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Ricardo Remond:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Juan F Martinez-Murillo reports financial support was provided by University of Malaga. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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