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ORIGINAL ARTICLE

A GIS-supported Multidisciplinary Database for the Management of UNESCO Global Geoparks: the Courel Mountains Geopark (Spain)

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Abstract
The management of a UNESCO Global Geopark (UGGp) requires a vast wealth of miscellaneous scientific knowledge that can be successfully organised using a Geographical Information System (GIS). This paper presents a pragmatic GIS database to assist in the suitable governance of the Courel Mountains UGGp (2017) in Northwest Spain. The database is structured in 66 coverages compiled from public sources and previous works or produced through traditional mapping (combining fieldwork and photointerpretation) and GIS tools. The acquired data was later homogenised and validated by a multidisciplinary team and archived in independent coverages. Forty thematic maps illustrate the broad range of cartographic information included in the GIS database. Among them, 25 basic maps provide an overview of the UGGp and 15 new maps focus on crosscutting and technical issues. All maps illustrate the huge potential of GIS to create new resources combining coverages and adapting the legend according to their purpose and audience. The database facilitates the suitable publishing of consistent outputs (e.g., brochures, books, panels, webpages, web serves), as well as the elaboration of technical data to assist the park management. The database furnishes information on the design of education actions, touristic routes, activities and Geopark facilities. The GIS database is also a supportive tool for scientific research and provides the necessary knowledge to conduct geoconservation actions based on land use, geological hazards and the occurrence of natural and cultural heritages. Altogether, the GIS database constitutes a powerful instrument for policy-making, facilitating the identification and evaluation of alternative strategy plans.

Keywords Cultural heritage · Geoheritage · Courel mountains UGGp · GIS · Management · Natural heritage

Introduction

The governance of a UNESCO Global Geopark (UGGp) is a major challenge mainly due to the participation of many unequal actors (local people, managers, regional to local public administrations, businesspersons, cultural associations and scientists) and the mixing of potential conflicting issues involved with the suitable development, such as economic factors and the conservation of nature (Brilha 2018; Justice 2018). The progress in scientific knowledge is the basis for growth sustained in time (Farsani et al. 2014; Ramsay 2017; Pásková and Zelenka 2018; Telbisz et al. 2020), as well as other issues, including tourism marketing (Cheung et al. 2014; Farsani 2018). However, the management of scientific data is complex due to the great scope and depth of thematic areas involved (e.g., geography, geology, biology, soil sciences, archaeology, history, ethnography, mining and engineering) and the varied spatiotemporal scales of different studies. Whereas decades ago, this management would be tough, effort-demanding work, nowadays, geographic information systems (GIS) facilitate this work (Williams and McHenry 2020) as they allow capturing, storing, quantifying and transforming data into useful information that can be edited and displayed for specific requirements or decisions by local managers (Rutherford et al. 2015; Reddy 2018).

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GIS allows the input of data from external sources such as the GIS datasets provided by European governments, following the INSPIRE European Council Directive 2007/2/CE, or from its acquisition by experts through fieldwork, remote sensing and other ways (e.g., Google Street View). Databases in GIS are organised by combining vector and matrix files (named all of their coverages), each one with specific information (Reddy 2018). Vector coverages (points, polylines and polygons) combine spatial and attribute data. In each coverage, the spatial data describes the absolute location of each geometric feature (e.g., geosite, tourism office), including its shape, size, coordinates and orientation. The attribute table describes details of the spatial feature (e.g., lithology, age), which are stored in tables in which each row is a feature and each column an attribute of the feature. Raster coverages contain a numerical value per pixel and are often used for representing terrain properties (e.g., altitude, slope and reflectivity). GIS offers the possibility to quantify each feature using measurement tools and statistical analyses, recognising changes in an area over a period of time (e.g., land use changes).

Besides information storage (that can be accessed remotely; Luo 2015), what makes GIS a powerful tool is its analysis system, which allows extracting the required information, grouping it according to defined criteria, discarding what is not useful and transforming data into new coverages by mathematical operations. From raw data, thematic maps can be drawn, which is the end product for different users, containing all the relevant information in a simplified and user-friendly way (Reddy 2018).

Despite the advantages of GIS for spatial data management (Williams and McHenry 2020), its implementation in UGGp management is still underused and is mainly applied to the elaboration of geological, geosites and touristic maps (Hartoko et al. 2018), as well as for geoheritage and geodiversity studies (Galindo et al. 2019; Perotti et al. 2019) and other research in geoparks (Melinte-Dobrinescu et al. 2017). In a few cases, land use practices were integrated into the UGGp management following the analysis of land use changes and natural risks with GIS, as performed in the Batur volcanic UGGp in Indonesia (Utama and Sandi Adnyana 2019). Sporadically, geoparks have used GIS for other technical purposes, such as the Sardinian Mining UGGp in Italy, where GIS was involved in a regional delineation and development model (Manca and Curtin 2012), the Hondsrug UGGp in the Netherlands, where the spatial affinity of inhabitants within the UGGp was analysed via GIS (Stoffelen et al. 2019), or the Ciletuh-Palabuhanratu UGGp in Indonesia, which performed a visual analysis in GIS (Nandi 2019). Furthermore, a small number of UGGps have started the development of a tourism geographic information system (TGIS) for travel information inquiry, making specific tourism charts, and helping take decisions on tourism development, as in the case of Mount Sanqingshan UGGp in China (Ye et al. 2012, 2014). In recent years, selected coverages are transferred to visitors through mobile applications (Chu et al. 2012; Li et al. 2015) and web viewers such as WebGIS (Hartoko et al. 2018) and Google Maps (Nurpandi et al. 2020), facilitating access to information for tourists.

The Spanish UGGp Forum hosts 15 UGGps (Fig. 1a) in mountainous and coastal rural areas with an extraordinary and varied geoheritage (Hilario Orús and Carcavilla Urquí 2020). In Spain, the Law 42/2007 of Natural Patrimony and Biodiversity (Carcavilla et al. 2009) and other lower legislation acts consider UGGps as protected areas, albeit the protection measures and land uses are not regulated until now. Spanish UGGps are essentially place brandings (Van Geert 2019) associated with a local development strategy based on a noticeably geoheritage (Fernández et al. 2014; Ortega-Becerril et al. 2017; Galindo et al. 2019; Horacio et al. 2019) with international standards (Finney and Hilario 2018). This development strategy promotes a growing geotourism industry (Poch and Llordes 2011; Rivero et al. 2019), broadly reinforced by public geological/palaeontological museums (Alcalá 2018; Moliner and Mampel 2019) and specific educational actions (Martínez-Frías et al. 2017; Álvarez 2020). Furthermore, Spanish geoparks are usually linked to natural protected areas that act as good references for territorial management (Canesin et al. 2020).

The Courel Mountains UGGp (2017) is based on the relationship between its geology, biodiversity and human development since prehistoric times. Therefore, a great amount of heterogeneous information should be integrated for the suitable development of the UGGp, making GIS an indispensable tool for this purpose. Here, we aim to design a GIS-supported database for the management of the Courel Mountains UGGp by means of a multidisciplinary team including geographers, geologists, archaeologists, biologists, engineers and managers. For the elaboration of thematic maps, 'use cases' are reported as the base for the implementation of the GIS database in the decision-making processes.

Setting

The Courel Mountains UGGp (578 km^2 in extension) is located in the historic region of Galicia, in northwestern Spain (Fig. 1). The UGGp is conducted by the Ribeira Sacra-Courel Local Action Group (ES-212; LEADER Program of the European Union) in coordination with the three municipalities that constitute the Geopark (from north to south: Folgoso do Courel, Quiroga and Ribas de Sil). The Courel Mountains UGGp was conceived following a clear bottom-to-up approach, resulting from the embracement of its geoheritage for more than 10 years. The target of the UGGp is the suitable rural development of the Courel Mountains to

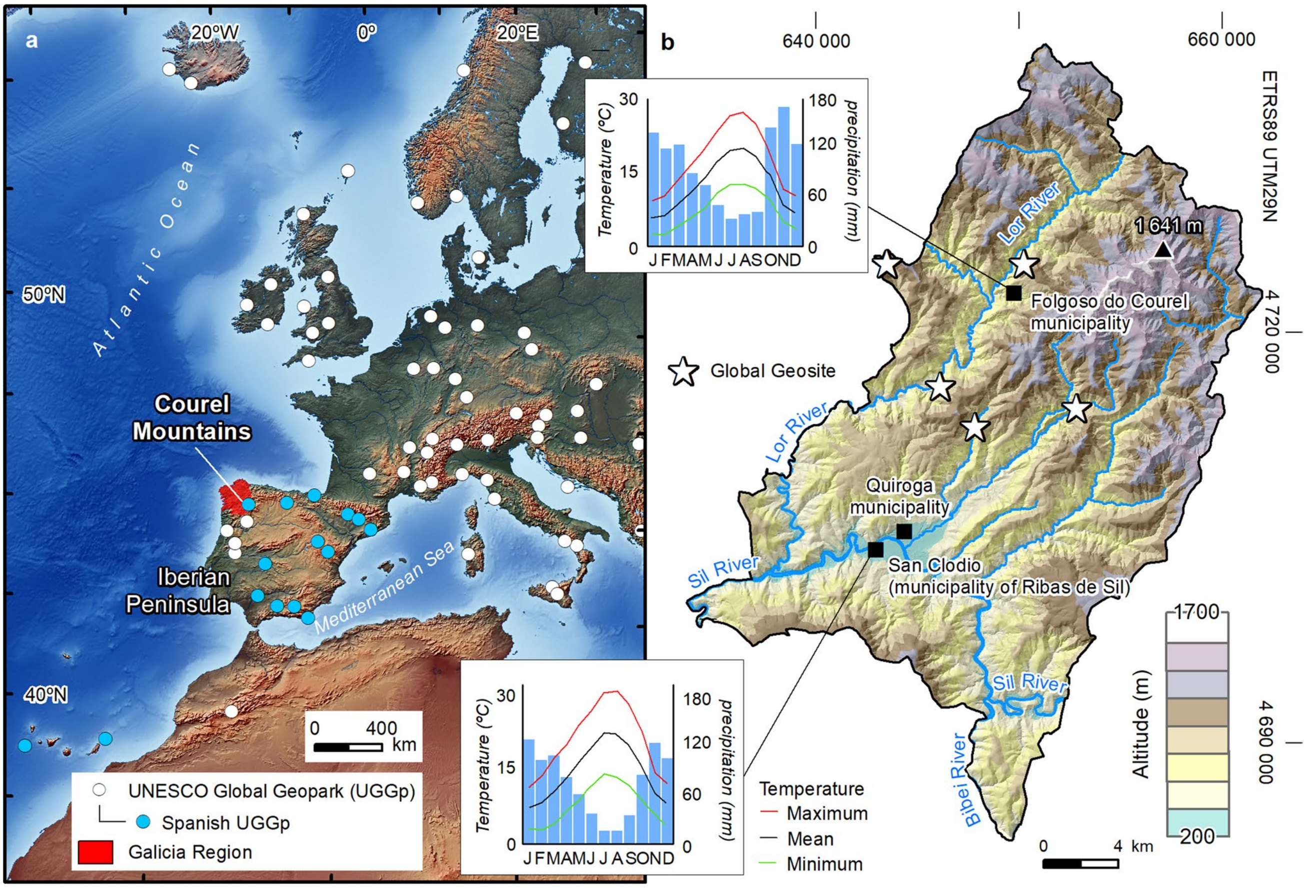

Fig. 1 **a** Location of the Courel Mountains UNESCO Global Geopark (UGGp) in the region of Galicia (Spain), in the Southwest of Europe. **b** Overview of the Courel Mountains UGGp highlighting its global geosites related to five outcrops of the Courel recumbent fold. Climographs were carried out performing raw data (2000–2020) from *Meteogalicia* (meteorology agency of Galicia; www.meteogalicia.gal)

avoid the economic and demographic depletion of the territory, promoting geotourism, science education and conservation. The cornerstone of the UGGp is the singular relationship between its noticeable geoheritage, the extraordinary biodiversity and the abundant cultural patrimony. Courel Mountains have another distinctive feature as both Galician and Spanish are their official languages. Place names and the indigenous knowledge are in Galician, with a particular vocabulary used only in the territory. This regional language represents an intangible cultural heritage that is combined with Spanish and English for UGGp communications and outreach.

The territory is completely mountainous, with differences in altitude up to 1400 m (Fig. 1b). The orography determinates the humid climate with cool-dry summers (Csb climatic type according to the Köppen-Geiger classification; Cunha et al. 2011) with two clearly distinct areas: Atlantic influence to the north of the UGGp, with 1200 to > 2000 mm of annual precipitation, and Mediterranean conditions to the south, with valleys receiving a total annual rainfall of ca. 800 mm. Average extreme temperature ranges from − 10℃ to 40℃ along the year, and snow usually covers the mountains ranges from November to April.

The geology of Courel Mountains spans three tectonic cycles (Cadomian-Avalonian, Variscan and Alpine) since the Upper Proterozoic to the Quaternary, although the most prominent bedrock features are Variscan (Martínez Catalán et al. 1992). The geological history is mostly restricted to the Permian-Paleogene time interval. For these reasons, the UGGp forms part of the so-called Variscan domain covering ca. 20% of Europe (Matte 1991; Nance et al. 2012). The Variscan bedrock recorded the sediments and environments of extinct Palaeozoic seas, where life fully spread. The history of one of these seas, the Rheic Ocean, is depicted in Courel Mountains from its origin as the back-arc basin of the Cadomian-Avalonian magmatic belt during the Neoproterozoic-Cambrian (Fernández-Suárez et al. 2000) to its closure by the Variscan orogeny in the lower Carboniferous (Martínez Catalán et al. 2004). Coevally, metallic ore deposits were formed (Tornos et al. 1995). The relief of the Variscan orogen was eroded, but its structural evidence is well-represented in Courel Mountains by a unique huge recumbent fold, the Courel syncline (Martínez Catalán et al. 1992; Fernández et al. 2007), which represents the flagship of the UGGp. Later on, Cenozoic tectonic collisions created the Alpine-Himalayan orogen, in which the westernmost part of Courel Mountains was uplifted along the Oligocene and Miocene (Martín-González and Heredia 2011a,b; Martín-González et al. 2012). Then, alluvial terraces and fans were developed from the erosion of the mountains, and karst caves were formed since at least the Chibanian (middle Pleistocene) (Railsback et al. 2011, 2017). Glacial and interglacial periods have influenced the Quaternary climate and landscape evolution, overprinting previous landforms (Pérez-Alberti and Cunha 2016; Oliva et al. 2019; Viana-Soto and Pérez-Alberti 2019), and causing noticeable changes in vegetation (Santos et al. 2000; Muñoz Sobrino et al. 2001) and the historic development of human societies (de Lombera Hermida 2011; Tejerizo-García and Canosa-Betés 2018). Human populations in Courel Mountains extracted the local bedrock for obtaining building stone and ore minerals, including gold and iron (Sánchez-Palencia et al. 2006; Cardenes et al. 2015), and produced crops, today represented by local products such as wine, olive oil, chestnuts and honey.

Methodology

The database of the UGGp was framed in ArcGIS 10.8 (ESRI®) following the workflow detailed in Fig. 2.

Data Acquisition

Data acquisition was performed with the cooperation of municipal officers and local people. The information was captured from four sources: public repositories, the IGME database, previous works, and fieldwork/photointerpretation. (1) Public agencies of Spain and Galicia conduct open-source repositories (with open-source license) that include datasets in raster and vector formats related to the topography, aerial photography, administrative boundaries, infrastructures, land uses, floods, forest cover and soil erosion (Table 1). Datasets from six repositories were cut by the limits of the geopark and put into GIS to perform mainly the technical data and vegetation coverage. (2) The Instituto Geológico y Minero de España (IGME; Spanish geological survey) belongs to the Consejo Superior de Investigaciones Científicas (CSIC; Spanish national research council) and manages an extensive database comprising geological features from local to national scales. The database comprises the vector files of the GEODE digital geological map (at 1:50,000 scale) and the national geosites inventory (IELIG) (Table 2), which were projected into the ETRS89 reference system and imported into GIS. Additionally, the IGME database contains raw data of local mineral ore deposits, mining, and igneous and metamorphic petrology (e.g., thin section descriptions under microscopy). These data were employed to conduct the new coverages related to mineralizations and rocks. (3) Previous works (reported in Supplementary information 1) supplied information for the elaboration of coverages (e.g., hydrogeological datasets, paleontological and archaeological inventories) and the definition of the feature attributes. Several of these published maps (e.g., geomorphological maps) were digitalized into GIS. (4) Fieldwork and photointerpretation supplied data to draw up coverages (e.g., surface formations). The manual acquisition was carried out using editing GIS tools. Local people played a relevant role to indicate the presence of ethnographical sites, which are abandoned or hidden within the vegetation at present.

Data Treatment

Acquired data were homogenised and revised, while the topological relationships between vector features were analysed via inspector tools following Ubeda and Egenhofer (1997). The homogenisation step was used to standardise the data for the entire UGGp in accordance with previous works, understanding among scientists and updated scientific criteria. The standardisation involved the definition of common terminology, data pooling and filling gaps in attribute tables of the coverages. Frequently, previous works developed since the mid-twentieth century only covered specific areas employing different terminologies and methodologies according to their targets and new insights. For instance, different geological and geomorphological units defined along the territory were unified by grouping equivalent units and extending the cartographies to all the territory in order to create the stratigraphic sequence and draw the geological and geomorphological maps of the UGGp. Coevally, captured data was revised to remove mistakes, shortcomings and inconsistencies that are expected from the combination of different data sources and works conducted over the years. Former data was checked by means of photointerpretation and local fieldwork, as well as the assistance of partner experts and the collaboration between scientists. Altogether, the homogenization and revision of the database led to the validation of the coverages and their attributes.

Data Storage

The database is hosted at the workstation of the Courel Mountains UGGp, which is managed by UGGp agents to preserve the privacy of the raw data. The information was compiled in 66 independent coverages according to their topic and data geometry (Table 3). Topics are grouped into

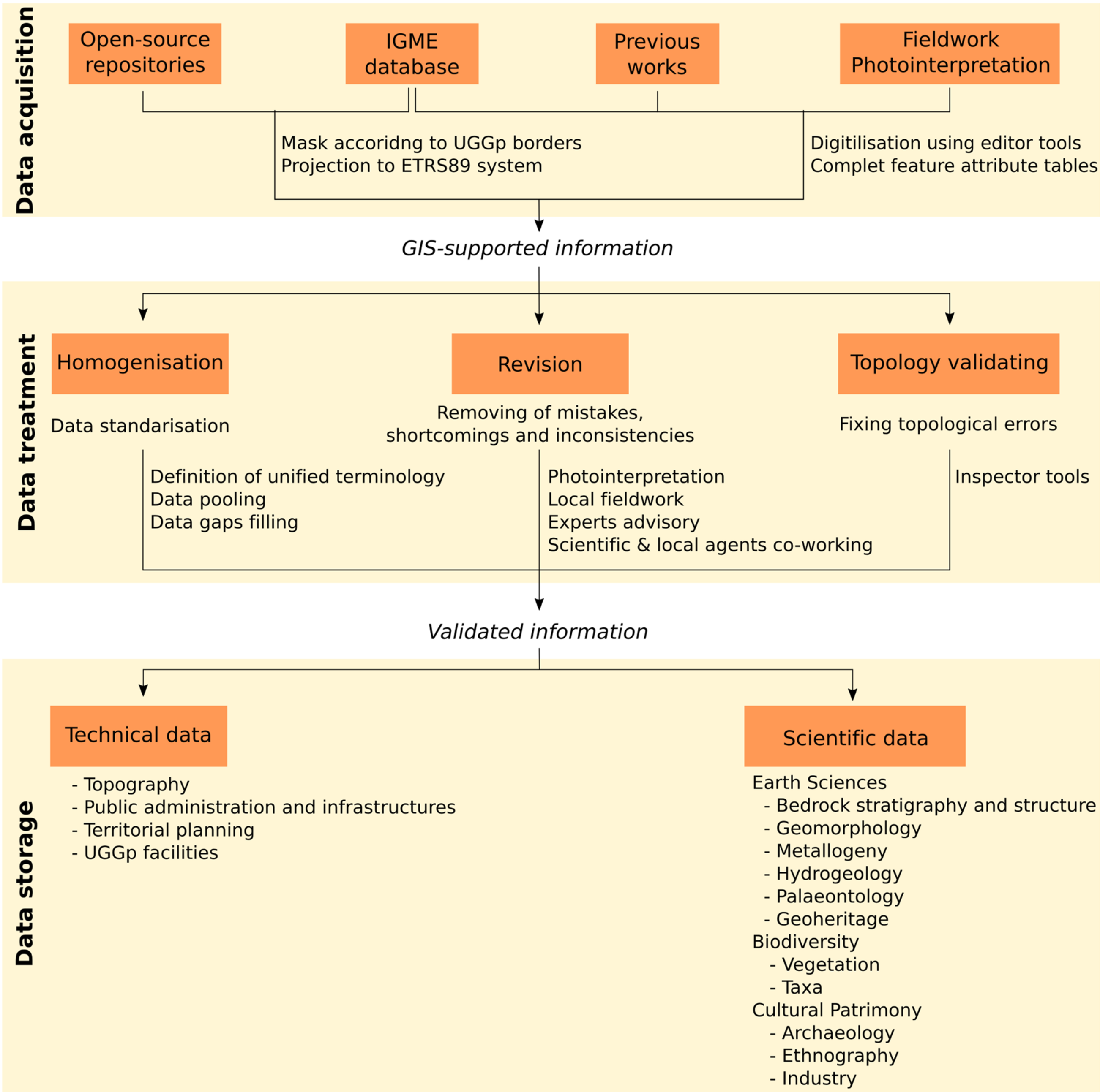

Fig. 2 Workflow of the construction of the GIS database of the Courel Mountains UGGp showing the main steps and tasks

technical and scientific data, which are divided into geosciences, biodiversity and cultural heritage.

The technical data correspond to 36 coverages including topography, public administration, infrastructures, territorial planning and UGGp facilities. Topographic data represent the reference base map for data acquisition and comprise topographical contours, four digital models (elevation, slope, hillshade and aspect), aerial orthophotographs and watercourses (Table 3). Public administration and infrastructure data comprise municipalities (local authorities), parishes and communal areas (public lands managed jointly by neighbouring residents), as well as villages, individual buildings and communication routes (roads and railways). The territorial planning shows the spatial distribution of human activities and protected areas covering land use (updated in 2019), protected areas, fishing reserves, singular trees catalogue, burnt areas and protected cultural sites (Table 3). These monuments are grouped in two legal categories, declared site of cultural interest (*Bien de Interés Cultural* in Spanish; the major category) and catalogued patrimony (*Bien*

Table 1 Public open-source repositories conducted by public administrations and agencies, which provide GIS datasets according to the Law 14/2010 of Spain

Acronym	Source		Public administration or agency		Scale	Webpage
Name	Description	Source	Description			
CNIG	Centro Nacional de Información Geográfica	National Centre of Geographic Information	Instituto Geográfico Nacional (IGN)	Geographic national institute	National	https://bit.ly/3k8KBeK
SIOSE	Sistema de Información sobre Ocupación del Suelo de España	Land Use Information System of Spain			National	https://www.siose.es
SNCZI	Sistema Nacional de Cartografía de Zonas Inundables	National Flood Zone Mapping System	Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO)	Environment ministry	National	https://bit.ly/352bV84
MFS	Mapa Forestal de España	Forest Map of Spain			National	https://bit.ly/3jaIsOa
INES	Inventario Nacional de Erosión de Suelos	Spanish National Inventory of Soil Erosion	Ministerio de Pesca, Agricultura y Alimentación (MAPA)	Fishing, agriculture and food ministry	National	https://bit.ly/37go8Zm
IDEG	Infraestrutura de Datos Espaciáis de Galicia	Spatial Data Infrastructure of Galicia	Xunta de Galicia	Regional Government of Galicia	Regional	http://mapas.xunta.gal/ideg/

Table 2 Queried geoscientific databases of the *Instituto Geológico y Minero de España* (IGME; Spanish geological survey) (www.igme.es)

Acronym	Source	Description	Webpage
GEODE	GEODE	Digital continuous geological mapping of Spain at a scale 1:50 000	https://bit.ly/3oUsdsE
BDMIN	Base de Datos de Recursos Minerales	Mineral resources database	http://doc.igme.es/bdmin/
IELIG	Inventario Español de Lugares de Interés Geológico	Spanish Inventory of Geosites	https://info.igme.es/ielig/
RIM	Base de Datos de Rocas Ígneas y Metamórficas	Database of igneous and metamorphic rocks	https://bit.ly/3ekvWuT

Catalogado). The UGGp facilities include the extension (base map), infrastructures (visitors centres, museums, tourism offices, viewpoints, panels with geological, biological and archaeological information), touristic routes and suitable areas for outdoor activities (hiking, swimming, canyoneering, navigation, technical rock climbing), in addition to local services for accommodation and nourishment (Table 3).

The geoscientific data spans from the Palaeozoic bedrock to the Quaternary sciences, including 29 coverages related to geology, geomorphology, metallogeny, hydrogeology, palaeontology and geoheritage (Table 3). The geological map is based on GEODE (Table 2) and is composed of geological formations (lithostratigraphical units and igneous intrusions), contacts, fold axes and orientation data. The stratigraphical section resulted from the correlation, homogenization and simplification of rock formations following Martínez Catalán et al. (2016) and other works compiled in Supplementary information 1. The geomorphology comprises a geomorphological map supplemented by the active landslide inventory, map of flood-prone areas, geometric 2D reconstruction of ancient palaeoglaciers and the karst cave inventory (Table 3). Also included is topographic restitution of the A Seara palaeoglacier based on field evidence and applying the numerical model described in Benn and Hulton (2010) and the ArcGIS GLARE toolbox (Pellitero et al. 2016). Karst caves were 3D modelled and integrated into GIS based on cave survey data following Ballesteros et al. (2019). Metallogeny data are represented by the ore deposits of economic interest; many of them mined in the past. The hydrogeological information corresponds to the map of aquifers, aquitards, springs, rivers and effluent watercourses (stream sections whose flow decreases downstream due to water infiltration), while the palaeontological inventory incorporates the fossil assemblages discovered within the UGGp limits. The collated geological information provides the base for the ongoing geoheritage inventory of the UGGp according to its natural, scientific and use values, as was stated by the Spanish Law 42/2007 (Carcavilla et al. 2009).

The high biodiversity of the Courel Mountains is depicted by general vegetation and forest type maps, in addition to

Table 3 Structure of the data followed in the GIS database of the Courel Mountains UGGp, indicating the coverages and their descriptions, formats, geometry, scale of work (vector format) or cell size (raster format), and their source or acquisition procedure

Data		Coverage	Description	Format	Geometry	Scale/cell size (m)	Acquisition/Source
Technical data	Topography	Topographical contours	Relief contours	Vector	Polylines	1:5000	CNIG
		Digital elevation model (DEM)	Altitude (above sea level) of each cell	Raster	Matrix	5 m	
		Digital slope model	Slope grade of each cell	Raster	Matrix	5 m	GIS analyses of DEM
		Digital hillshade model	Insolation grade of each cell	Raster	Matrix	5 m	
		Digital aspect model	Azimuth of each cell	Raster	Matrix	5 m	
		Orthophotographs	Rectified aerial photographs	Raster	Matrix	0.25 m	CNIG
		Rivers	Watercourses network	Vector	Polylines	1:5000	
	Public administration and infrastructures	Administrative boundaries	Limits of municipalities and parishes	Vector	Polygons	1:25,000	IDEG
		Communal areas	Public communal areas managed by the neighbourhood association	Vector	Polygons	1:25,000	
		Buildings	Dwellings and other buildings	Vector	Polygons	1:5000	
		Villages	Populated areas	Vector	Points	1:25,000	Data performed by the CNIG
		Roads	Paved and earth roads, and railways	Vector	Polylines	1:5000	CNIG
		Toponymy	Place names	Vector	Polylines	1:5000	
	Territorial planning	Land use	Territory zonation according to land use and vegetation	Vector	Polygons	1:25,000	SIOSE
		Protection areas	Area with specific legal status	Vector	Polygons	1:5000	IDEG and *Asociación Galega de Custodia do Territorio* (local environmental association)
		Singular trees catalogue	Official catalogue of long-lived, beauty and size trees specimens	Vector	Points	1:5000	IDEG
		Fishing reserves	River reach with fishing regulation	Vector	Polylines	1:5000	
		Burnt area	Wildfire-affected areas between 2010 and 2018	Vector	Polygons	1:5000	
		Catalogued landscapes	Areas belonging to the official catalogue of landscapes of Galicia	Vector	Polygons	1:5000	
		Official sites of cultural interest	Official historical monuments – 1st category – declared by the Regional Government	Vector	Points	1:5000	

Table 3 (continued)

Data		Coverage	Description	Format	Geometry	Scale/cell size (m)	Acquisition/Source
		Official landscapes of cultural interest	Official historical landscape – 1st category – declared by the Regional Government	Vector	Polygons	1:5000	
		Official catalogued cultural patrimony	Official historical monuments – 2nd category – declared by the Regional Government	Vector	Points	1:5000	
		Mining concessions	Official permission for mining exploration/exploitation on geological resources	Vector	Polygons	1:25,000	
	UGGp facilities	UGGp extension	UGGp limits	Vector	Polygons	1:25,000	Administrative boundaries coverage
		Visitor centres	Museums, interpretation centres and tourism offices	Vector	Points	1:5000	Own data and photointerpretation
		Viewpoints	Viewpoints of geological interest	Vector	Points	1:5000	
		Picnic areas	Picnic-equipped areas (with tables and benches)	Vector	Points	1:5000	
		Panels	Panels with touristic/educational information of the UGGp	Vector	Points	1:10,000	
		Touristic routes	Routes for the general public	Vector	Polylines	1:5000	
		Hiking trails	Trails for hiking	Vector	Polylines	1:5000	*Wikiloc* trail database (https://es.wikiloc.com)
		Swimming areas	Fluvial beaches, natural stream ponds and other swimming areas	Vector	Points	1:5000	Own data and photointerpretation
		Ravines	Ravines equipped for descent (canyoning, canyoneering)	Vector	Polylines	1:5000	
		Climbing areas	Walls equipped for climbing	Vector	Points	1:5000	
		Paragliding	Paragliding take-off spots	Vector	Points	1:5000	
		Climbing areas	Areas equipped for climbing	Vector	Points	1:5000	
		Navigation	Rivers and streams for wild-water sport and shipping (calm water)	Vector	Polylines	1:5000	
		Local services	Restaurant and/or accommodation	Vector	Points	1:5000	
Earth Sciences	Bedrock stratigraphy and structure	Lithologies	Geological formations	Vector	Polygons	1:50,000	GEODE and revision via photointerpretation and fieldwork

Table 3 (continued)

Data		Coverage	Description	Format	Geometry	Scale/cell size (m)	Acquisition/Source
		Contacts	Stratigraphical contacts, faults and fold axes	Vector	Polylines	1:50,000	
		Orientation	Bedding and foliation data (strike and dip angles)	Vector	Points	1:50,000	
		Rocks	Rock description under a microscope	Vector	Points	1:50,000	RIM
	Geomorphology	Surface formations	Alluvial, slope, glacial, periglacial and karst deposits	Vector	Polygons	1:5000	Previous works, photointerpretation and fieldwork
		Lineal geomorphological features	Alluvial, slope, glacial, periglacial and karst lineal features	Vector	Polylines	1:5000	
		Flooding areas	Fooding areas for return periods of 5 years, 10 years, 50 years, 100 years, and 500 years	Vector	Polygons	1:5000	SNZCI
		Active landslides inventory	Current landslides in motion	Vector	Points	1:25,000	INES
		Palaeoglacier	Geometric reconstruction of ancient glaciers	Vector / Raster	Polylines	1:5000	Reconstruction using Excel and ArcGIS tools
		Karst cave inventory	Inventory of karst cave entrances	Vector	Points	1:1000	Cave survey data collected by speleological teams
		Karst cave conduits	3D geometry of karst caves	Raster	Polygons	1:200	
	Metallogeny	Ore deposits	Ore deposits of economic interest	Vector	Points	1:25,000	BDMIN, previous works and fieldwork
	Hydrogeology	Hydrogeological units	Aquifers and aquitards	Vector	Polygons	1:20,000	Performing geological and geomorphological maps
		Springs inventory	Springs and fountains	Vector	Points	1:20,000	Previous works and fieldwork
		Effluent watercourses	Streams with flow lose by water infiltration	Vector	Polylines	1:20,000	
	Palaeontology	Palaeontological inventory	Palaeontological sites	Vector	Points	1:25,000	Previous works and fieldwork
	Geoheritage	Geosite	Preliminary inventory of geosites	Vector	Points	1:5000	Expert suggestions, previous works, GIS database and fieldwork
		Geosites extension	Limits of preliminary geosites	Vector	Polygons	1:5000	
Biology	Vegetation	Vegetation map	Vegetation types	Vector	Polygons	1:25,000	SIOSE
		Forest and scrups maps	Forest types and main threes	Vector	Polygons	1:25,000	MFE

Table 3 (continued)

Data		Coverage	Description	Format	Geometry	Scale/cell size (m)	Acquisition/Source
	Taxa	Species list	Non-exhaustive list of flora, fauna and fungi	Vector	Polygons	1:25,000	*iNaturlist* database (www.inaturalist.org), *BioBlitz* Courel project, Asociación Galega de Custodia do Territorio, previous works
Human history	Archaeology	Archaeological inventory (points)	Archaeological sites	Vector	Points	1:10,000	IDEG, previous works, photointerpretation and fieldwork
		Archaeological inventory (extension)	Archaeological sites	Vector	Polygons	1:5000	
	Ethnography	Beehive protection barriers	Circular stonewalls around beehives to prevent bear attacks	Vector	Points	1:5000	
		Lime kiln	Kilns for lime production from carbonate calcination	Vector	Points	1:5000	
		Watermill	Hydraulic mills for cereal flour manufacture	Vector	Points	1:5000	
		Oil mill	Mills for oil manufacture	Vector	Points	1:5000	
		Manor houses	Traditional manor houses	Vector	Points	1:5000	
	Industry	Modern industry	Mining industry, hydroelectric power stations and dams, and bridges	Vector	Points	1:25,000	

The acronyms are detailed in Tables 1 and 2 species list coverages. The general vegetation map shows scrublands, woodlands and crop areas mapped in 2018, whereas the forest coverage map shows the types of woodlands, scrublands, main taxa and biogeographic regions, updated in July 2020. A non-exhaustive list of flora, fauna and fungi was elaborated to approach the biodiversity of the Courel Mountains. The list integrates a local initiative named BioBlitz Courel conducted in 2018–2019 by the scientific station for surveying species (Alonso Díaz et al. 2018a, b) and ground surveys of flora micro-reserves (Asociación Galega de Custodia do Territorio 2020).

The cultural heritage includes archaeological, ethnographic and industrial sites. Archaeological sites considered are those prior to the Industrial Revolution (nineteenth century in Spain). Ethnographical data represent indigenous knowledge linked to geological resources and local products. The industrial heritage covers sites related to past and ongoing industrial activities of interest, developed after the Industrial Revolution.

Outputs

Selected data of the GIS dataset was exported to online applications or used to elaborate maps as new graphic resources of the UGGp. Sites of geological, ecological and cultural value were transferred to the web viewer Google Maps (http://cutt.ly/YyPhopF) to guide visitors along the UGGp. New maps were made by overlapping selected coverages and designing a legend according to the target audience and purpose. These maps will be used directly in touristic and dissemination activities, panels and visitor centres or transferred to internal or external assistance specialised in the dissemination to a broad or specific audience (see examples in the Supplementary information 2). In this sense, maps were exported as individual layers in file formats (e.g.,.eps,.ai,.svg) used commonly by designers and illustrators. This procedure ensures the correctness and quality of the touristic and educational contents in brochures, leaflets, books, panels, web pages and other outputs and actions, favouring the homogeneity of the publishing information.

Data Analysis

Archived data were analysed using statistical and spatial functions available within GIS operations for the elaboration of educational contents and the technical advisory of UGGp actions. Statistics and spatial functions provided data of geological, biological and cultural features and their relationships, which can be used for outreach actions. For example, GIS functions were applied to retrieve the number of Roman mines, average slope at the watermill locations, average orientation of beehives, location of villages on ancient landslides, length and vertical range of routes, relative abundance of a rock type and distribution of particular species, or to compute the profile of a glacial valley. Spatial operations also helped the technical advisor in designing touristic products (e.g., routes) or facilities (e.g., panels, viewpoints) and developing specific assessments to policy-making. Spatial operations quantified the spatial distributions of facilities and services to create new touristic products.

Results

Territorial Organization and Facilities of the UGGp

Six technical basic maps exhibit the territorial structuration and the educational, touristic and research facilities of the UGGp. The population (5178 inhabitants in 2019) is widespread in 190 small villages, most of them with less than ten dwellings. Nowadays, most villages have around 5–20 residents or are completely abandoned. Villages are connected by 407 km of roads concentrated in the southern part of the UGGp, where most populated areas are located (Fig. 3a). There, a national road and railway line constitute the main access points to the UGGp following the Sil river. Communal areas (64% of the territory) are handed by the neighbour associations of 89 villages, which play a relevant role in the territory management at a local scale.

Natural areas represent 77% of the UGGp, covering mainly scrublands (52%) due to historic deforestation, although native forests of high biodiversity are preserved in 23% of the Courel Mountains (Fig. 3b). Native woods include woodlots traditionally managed for producing chestnut as a local product in the north (Guitián et al. 2012). Furthermore, natural areas also include bare-rock outcrops (2%) linked frequently to the geoheritage. The remaining 23% corresponds to anthropic areas including conifers afforestation projects (14%) for timber harvest, which generate a modest benefit to the local communities. Agriculture areas (6%) are mainly arable crops, vineyards and citric and olive trees concentrated in the south, while traditional villages conduct pastures for livestock feed in the north. These traditional activities of low cost-effective benefits are being abandoned, while the wine (belongs to an appellation of origin named Ribeira Sacra) and the Quiroga olive oil are being promoted as noticeable local products. The Spanish Government authorised the private investigation and exploration of 44% of the UGGp territory for mining and water resource concessions, including metallic minerals, industrial minerals and rocks (building stone) and bottled water (Fig. 3c). Nevertheless, only 1% of the territory is quarried for roofing slate and aggregates, while its wastes occupy another 1% of the UGGp. The mining industry represents a relevant local economic engine, although this comes with negative impacts

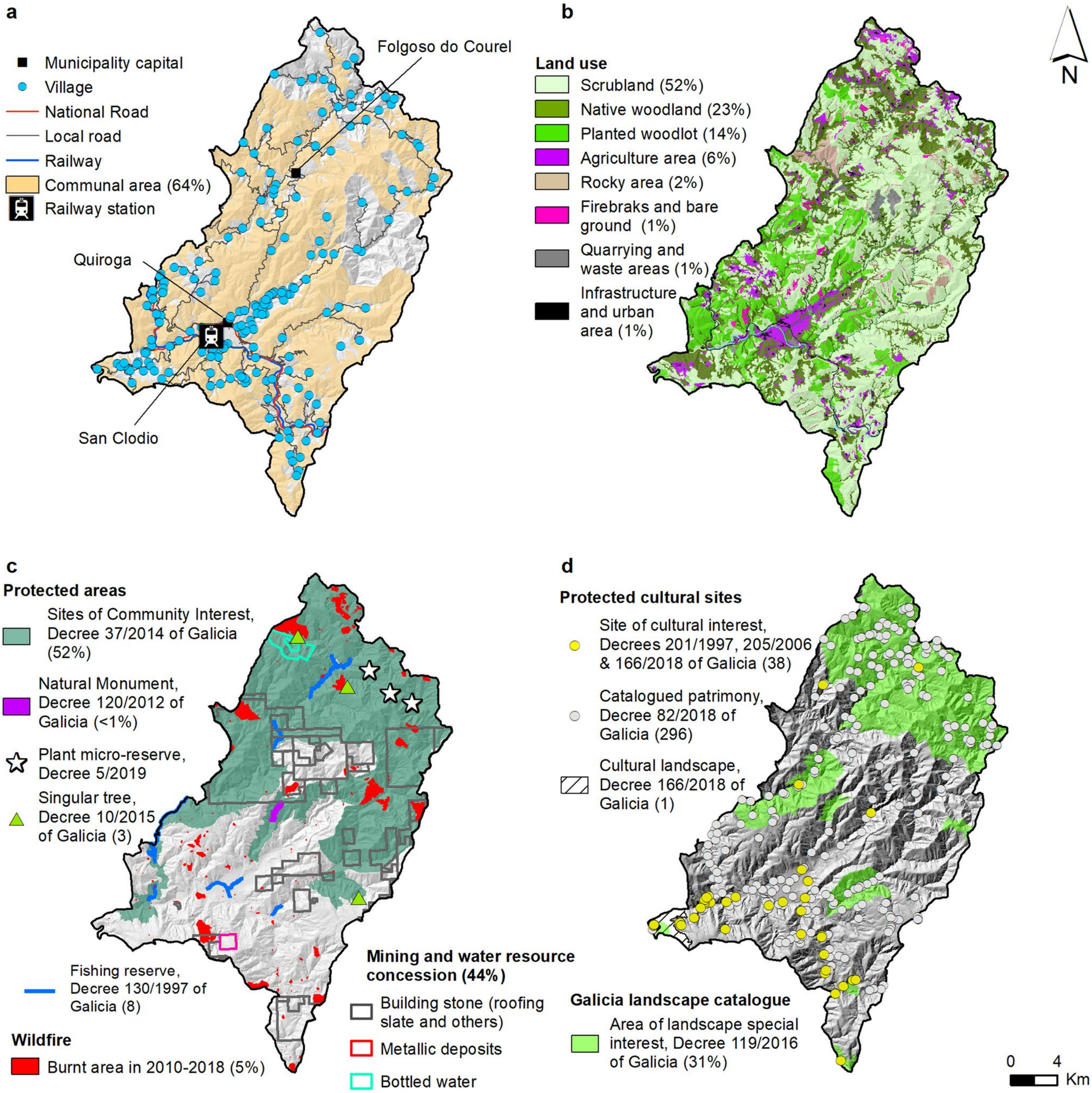

Fig. 3 Territorial organization of the Courel Mountains UGGp. **a** Population and infrastructures. **b** Land use derived from the SIOSE (Table 2). **c** Protected areas, catalogued trees, wildfire, and mining and water resource concessions. **d** Protected cultural sites. Data in brackets indicates the relative extension (%) in respect to the UGGp or the number of features

to natural areas and the geoheritage (Fig. 3b). Finally, urban and other areas represent just 1% of the UGGp.

Protected areas where mining and other activities are unauthorised represent 52% of the UGGp (Fig. 3c). Conservation areas include two sites of community interest within the Natura 2000 network (Habitats and Birds European Council Directives, 92/43/EEC and 2009/147/CE), the Courel recumbent fold Natural Monument also inscribed as Global Geosite in the IELIG (Table 2), and three micro-reserves for protecting endemic and threatened orchids and other flora, managed by a local environmental association (*Asociación Galega de Custodia do Territorio)* in the framework of the EU-funded LIFE project. In addition, fishing is legally regulated by the regional government in eight river reaches, while two chestnut trees (*Castanea sativa*) and a common yew (*Taxus baccata*) are legally protected by their age, size and attractiveness (Fig. 2c). Unfortunately, 5% of the UGGp has been affected by wildfires between 2010 and 2018, including scrub areas, woodlands and geosites (Fig. 3c). Finally, the law also protects 38 sites of cultural interest, a cultural landscape and 296 catalogued patrimonies, while 31% of Courel Mountains are included within the Galician landscapes catalogue (Fig. 3d).

Visitor receptions are facilitated in five museums/interpretation centres and two tourist offices, complemented by 22 viewpoints with geological information distributed over the territory. Additionally, the UGGp has a scientific station conducted by the Universidade de Santiago de Compostela for research, education and outreach purposes (Fig. 4a). The UGGp established seven touristic routes (by car) summing 391 km, such as the Palaeozoic Villages Route (Ballesteros et al. 2021b, a) and the Camiño de Inverno a Santiago de Compostela (Winter Way of Saint-James) (Fig. 4b). Outdoor activities constitute an increasing economical resource, especially in the north of the UGGp, where tourist businesses operate. Outdoor activities include mainly fourteen hiking trails with a total of 189 km (Fig. 4c). There is also a fluvial beach and other twenty natural swimming areas, five dammed rivers suitable for boating (summing 12 km long) and three white-water rapids (summing 57 km in length) for kayaking and other water sports. Additionally, fifteen ravines with waterfalls are equipped for canyoneering (summing 21 km in length), and paragliding can be practised from six take-off spots (Fig. 4c).

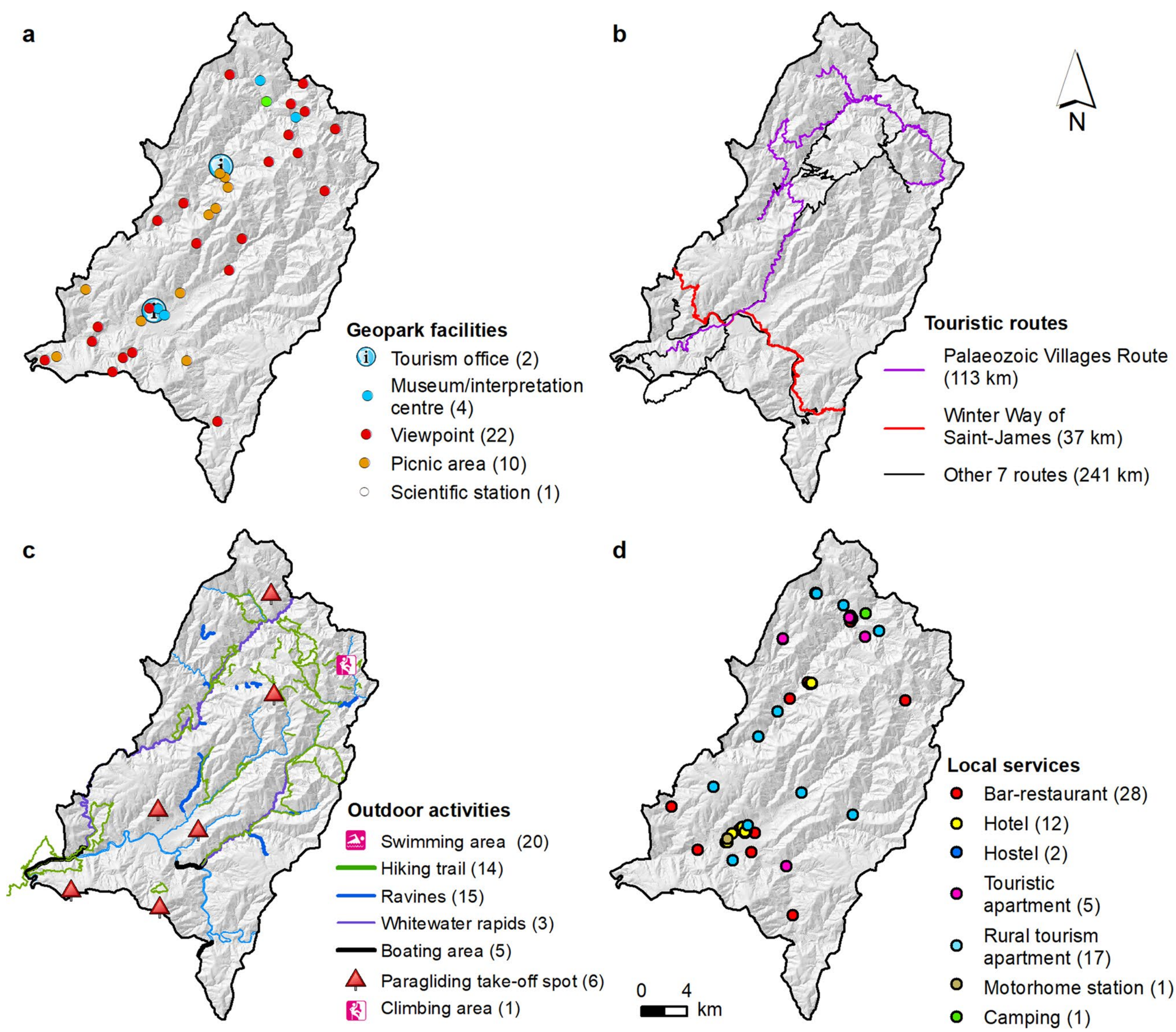

Fig. 4 Facilities of the Courel Mountains UGGp. **a** Visitor centres, viewpoints, picnic areas and scientific station. **b** Touristic routes. **c** Areas for outdoor activities. **d** Local services for accommodation and nourishment. Data in brackets indicates the number of features or total length (km)

Nowadays, 28 restaurants and bars are in the south, whereas 34 hotels, hostels, apartments and camping sites, totalling ca. 700 beds, are distributed throughout the UGGp (Fig. 4d). Among them, hotels and the motorhome service station operate in the south and apartments in traditional villages are in the north. The service distribution limits the development of touristic activities in the northern part of the UGGp, where main natural values are preserved and outdoor activities are concentrated. For this reason, major groups of visitors are frequently accommodated in the south of the UGGp.

Earth Sciences

The geological knowledge of the Courel Mountains is summarised by six geoscientific basic cartographies: the geological, geomorphological, metallogenic, hydrogeological, palaeontological sites and geosites maps. The geological map and cross-section (Fig. 5a–c) exhibit a folded Palaeozoic bedrock affected by greenschist facies metamorphism dominated by Upper Proterozoic to Devonian slate and quartzite (Dozy 1983; Martínez Catalán et al. 1992). Among these rocks, Lower Ordovician Armorican Quartzite and Silurian chloritoid slate and ampelithic black-slate outline over the UGGp, as well as meta-limestone in the north and (porphyroid) gneiss in the southwest. The origin and chronology of the gneiss is a controversial topic; recent studies suggested that the gneiss resulted from the metamorphism of igneous rocks and volcano-sedimentary rocks (e.g., Díez Montes et al. 2010; Montero et al. 2017). Variscan recumbent folds are the major geological structures, from which the Courel recumbent syncline was declared Natural Monument and Global Geosite by its singularity and scientific interest (Martínez Catalán et al. 1992; Fernández et al. 2007; Bastida et al. 2010, 2014). Variscan vertical folds are also reported causing a distinctive superposed folding. In general, Variscan mountain-building processes were coeval with unique synorogenic Lower Carboniferous rocks (Martínez Catalán et al. 2004). Furthermore, a singular granite crystallised during the Carboniferous-Permian limit (Fernández-Suárez et al. 2000) crops out in the southeast of the UGGp, and 99 documented dykes have intruded during the Permian-Mesozoic.

Courel Mountains UGGp shows singular fluvial and slope landforms and deposits, as well as local karst, glacial and periglacial features (Fig. 5a) (Pérez-Alberti 2018). Alpine orogeny uplifted Courel Mountains (Martín-González 2009) developing pop-down tectonic basins mainly filled by alluvial fans during the Oligocene and Miocene (Martín-González and Heredia 2011a, b; Martín-González et al. 2012). The uplifting also triggered the development of deep and narrow valleys of relevant geomorphological character (Horacio et al. 2019), while the high slopes (> 30°) favour landslides. Speleological teams documented 25 main karst caves 7 km in length, hosting stalagmite palaeoclimate records up to 550 ka (Railsback et al. 2011, 2017). Courel Mountains commonly exhibit stratified talus deposits and other periglacial features, some of them formed before 44 ka (Pérez-Alberti and Cunha 2016; Viana-Soto and Pérez-Alberti 2019). Glacial evidence, preserved above ca. 950 m altitude (Pérez-Alberti 2018; Oliva et al. 2019), allowed the reconstruction of eight palaeoglaciers in 2D and one glacier in 3D (Fig. 5d) occupying a total inferred maximum surface of ca. 22 km^2 before 21 ka cal BP (Muñoz Sobrino et al. 2001). Finally, surface processes are related to geological risks since landslide areas are common and rivers would inundate a total area of 1.7 km^2 each 500 years (Fig. 5d).

Surface run-off dominates the UGGp (Fig. 6a) since it is mainly formed by bedrock aquitards (slate, quartzite and gneiss of low permeability even if increased by local fracturation) and surface aquitards (clayey-silty deposits with low permeability; e.g., tills). Locally, karst aquifers are developed within meta-limestones in the north and surface (alluvial) aquifers mainly developed in the south, supplying up to 250 $l{\cdot}s^{-1}$ discharge. In general, aquifers are recharged from precipitation and sometimes by direct infiltration from an effluent watercourse. The aquifer discharge takes place either directly to rivers and streams or through 70 inventoried springs (with more than 5 $l{\cdot}s^{-1}$ average discharge). Karst springs (3) and ferruginous sulphate-bicarbonate springs (3) related to the Silurian black-slate stand out (Fig. 6a).

The metallogenetic map shows 99 mineralizations of Fe, Au, Sb, Pb–Zn-(Cu) and other elements (Fig. 6b). Iron deposits are mainly stratified breccia and mineralised fractures, as shown by goethite, hematite and other oxides and hydroxides. Native gold is disseminated in placer deposits or in quartz veins related to tectonic structures and, sometimes, ironstone (Cepedal et al. 2018). Stibnite constitutes stratabound deposits, one of them unique at a national scale, within Upper Ordovician marble (Guillou 1976; Gumiel and Arribas 1987). Galena and sphalerite mineralisation is stratabound or disseminated in ores within lower Cambrian carbonate rocks (Tornos et al. 1995). In general, metallic minerals resulted from exhalative and sedimentary processes during the lower Palaeozoic and, later, by magmatic-hydrothermal events that remobilised and concentrated elements coevally to the Variscan orogeny. Finally, the erosion of primary gold deposits and subsequent detrital sedimentation originated placer-type ores in Miocene-Quaternary alluvial fans (Pérez-García et al. 2000).

The paleontological inventory comprises 14 sites related to Palaeozoic marine invertebrates and seven karst caves where Quaternary mammal remains were discovered (Fig. 6c). Palaeozoic fossils normally have scarce occurrence in metamorphic regions. These fossils comprise singular regional specimens of Cambrian to Silurian trilobites

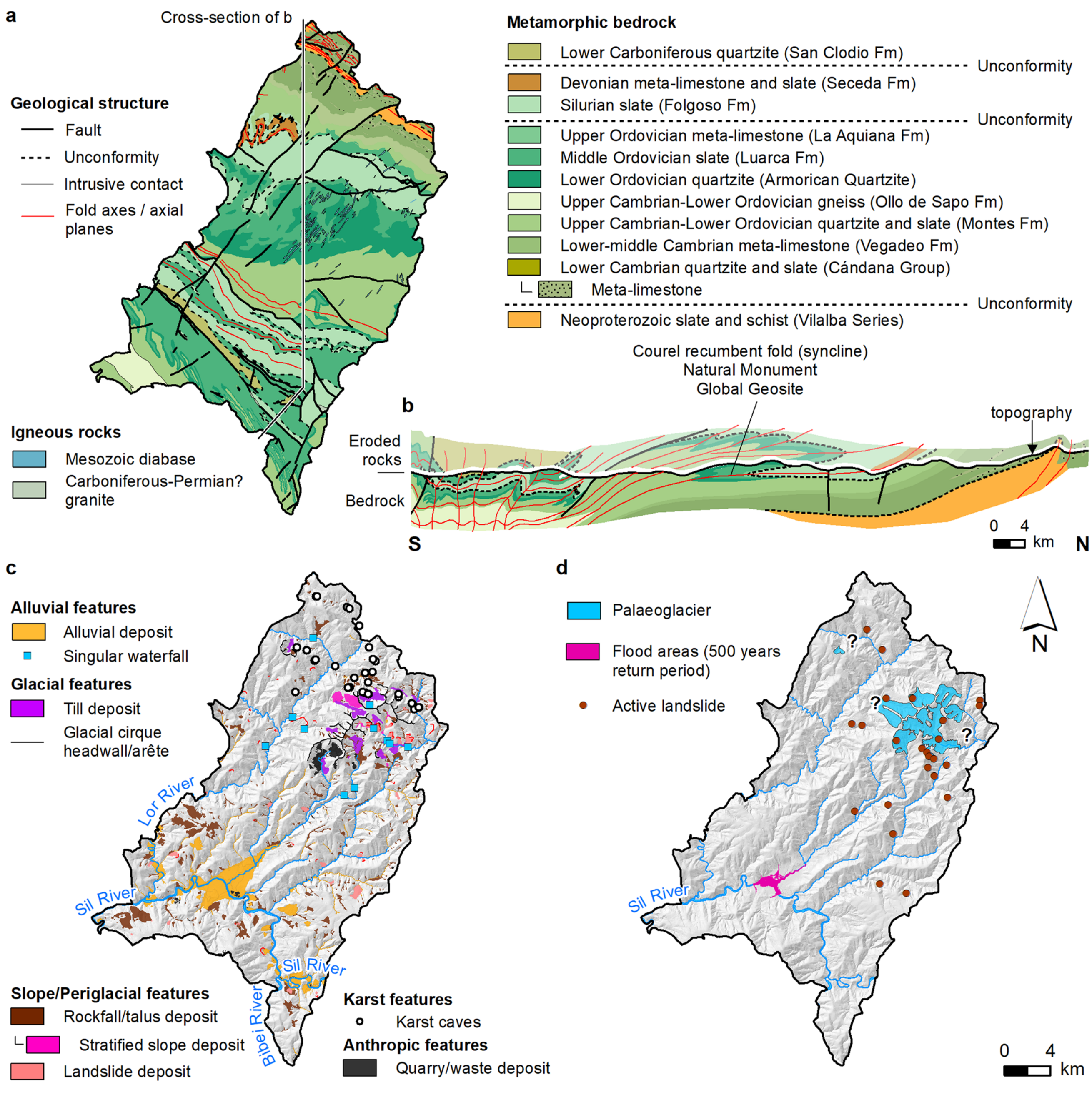

Fig. 5 Geology and geomorphology of the Courel Mountains UGGp. **a** Geological map based on the GEODE map (Table 2). **b** Geological cross-section after Martínez Catalán et al. (1992, 2004) showing the Variscan Courel recumbent fold. **c** Geomorphological map. **d** Reconstruction of palaeoglaciers at their local maximum extension and flooding areas for a return period of 500 years according to the SNCZI (Table 1). Data in brackets indicates the relative extension (%) in respect to the UGGp or the number of features

(Hammann 1983; Gutiérrez-Marco et al. 2001) and Silurian monograptids, highlighting their association with orthoceratids (Rábano et al. 1993) and the presence of uncommon Spanish Pridoli graptolites (Piçarra et al. 1998). Bones of brown bears and cave bears spanned the Upper Pleistocene-Holocene and allowed the conduction of stable isotope and DNA studies to address the hibernation, diet and social behaviour of both species (Pérez-Rama et al. 2011; Fortes et al. 2016; García-Vázquez et al. 2018), the local extinction of cave bears (Grandal-d'Anglade et al. 2019) and the arrival of brown bears from Europe after the Last Glacial Maximum (García-Vázquez et al. 2019).

Overall, the Courel Mountains UGGp shows an extraordinary geoheritage, hosting 67 preliminary geosites (Fig. 6d), which represent the entire aforementioned geological features and processes: 61% of them have

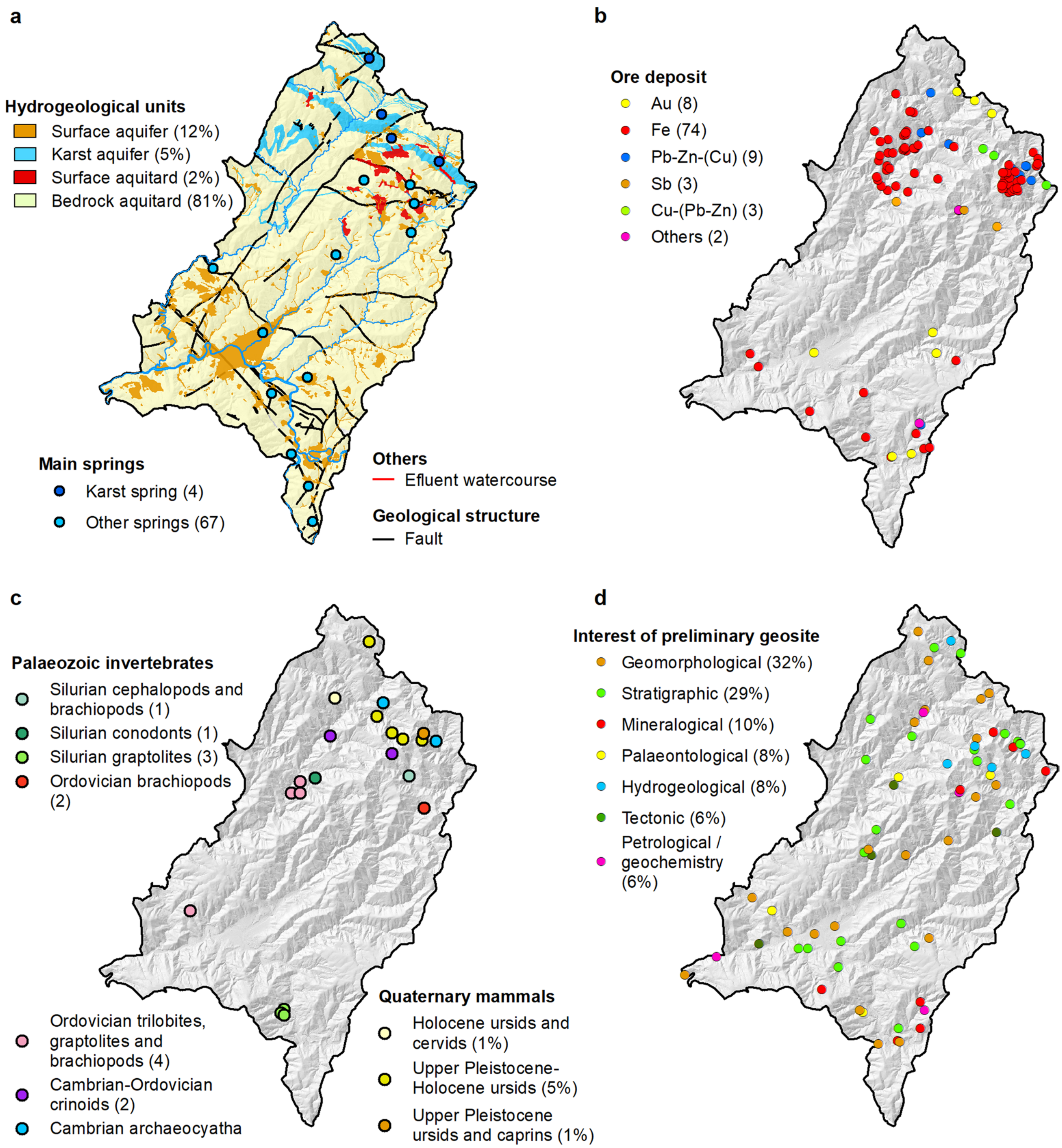

Fig. 6 Hydrogeology, metallogeny, palaeontology and geoheritage of the Courel Mountains UGGp. **a** Hydrogeological map depicting aquitards, aquifers, springs and an effluent watercourse. **b** Metallogenic map showing metallic ore deposits of economic interest. **c** Palaeontological inventory. **d** Preliminary geosites inventory representing only the extension of the largest geosites. Data in brackets indicate the relative extension (%) in respect to the UGGp or the number of features

geomorphological and stratigraphic interest, followed by mineralogical deposits (10%), palaeontological sites (8%) and hydrogeological features (8%). Lastly, geosites of tectonic and petrological/geochemistry interest represent 5% respectively, although the most relevant site, declared Global Geosite, is a recumbent fold. All geosites cover 5% of the Courel Mountains UGGp and are concentrated by sectors distributed over the UGGp.

Biodiversity

The biogeographic regions, general vegetation, scrubs and forest type maps (Fig. 7a,b) show the high biodiversity of Courel Mountains, linked to the occurrence of two climatic regions, a vertical range up to 1400 m, and the presence of a siliceous bedrock (95% of the UGGp) with minor carbonate rocks (5%). The Atlantic biogeographic region (53%) occupies the northern part of the Courel Mountains, while the Mediterranean region (47%) is the southern part (Fig. 7a), conditioning the vegetation (Rubiales et al. 2012) and food production. Chestnut predominates as a local product in the wettest areas in the north (Guitián et al. 2012), whereas oil and wine production are favoured by the drier and warmer conditions in the south (Blanco-Ward et al. 2007). Vegetation cover is strongly influenced by humans

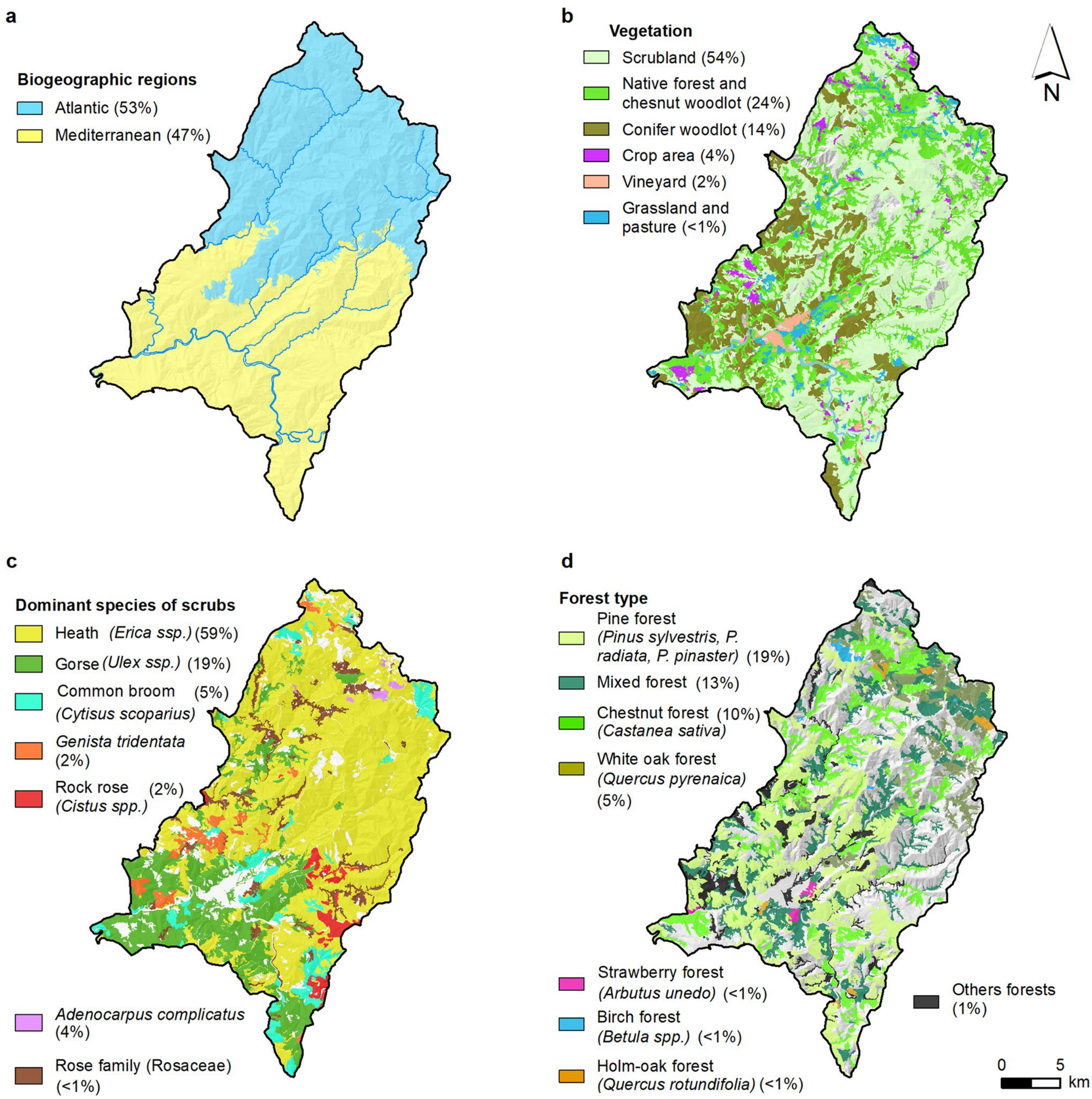

Fig. 7 Biodiversity basic maps of the Courel Mountains UGGp. **a** Biogeographic regions. **b** Vegetation map performed from SIOSE (Table 2). **c** Scrub dominant taxa from the MFE (Table 2). **d** Forest types from the MFE. Data in brackets indicates the relative extension (%) in respect to the UGGp

since ca. 4 ka ago, due to deforestation and the spreading of cereal agriculture back to 2 ka, as evidenced by the pollen and diatom records of the Lucenza tarn lake (Santos et al. 2000; Muñoz Sobrino et al. 2001; Leira and Santos 2002). Human activities favoured the development of scrublands (54%), although native forest woodlands are preserved in isolated areas (Fig. 7b). Nowadays, the native forest has spread due to the abandonment of traditional (indigenous) activities, reducing agricultural areas, scrubs and chestnut woods but not the area devoted to growing conifers for forestry production (14%).

Heather (genus *Erica: E. australis, E. umbellata, E. cinerea*) dominate the scrub vegetation except in the south part of the UGGp, where the gorse (genus *Ulex: U. gallii, U. europaeus*) is most common (Fig. 7c) due to anthropogenic activities associated to the driest climatic conditions. In the Mediterranean biogeographic region, the *carqueixa* (*Genista tridentate*; an endemic species from the Iberian Peninsula), and rock roses (genus *Cistus*), as well as lavender (*Lavandula stoechas*) and thyme (*Thymus mastichina*), are abundant in some sunny slopes in the west and southeast of the UGGp, respectively. The flowering of these and other taxa allows the production of honey as another characteristic local product of the Courel Mountains. Other scrubs are dominated by legumes like broom (*Cytisus scoparius, C. striatus, C. multiflorus*) or French broom (*Genista florida*) that colonise abandoned agricultural areas or, for French broom, also forest borders in areas with deep soils and high rainfall. Native forests cover 18% of the UGGp (Fig. 7d) and correspond to the deciduous forests whose colour variety during atom that constitute one of the outstanding features of the northern Courel Mountains. These forests are mixed or are dominated by broad-leaved trees, such as white oaks (*Quercus pyrenaica*, the hybrid between *Q. petraea* and *Q. robur, Quercus x rosacea,* and *both parentals*), chestnut trees (*Castanea sativa*) and, locally, birches (*Betula alba*) that constitute the upper limit of the forest, beeches (*Fagus sylvatica*) at their westernmost distribution, or holm-oak trees (*Q. rotundifolia*) linked to calcareous bedrocks (Table 4). Chestnut trees are considered a native species that arrived at the territory 4 ka ago (Santos et al. 2000). Chestnut trees are traditionally grown in groves called '*soutos*', monospecific

Table 4 Main taxon of trees reported in Courel Mountains UGGp. Abundance according to MFE (Table 2)

Abundance (%)	Taxon	English name	Local preferred soil nature	Forest type	Main biogeographic region
19	*Pinus sylvestris*	Scots pine	Without preference	Pine groves	Atlantic
	Pinus radiata	Monterrey pine	Acid		Introduced from North America
	Pinus pinaster	Maritime pine	Acid		Mediterranean
13	*Quercus robur*	Oak	Acid	Mixed forest	Atlantic
	Quercus petraea	Sessile oak	Acid		Atlantic
	Sorbus aucuparia	Rowan	Acid		Atlantic
	Ilex aquifolium	Holly	Acid, however, it can also grow in basic soils		Both
	Taxus baccata	Common yew	Neutral or basic, but sometimes in acid soils		Atlantic
	Fraxinus excelsior	European ash	Neutral or basic	Mixed forest (gallery forest)	Atlantic
	Corylus avellana	Common hazel	Slightly acid or neutral, but also in slightly basic soils		Atlantic
	Ulmus glabra	Wych elm	Basic, but it can grow in all soils		Atlantic
	Salix caprea	Goat willow	Basic, but it can grow in all soils		Atlantic
10	*Castanea sativa*	Chestnut	Acid or neutral	Chestnut woodlot	Mediterranean
5	*Quercus pyrenaica*	White oak	Acid	White oak trees	Atlantic
1	*Betula alba*	Birch	Acid	Birch trees	Atlantic
	Alnus glutinosa	Common alder	Acid	Gallery forest	Atlantic
	Quercus suber	Cork oak	Acid	Cork trees	Mediterranean
	Fagus sylvatica	Beech	Basic	Beech trees	Atlantic
	Quercus rotundifolia	Holm-oak	Basic	Holm-oaks	Mediterranean

Acid preferred soils are usually developed above siliceous bedrocks, while basic soils are formed in calcareous areas woodlots surrounding the villages, composed of large and old/elderly specimens selected for many generations by the quality of their fruit or timber. These groves are slightly grazed or managed to prevent understory development (Guitián et al. 2012). Other abundant tree taxa are pines, which occupy 19% of the territory (Fig. 7d), and are introduced for the forestry industry. Furthermore, thorny shrub communities dominated by species of the Rosaceae family (*Prunus spinosa*, *Rosa* spp., *Crataegus monogyna*, *Pyrus cordata*, *Rubus spp*.) appear throughout the UGGp either bordering forests, as a forest substitution stage, or on some calcareous outcrops (Fig. 7c).

The species list shows the occurrence of more than 1000 species of flora, fauna and fungi in the UGGp (Fig. 8). The list includes part of the 800 plants identified in the Courel Mountains (more than 82 families and 400 genera), which represent 40% of the terrestrial vascular plants of Galicia. Asteraceae (Compositae), Poaceae (Graminae), Ericaceae, Fabaceae and Cistaceae are the most common families which is consistent with the data for Galicia (Buide et al. 1998); however, singular species frequently belong to the Orchidaceae and Ranunculaceae families (Manzaneda et al. 2005; Pedersen 2006). Plant endemism is relatively low in Courel Mountains, but an important number of species of biogeographic interest are presented in this area (Buira et al. 2017). Native forests and chestnut woodlots display the highest biodiversity levels (Guitián et al. 2012), together with orchids-rich dry grassland and scrubland facies on calcareous substrates (Directive Habitat 92/43/EEC, priority habitat N°6210) where the endemic *Dactylorhiza cantabrica* (Pedersen 2006) can be found. Thirteen plant species growing in the UGGp are protected under the Habitats Directive, being included in annexes II, IV and V or in national and/or regional regulations (Table 5). In addition to this, nine priority habitats for the EU Directive (92/43EEC) are present in the geopark. Four of them support plant communities developed on meta-limestone wherein a high number of endemic or rare species can be found. In addition, two of the priority habitats are woodlands linked to waterways (Table 6). Among them, 85 species were used for folkloric medicinal and veterinary purposes (Blanco et al. 1999). More than 500 macromycetes were reported linked to the great variety of environments in the northern UGGp (Alonso Díaz and Rigueiro Rodríguez 2020). Scrublands and native forest with fungi associations (Albertos et al. 2000) constitute the main natural habitat by a singular fauna, reporting the occurrence of species linked to the handed chestnut woods (González-Varo et al. 2008). The representative fauna includes brown bear (*Ursus arctos*) inscribed in the National Catalogue of Threatened Species (Royal Decree 139/2011 of Spain), or taxa characteristic of temperate and wet environments, such as wild boar (*Sus scrofa*) and roe deer (*Capreolus capreolus*). Insects like butterflies (Papilinoidea superfamily) and syrphids (Syrphidae family) have singular and endemic species (Ricarte et al. 2014), one of them also included in the National Catalogue of Threatened Species. Reptiles are linked to the Mediterranean conditions of the geopark and include the viperine water snake (*Natrix maura*), viper (*Vipera seoanei*) and many lizards (e.g., *Psammodromus algirus*).

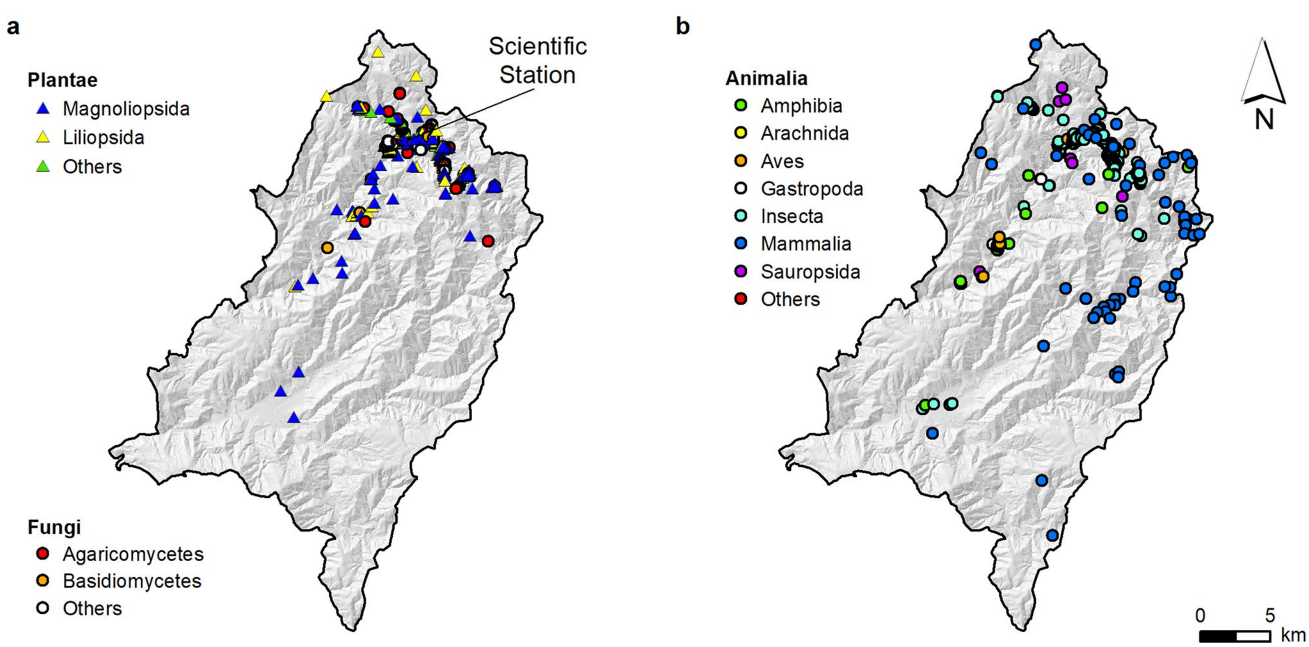

Fig. 8 Non-exhaustive inventory of the biodiversity of Courel Mountains UGGp. **a** Plantae and fungi regnum. **b** Fauna regnum

Table 5 Threatened species occurring in the Courel Mountains UGGp

Taxa	Directive habitats 92/43/EEC	Catalogue of threatened species of Galicia region	Local preferred soil nature	Habitat
Arnica montana L	Annex V		Acid	Wet grassland and shrublands, high mountain
Campanula adsurgens Leresche & Levier		Vulnerable	Basic	Limestone rock crevices
Cardamine raphanipholia Pourret subsp. *gallaecica* Lainz		Vulnerable	Oligotrophic springs	By streams or sources, wet and dark meadows
Gentiana lutea L	Annex V		Acid	Wet grassland and shrublands, high mountain
Iris boissierii Henriq	Annex IV	Threatened	Acid-neutral	Mountain grasslands
Leontodon crispus Vill. subsp. *bourgaeanus* (Willk) Finch & P.D.Sell (*L.farinosus* Merino & Pau)		Vulnerable	Basic	Limestone rock crevices
Narcissus asturiensis (Jordan) Pugsley	Annexes II, IV	Vulnerable	Basic	Grasslands, open heaths and edges of deciduous forests
Narcissus bulbocodium L	Annex V		Acid	Wet grassland and shrublands
Narcissus pseudonarcissus L. subsp. *nobilis* (Haw) A. Fernández	Annexes II, IV	Vulnerable	Acid	Open deciduous forest, by sources and streams
Narcissus triandrus L	Annex IV		Acid	Rupicolous, open shrublands
Rhamnus pumila Turra subsp. *legionensis* Rothm		Vulnerable	Basic	Limestone rock crevices
Ruscus aculeatus L	Annex V		Without preference	Mediterranean and white oak forests
Santolina semidentata Hoffmanns & Link	Annexes II, IV	Vulnerable	Basic	Stony soils, grasslands on limestone, rupicolous

Table 6 Priority habitats according to Directive 92/43/EEC present in the Courel Mountains UGGp

Code according to the Nature 2000 Network	Name of the habitat type
4020	Temperate Atlantic wet heath with *Erica ciliaris* and *E. tetralix*
6210	Semi-natural dry grasslands and shrubland facies on calcareous substrates (*Festuco-Brometalia*) *important orchids sites
6220	Pseudo-steppe with grasses and annuals of the *Thero-Brachypodietea*
6230	Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas (and submountain areas in Continental Europa)
7110	Active raised bogs
7220	Petrifying springs with tufa formation (*Cratoneurion*)
8240	Limestone pavements
9180	*Tilio-Acerion* forest of slopes, screes and ravines
91E0	Alluvial forest with *Alnus glutinosa* and *Fraxinus excelsior*

Cultural Heritage

Historical, archaeological and ethnographical studies have revealed an outstanding cultural patrimony, including remarkable mining and industrial heritages. The cultural patrimony of the Courel Mountains is formed by 355 sites running from prehistorical times to today (Fig. 9), which are linked to the historical use of geological resources, including settlement areas, building stones, lime kilns, forges (foundries) and Au, Fe, Sb and Pb mining. The Sil River valley constituted one of the main migration routes from Iberia inland to Galicia, as evidenced by a Palaeolithic site and 33 mounds and 2 petroglyph areas ascribed to the recent Prehistory (de Lombera Hermida 2011). Palaeolithic tools recovered in Gándara Chá (southern geopark) are choppers, flakes and cores made on quartzite and quartz, culturally ascribed to the Lower/Middle Paleolithic. The Neolithic megalithic mounds were made on quartzite and slate slabs and covered

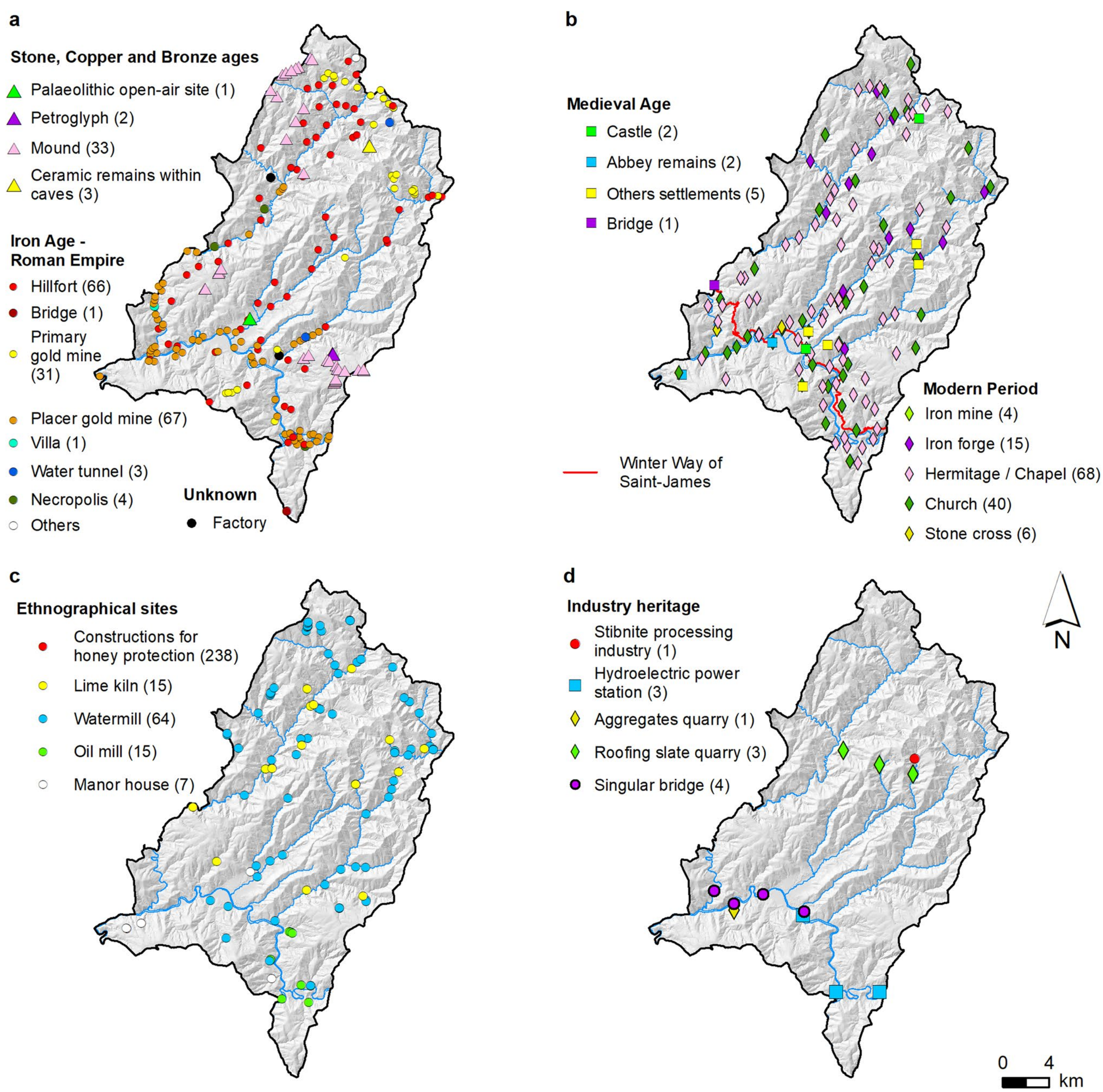

Fig. 9 Cultural heritage of the Courel Mounains UGGp. **a** Prehistoric and Roman sites. **b** Medieval and Modern Period sites. **c** Ethnographical sites. **d** Industry heritage. Data in brackets indicates the number of sites

by rubble stones and other sediments, showing a layer of white quartz boulders on the top to increase their visibility. Petroglyphs, usually pits, were elaborated on metamorphic rocks, which is a distinctive feature of the Courel Mountains, since the rock art is from the northwest of the Iberian Peninsula is commonly preserved in igneous rocks. During the Iron Age, hillforts were constructed in strategic areas and fortified, combining drystone walls, excavated moats and natural scarps resulted from the fluvial incision and the occurrence of quartzite interbedded within slate sequences. In the hillfort, dwellings and other structures were also walled and roofed with local Palaeozoic rocks. The Roman Empire conquered the territory, running a new territorial organization during the 1st–second centuries AD to exploit 98 gold mines in Courel Mountains (Sánchez-Palencia et al. 2006) (Fig. 9a). Romans reworked previous settlements and built new hillforts (using local stones), routes and one bridge in granite, as well as more than 5 km of water channels and tunnel. The best known Roman site is Montefurado, a 120-m-long tunnel dug to diverge the Sil River and exploit its gold-rich sediments. After the fall of the Roman Empire, many hillforts continued being run by ruling classes until their abandonment (Tejerizo-García and Canosa-Betés 2018), coevally with the growing of hamlets in valleys and sporadic settlement or shepherd refugees in caves (Teira Brión et al. 2011). Two castles were built by the military Order of Santiago (Order of Saint James of the Sword) and the Sovereign Military Hospitaller Order of Saint John of Jerusalem, Rhodes and Malta (commonly known as Order of Malta) to protect the pilgrims of St. James' Way during the Late Medieval Age (Fig. 9b). Castles were built around the 12th–thirteenth centuries using the local Palaeozoic rocks, introducing the application of Cenozoic rock for doorjambs. Nevertheless, two Romanesque abbeys (twelfth century) used granite for ostentation, although few remains of these and other probable abbeys are preserved at present. Most of the 40 churches and 68 chapels/hermitages of the UGGp were founded over the 16th–nineteenth centuries coevally with the development of a steelmaking industry. At least 15 forges were supplied by a large mining area in the northern UGGp (Fig. 9b).

The inventory of ethnographical sites reflects the folk tradition associated with natural resources (Fig. 9c). Seven manor houses continue using local stone for ostentation, while more than 15 kilns produced lime by the calcination of local meta-limestone; 238 documented constructions were built for the protection of beehives, evidencing a broad honey production during the last centuries. These constructions (locally known as *alvarizas or abellarizas*) are unroofed circular walls built in drystone around beehives to avoid attacks of brown bears, whose population is currently recovering in the Courel Mountains thanks to the European-funded Oso Courel LIFE Project. More than 64 water mills ground cereals to obtain flour leveraging the abundant stepped watercourses, but the local oil was produced in more than 17 mills by pressing olives cultivated in the south (Fig. 9c).

The industrial patrimony is relatively scarce due to the minor local industrial development following the steelmaking workshops. The industrial heritage includes stibnite furnaces and others constructions that operated sporadically between 1896 and 1958, three hydroelectric power stations launched during the 1950s, a truss bridge and three railway bridges built in the nineteenth century, and the 4 currently operating quarries. Nowadays, 59 mining concessions are running in the UGGp to investigate, explore or exploit building stone, metallic deposits and bottled water (Fig. 9c). Among them, the Middle Ordovician coarse-grained slate is quarried in order to export roofing slate to North-Central Europe, constituting a powerful economic sector. The local slate has been linked to the historic roofing since the first hillforts, representing a distinctive feature of the regional folkloric buildings. For this reason, Courel Mountains are part of the Iberian Roofing Slate (Cardenes et al. 2015), nominated Global Stone Province Resource by the Heritage Stones Subcommission of International Union of Geological Sciences (IUGS).

New Resources by the Coverage Combination

Ten topics relevant to the Courel Mountains UGGp were performed to illustrate the large variety of specific maps that can be successfully elaborated by combining coverages. These ten maps are presented here as examples and can be combined with additional resources (e.g., diagrams, pictures).

(1) Geological times, rocks and fossils. The Palaeozoic rocks and their fossils of the Courel Mountains represent a good example of a part of Earth History, when the Rheic Ocean was opened and closed (see Franke et al. 2017), hosting a singular marine fauna (Ballesteros et al. 2021b, a). This topic would be approached by combining the geological map, its stratigraphical section and the inventory of palaeontological sites (Fig. 10a). The edited map links geological periods and rocks with representative fossils from the UGGp according to the parallel evolution of life and Earth: Archaeocyatha and Cambrian meta-limestone, trilobites and Ordovician slate, graptolite and Silurian dark slate, crinoids and Devonian meta-limestone. In this case, the geological units are represented according to their main lithology.

(2) Lithology and canyoneering. The combination of ravines with the geological map provides an additional value to the distinctive gorges of the UGGp, linked to fluvial incision and alpine uplifting. The elaborated map named 'geological canyoneering' (Fig. 10b) relates lithology and ravines, resulting in varied fluvial landscapes that would be appreciated in situ by canyoneers. Waterfalls are usually related to the presence of quartzite interbedded with slate, while the carbonate bedrock shows singular dissolution features. The geological canyoneering map constitutes a good example of the application of the GIS database in outdoor sports, which was used in the elaboration of the canyoneering guide of the UGGp (see Section 2 in Supplementary information 2).

(3) Calcareous landscape. The geological data were combined with rivers, vegetation (holm-oaks), flora list and surveys of micro-reserves, and cave and karst springs to depict the calcareous landscape of the Northern UGGp (Fig. 10c).

This landscape (conceived as the sum of rocks, vegetation and atrophic features) has a singular attractiveness resulting

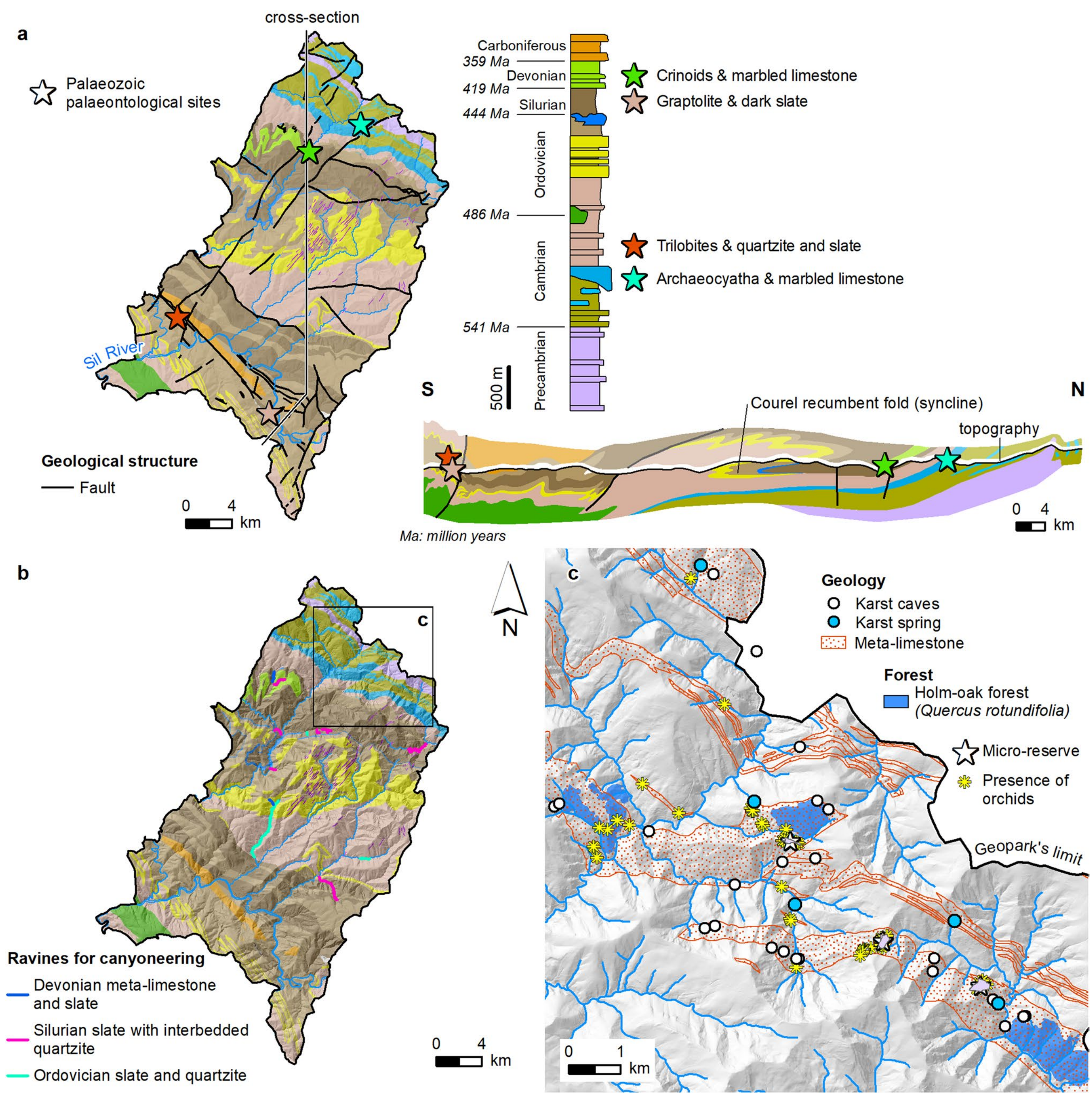

Fig. 10 **a** Geological map and cross-section of the UGGp relating fossils, rocks and periods; the geological cross-section is after Martínez Catalán et al. (2004). **b** 'Geological canyoneering' map linking ravines and specific rocks of the UGGp. **c** Distribution of holm-oak forest, flora, caves and springs according to meta-limestone outcrops in northern UGGp; the location of **c** is shown in **b**

from soluble and permeable meta-limestone. These geological characteristics cause underground drainage, as evidenced by the occurrence of karst springs and caves. The permeable bedrock also favours the growth of orchids and holm-oak trees. As such, the map shows the presence of orchids and holm-oaks along with calcareous areas with karst caves (Fig. 10c). The micro-reserves reinforces the natural value of the relationship between rocks and flora.

(4) Roman gold. Geological and geomorphological data were combined with the archaeological inventory to show the geological context of gold deposits mined by Romans (Fig. 11a). Romans quarried the bedrock by open-cast and underground excavations to obtain primary gold related to folds and faults in the northern and southernmost UGGp; however, they also mined alluvial fan sediments to grain the placer

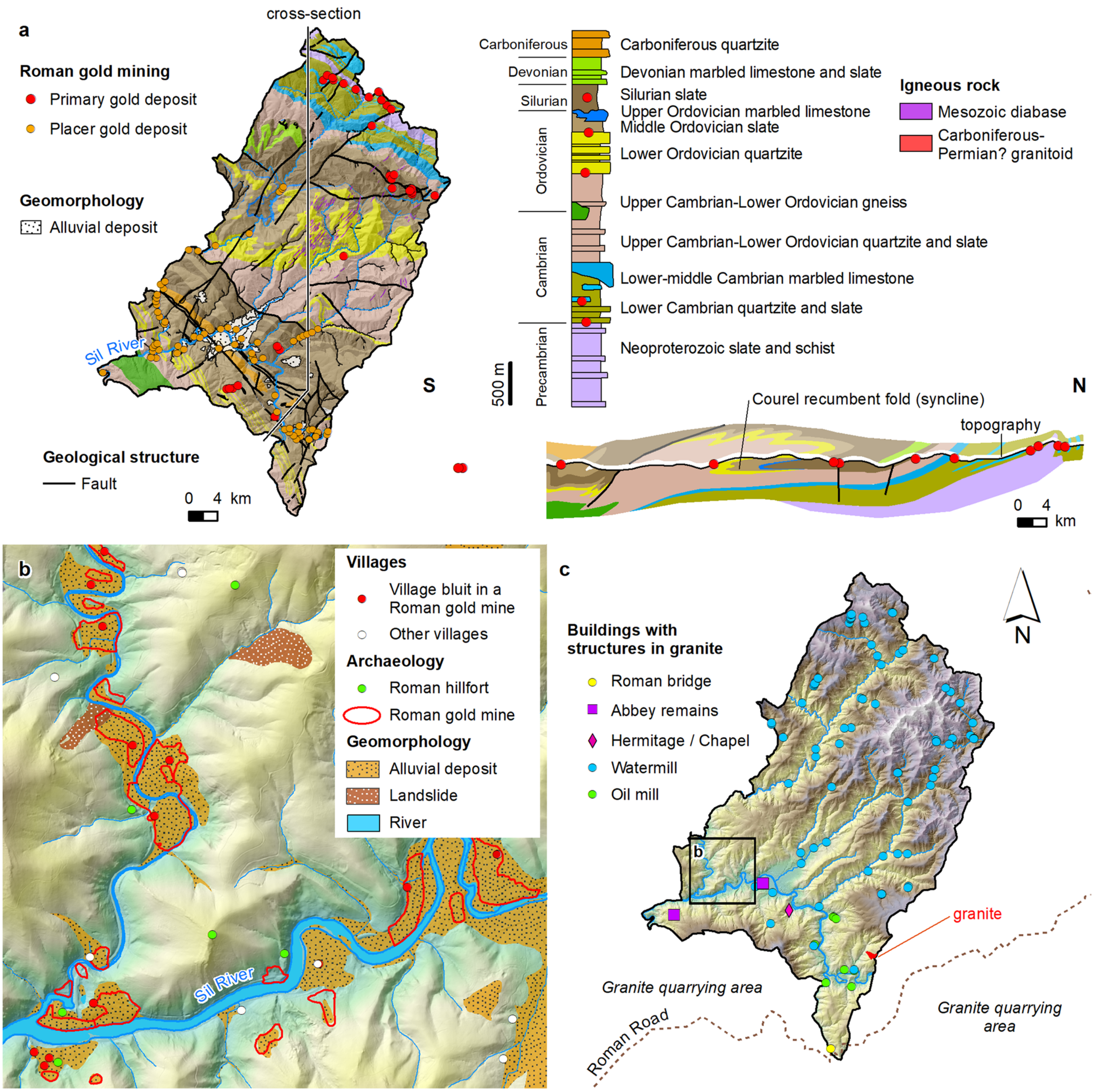

Fig. 11 **a** Roman gold mining related to the primary gold deposits (folded and faulted bedrock) and placer gold deposits (alluvial sediments); the geological cross-section is after Martínez Catalán et al. (2004). **b** Geomorphologic settings of Roman hillforts (1st–second centuries AD) and villages of the South-Western UGGp; location indicated in **c**. **c** Historical sourcing and uses of granite in the UGGp. The layout of the Roman road is from the Digital Atlas of Roman and Medieval Civilizations (https://darmc.harvard.edu/; accessed January 2021)

gold (Fig. 11a). These alluvial sediments came from the erosion of the primary deposits ca. 10–20 million years ago.

(5) Settlement context. The combination of hillforts, geomorphological data and the current villages reveals how the landscape contributes to the location of human settlements (Fig. 11b). The edited map shows Roman hillforts strategically constructed at the top of mountains or mounds to watch the territory from easily defensible positions. After the fall of the Roman Empire, the population looked for flatter areas to settle and cultivate, which was the origin of current villages. The occupied areas often correspond to alluvial deposits perched hundreds of metres above the current

riverbed, frequently matching with ancient Roman open-cast works.

(6) Granite diffusion. The sourcing and use of granite in the Courel Mountains can be illustrated by projecting the granite outcrops of the UGGp and sites of employment (Fig. 11c). The new map shows a Roman bridge and remains of two abbeys and a chapel, mills, and tiny outcrops of this igneous rock in the southeast limit of the UGGp. The granite was quarried in nearby areas to the south and southeast of the Courel Mountains and transported to the UGGp for three main uses: (1) the construction of a solid and long-lasting bridge using the *opus quadratum* architectural style, related to the 17th Roman road (Via *Nova*); (2) the walling of two abbeys (twelfth century) and one chapel (ca. seventeenth century) as a symbol of the Christian authority; and (3) the elaboration of mill components (wheels, presses and others) even if their main structures were walled in local stone. The map shows that granite was only used for buildings in the south (close to quarrying areas) due to the transport troubles of a great amount of stones in the past (Fig. 11c). On the contrary, granite millstones were spread along the UGGp since local stone is not suitable for cereal grinding. In conclusion, the edited map allows for the implementation of historical stone provision and archaeomaterial diffusion in the UGGp contents.

(7) Historical blacksmithing. A prominent traditional steelmaking industry ran in Courel Mountains, exploiting local natural resources from the early sixteenth century to the late nineteenth century. This industry is illustrated as a combination of metallogeny, archaeological and vegetation data (Fig. 12a). More than 75 mines supplied iron to 15 preserved forges with hydraulic mechanisms. Abundant wood was transformed into charcoal to reduce initially the iron and to supply the forges. This would be the origin of charcoal production as a traditional (indigenous) activity in the UGGp. The forges contributed strongly to the deforestation in Courel Mountains, and the scarcity of wood would be the main cause of the decline of the iron industry in the 1890s, causing an economic downturn and emigration (Bauer 1992).

(8) Natural risks. The cross-comparison of the geomorphological, flooding areas, active landslides and infrastructures maps enables to evaluate natural impacts from human activities (Fig. 12b). The edited map points out the occurrence of landslides in rough terrains in the northeast of Courel Mountains and floods in the Sil River valley, where San Clodio and Quiroga are located. Every year, landslides damage roads, sometimes disturbing the traffic in the UGGp, whereas floods affect the riverbanks, inundating buildings and other constructions. The map might be useful to improve the perception of natural risks in the UGGp.

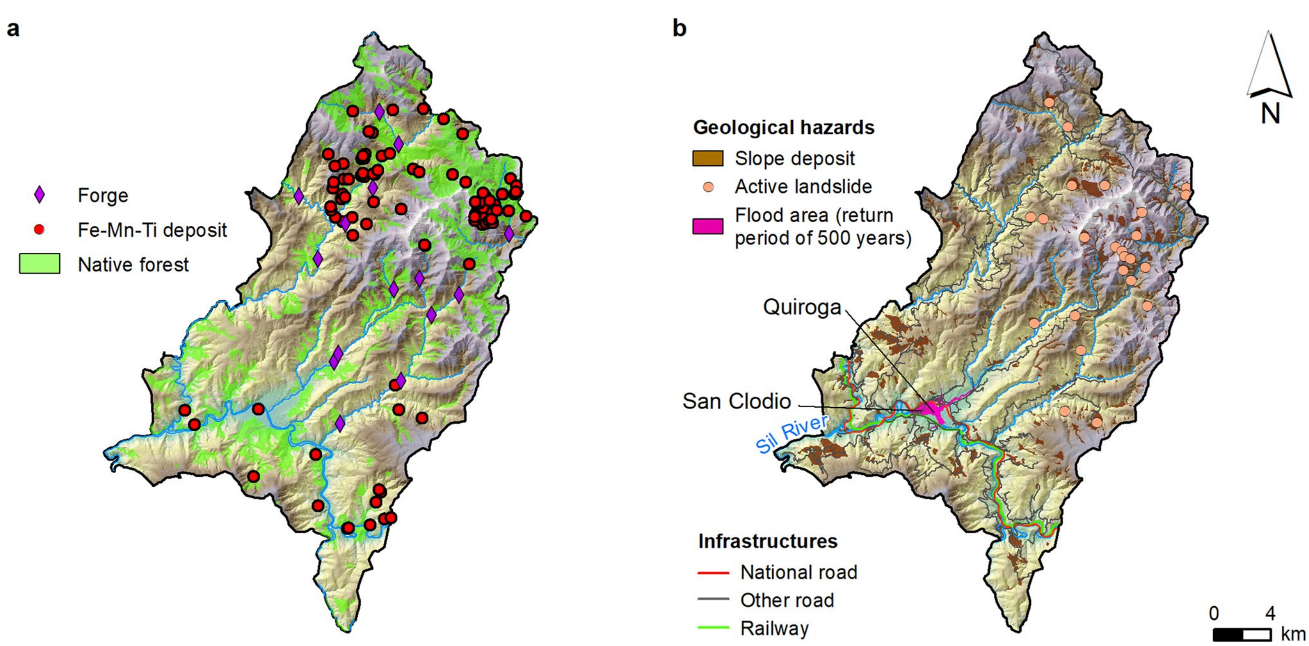

Fig. 12 **a** Documented forges (16th–nineteenth centuries) that consumed iron, wood and water, contributing to the deforestation of the Courel Mountains. **b** Geological hazards related to slope and flood processes

(9) Global changes. The climate evolution of the Courel Mountains UGGp over the last glacial-interglacial periods may be displayed showing how glaciated areas are today occupied by forests and villages. This way, the palaeoglacier reconstruction, forest maps and villages can be represented in two maps. The first map depicts the probable maximum expansion of glaciers during the Upper Pleistocene (Fig. 13a), and the second map shows the expansion of forest and village locations after glaciers vanished (Fig. 13c). The comparison is an example of the magnitude of past global changes that occurred in the UGGp.

(10) Local products. The relationships between the local products and climate, geology and vegetation of the UGGp can be approached by combining maps of villages, land use, geomorphology, forest, geomorphology, ethnographic and species list coverages. Figure 14a shows the presence of chestnut woods around villages to produce this fruit as a staple food in the past. At present, the chestnut is still the most representative local food of the Courel Mountains. Another map evidences the occurrence of 238 honey beehives in scrub areas dominated by the heath, mainly in the centre of the UGGp (Fig. 14b). GIS analyses show that beehives were preferably constructed in south-facing hillsides with 30° slope, between 500 and 800 m altitude. Finally, wine and oil are local products representative of the Mediterranean areas of the southern UGGp, in rain shadows caused by the mountainous relief. Vineyards and olive trees are cultivated mainly on alluvial fans and deposits in the Sil River valley (Fig. 14c).

Contributions to UGGp Management

Our results show that the application of the GIS database is a powerful tool to implement scientific knowledge into the education, tourism, research and conservation programmes of the UGGp, which are the four pillars of UGGp management (e.g., Zouros 2016). GIS maps provide an overview of thematic features of the Courel Mountains and constitute easy-to-understand resources employed in outreach activities, interpretation centres, scholar projects and training workshops for guides. As shown in the ‘Results’ section, a large variety of themes can be performed, including common topics relevant to UGGps, like global change, geological hazards, Earth resources, and local and indigenous knowledge (Henriques et al. 2012; Álvarez 2020).

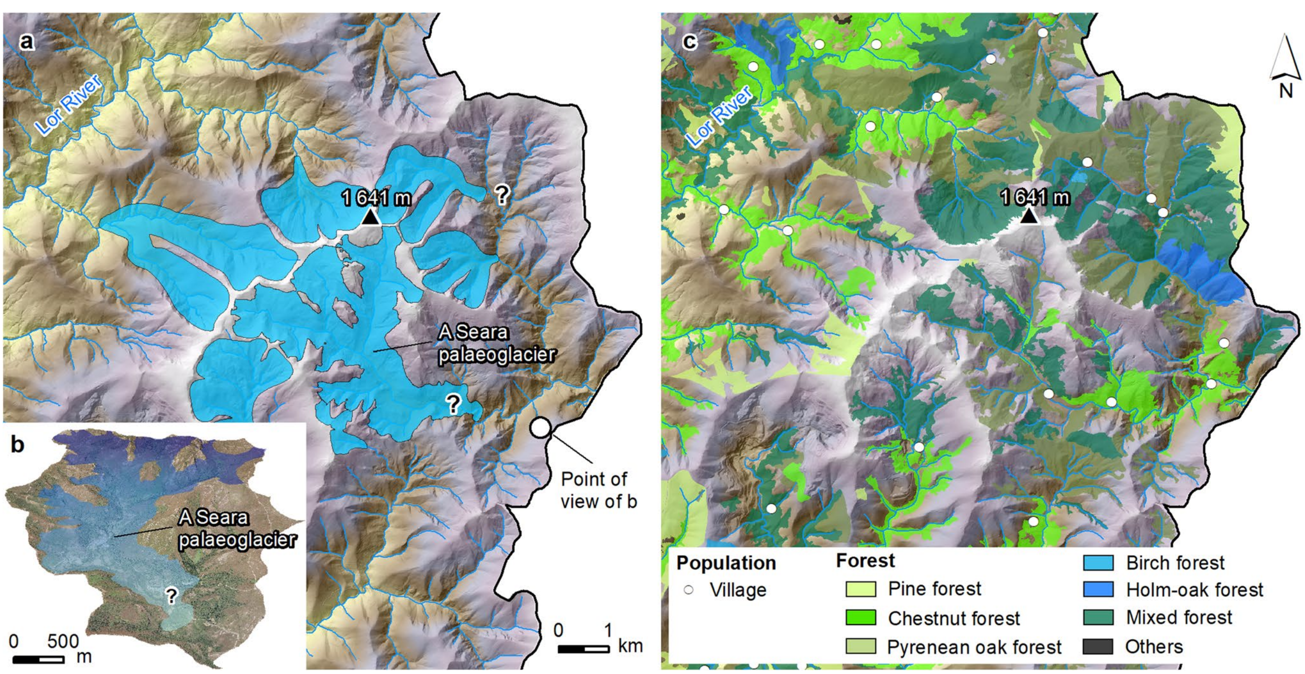

Fig. 13 Global changes occurred in the UGGp highlands since the maximum advance of glaciers before 21 cal ka BP (Muñoz Sobrino et al. 2001) to areas occupied by native forests and villages at present. **a** Maximum expansion of paleoglaciers reconstructed from previous works (Supplementary information 2). **b** 3D reconstruction of the A Seara palaeoglacier using the ArcGIS GLARE toolbox (Benn and Hulton 2010; Pellitero et al. 2016) and displayed in ArcScene. **c** Current distribution of villages and forests (derived from the MFE – Table 2)

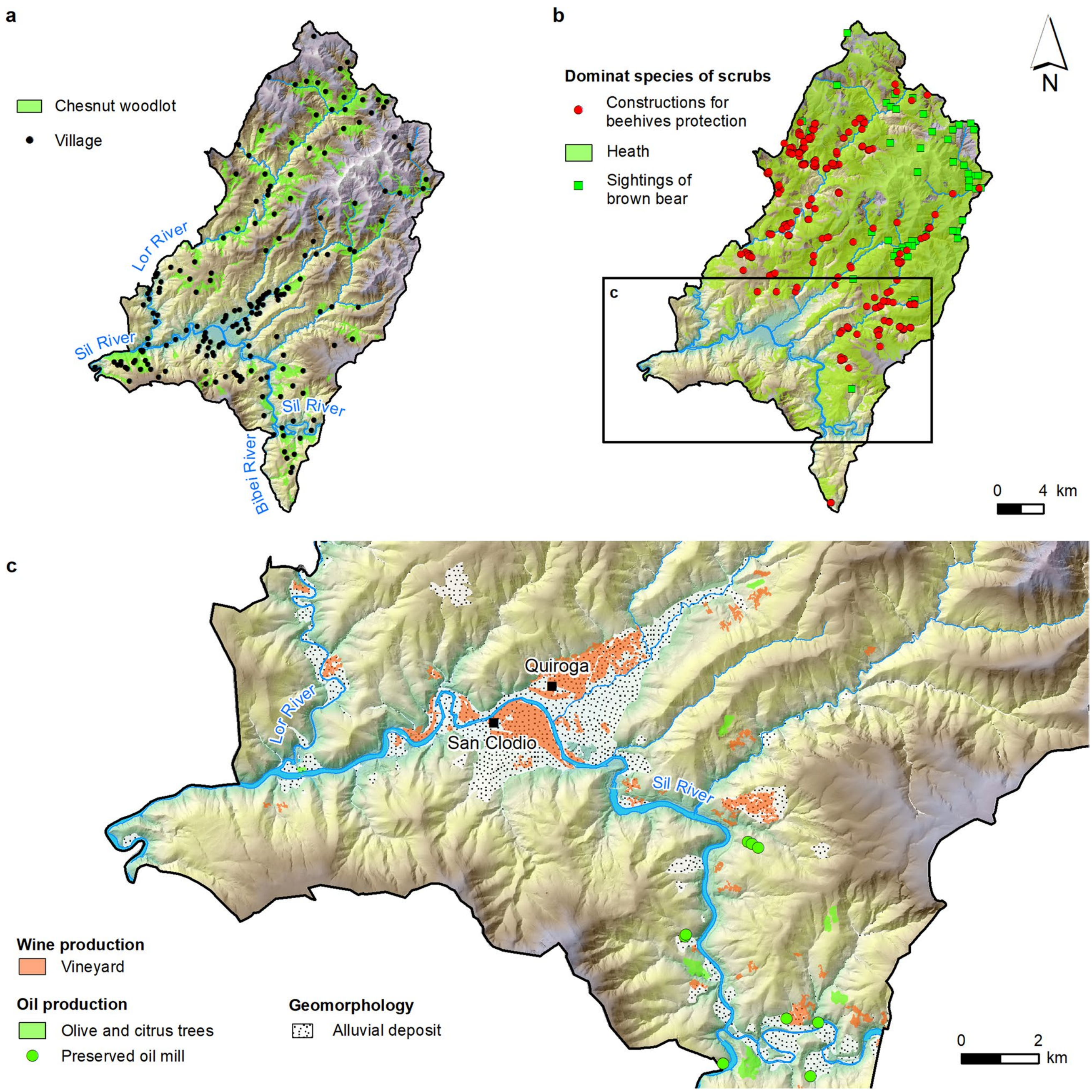

Fig. 14 **a** Chestnut woodlots located in the valleys of the UGGp, surrounding the villages. **b** Constructions for beehive protection sited in steep areas dominated by heath. **c** Geomorphological setting of vineyards and olives (represented together with citrus trees), related to the local wine and oil production; location is shown in **b**

The GIS database was used for planning and technical designing of touristic resources, such as routes, activities, touristic information documents and interpretation centres. For instance, the design of the Palaeozoic Villages Route (Ballesteros et al. 2021a, b) was supported by means of a density map of local services performed using GIS tools (Fig. 15a). This route was devised following the highest concentration areas of local services in order to provide facilities for visitors and to attract customers to bars and restaurants. GIS also aids the management of the UGGp, mapping the visible and non-visible areas from the current viewpoint network (Fig. 15b). The maps guide the construction of new viewpoints for watching the Courel Mountains. Therefore, GIS assists in the tourism scheduling of the UGGp, which would constitute a specific GIS-based tourism information system (Nurpandi et al. 2020).

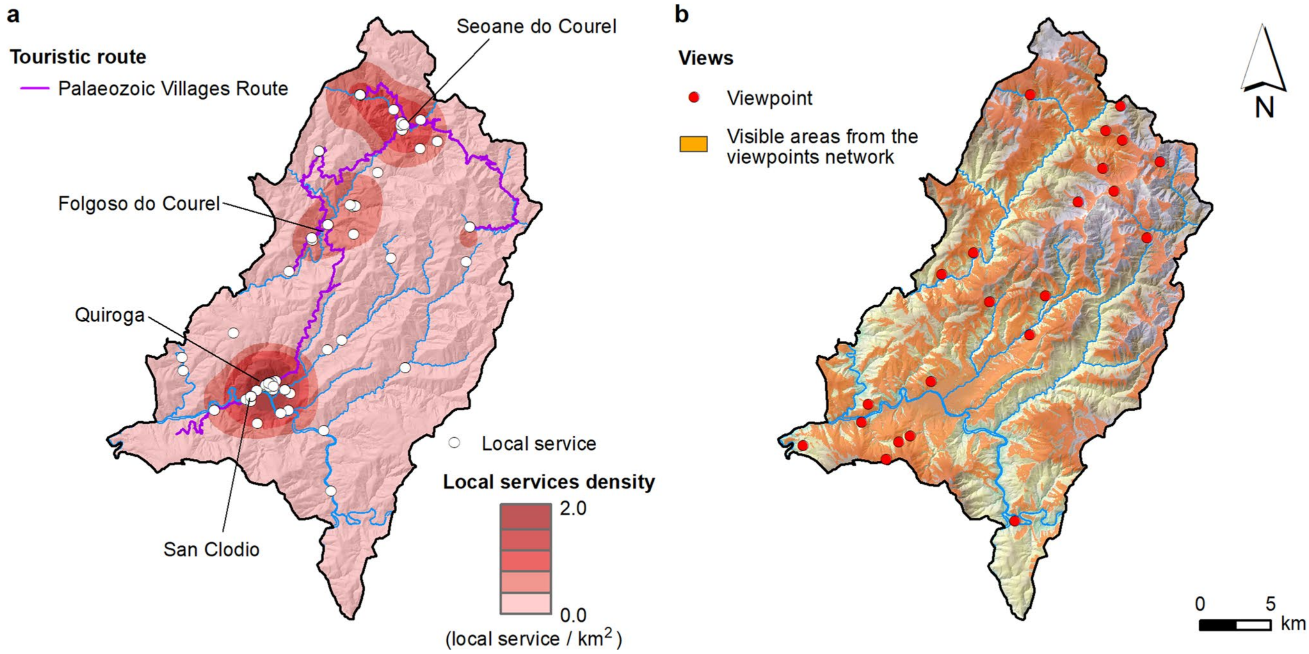

Fig. 15 Examples of new maps elaborated using GIS tools for assistance. **a** Local services density calculated through the Kernel density estimation to assist in the design of the Palaeozoic Villages Route (Ballesteros et al. 2021a, b). **b** Visible areas from current viewpoints were inferred through visibility functions to guide the construction of new viewpoints

The GIS database is a supportive tool facilitating scientific research in the UGGp, similar to in other previous works related to geosciences (Perotti et al. 2019), tourism (Nandi 2019) and local community (Stoffelen et al. 2019). Inventoried data in GIS can be included in scientific studies, and its results will provide feedback to the database. Most notably, the ongoing study of the Geosites of Courel Mountains is assisted by the created database. For example, studies using specific coverages of the database to develop new geomorphological and palaeontological studies could reveal the occurrence of new surface formations and fossil sites. These studies also supply new attributes of existing features, such as new data on rivers and fluvial deposits from a geomorphological point of view following Pérez-Alberti and Cunha (2016) and Horacio et al. (2017).

The GIS dataset provides the necessary knowledge to conduct geoconservation actions, considering protected areas, land use practices, geological hazards and the overlap of natural and cultural heritage. In fact, the use of GIS technologies for geoconservation is common (see Williams and McHenry 2020). The combination of coverages allows the identification of potential impacts on geoheritage to mitigate its damage. Moreover, themes related to climate change enable to raise awareness on the potential impact of climate change on the UGGp.

In summary, the GIS database offers a global and comprehensive vision of the UGGp supplying technical and scientific assistance based on relatively homogeneous, revised and structured scientific knowledge. Consequently, the GIS is a useful tool for policy-making towards development strategies, particularly during the phase of identification and evaluation of alternatives.

Contribution to the UGGp Conception

The conduction of the GIS database reinforces four relevant issues in the conception of an UGGp: cooperation, territorial unity, visibility and corporate identity. The cooperation was promoted by the collaborations among the UGGp staff, scientists, local administrations, companies and local people during the initial data acquisition, involving information from local and regional actions (e.g., Bioblitz Courel project, micro-reserves project). This networking agrees to the bottom-up approach of the UGGp and reinforces the participation and understanding between the actors involved in the UGGp. The territorial unity was reinforced by the creation of a unique database for the entire UGGp, homogenising information along the area. This result is key to blur the limits between municipalities and villages, strengthening the UGGp as a unified geographical area. Another contribution of the GIS database is the promotion of the visibility of the UGGp, creating new maps for outreach activities, including dissemination, publications and online resources. In the future, the database can supply information for the development of web visors and mobile applications of the UGGp (Luo 2015; Hartoko et al. 2018; Nurpandi et al. 2020). For that, the UGGp is well-equipped to edit its own maps adapted to final purposes and users, showing an end product whose main authorship already belongs to the UGGp. In addition, the silhouette of UGGp maps is already part of the singular identity of the Courel Mountains. Altogether, the GIS database and the produced maps promote the corporate identity of the UGGp, reinforced by its territorial unit and visibility.

Conclusions

A GIS database has been developed to assist the management of the Courel Mountains UGGp. The database includes 66 coverages storing technic, geoscientific, ecological and cultural data based on open sources, previous works, fieldwork, photointerpretation and GIS analyses. The methodological procedure implies an efficient acquisition, homogenization and validation of the archived data, which can be easily updated in the future. The combination of selected coverages allows for the elaboration of thematic maps showing specific relationships between Earth processes, biodiversity and human history. The maps are adapted to different final purposes and users, from general audiences to specialists. In addition, the GIS maps reinforce the territorial unity, visibility and corporative identity of the UGGp, as well as the cooperation between managers, scientists and local administrations, companies and people. The GIS coverages contain the necessary knowledge for the successful development of educational, tourism and geoconservation programmes of the UGGp, representing also useful support for scientific research. The design of educative and touristic actions is assisted by a database related to all the topics of the Courel Mountains, including Global Change, geological hazards, Earth resources and local and indigenous knowledge. The GIS facilitates the geoconservation strategy based on protected areas, land use practices, geological hazards and natural and cultural heritage. Altogether, the database is key for the identification and evaluation of potential alternatives undertaken during the policy-making for the development of the UGGp.

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Author Contribution DB conceived the original idea and developed the GIS database from the preliminary dataset created by PC and ML. DB and RV compiled technical, hydrogeological, ore deposits, biological and ethnographic data with the cooperation of XCB, who resumed the Variscan geology and the quarrying industry. DB and LRR performed geomorphological data. LRR conducted the numerical 3D reconstruction of ancient glaciers. JHG revised geomorphological information, and FMG provided data concerning the Alpine structure and deposition. MGA inventoried and summarised palaeontological sites under the supervision of JBD. MFF and ST revised ore deposit data. IA and AL collected archaeological data and provided a historical synthesis. ES summarised the biodiversity and completed information stored in the vegetation datasets. IPC carried out an overall review of contains. MA revised the mining and water resources concessions. POA assisted the conception of mining and industry patrimonies. MA carried out funding acquisition and project administration. DB and PC wrote the original draft, with contributions from co-authors to the discussion and final version.

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Data Availability All data and materials are public and free to use.

Code Availability Not applicable.

Declarations

Conflict of Interest The authors declare no competing interests.

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