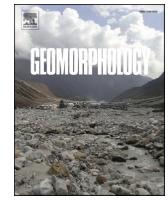
Geomorphology 461 (2024) 109298

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology



Exploring the Correlation between Geoheritage and Geodiversity through Comprehensive Mapping: A Study within the Sesia Val Grande UNESCO Global Geopark (NW Italy)

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ARTICLE INFO

Original content: Geodiversity and Geoheritage data from Alagna Valsesia, Sesia Val Grande UGGp (NW Italy) (Original data)

Keywords:
Geoheritage
Geodiversity map
Spatial correlation
Geostatistics
Geotourism
Alps

ABSTRACT

While geoheritage and geodiversity have been well defined in the literature, the multiplicity of definitions given to these two concepts makes it difficult to establish an unambiguous relationship between them. Basing on semantic-ontological studies, this study aims to reduce this ambiguity within the concepts by investigating the relationship between the geodiversity richness and the presence of geoheritage, and discussing whether the areas with the greatest geodiversity are the ones with the most relevant geoheritage, thus questioning the potential use of the geodiversity index map. Upon a strong theoretical framework, a quantitative geodiversity index map was created for the Alagna Valsesia municipality, within the Sesia Val Grande UNESCO Global Geopark (Italian Western Alps). Then, 25 geosites were identified and mapped in the same area. Notably, the exploration into the correlation between geodiversity and geoheritage on the field shows that in our study area there is no spatial correlation between the geodiversity class and the number of geosites, proving that some geosites may occur in areas of low geodiversity and the greatest geodiversity are not the ones with the most relevant geoheritage. Moreover, all the non-parametric regression models tested are not significant, indicating that there is no predictable relationship between geodiversity and geoheritage in Alagna Valsesia (NW Alps). For that reason, our work highlights that although the quantitative geodiversity map can have an important role for geoconservation and within biodiversity studies, it could not be a strong tool for geosites recognition and tourism promotion, while for this purpose should be better use a qualitative geodiversity map. Finally, the potential use of the geodiversity map depends on the purpose of the study and the approach used to produce it. For a comprehensive geoconservation and geoheritage promotion strategy, the two approaches (qualitative and quantitative) may be complementary.

1. Introduction

In recent years, there has been considerable interest in the application of the geodiversity concepts within sustainability and environmental studies. The importance of geodiversity for the sustainable management of territories has been generally recognized (Hjort and Luoto, 2012; Brilha et al., 2018; Schrodt et al., 2019), as well as the need to protect geodiversity from the new challenges of climate change (Gordon et al., 2022). However, the potential and usefulness of geodiversity assessment is still under debate within the scientific community (Zwoliński and Stachowiak, 2012; Hjort et al., 2015; Bétard and Peulvast, 2019; Brocx and Semeniuk, 2019, 2020; Gray and Gordon, 2020; Crisp et al., 2021; Gray, 2021; Gonçalves et al., 2022).

Over the past two decades, a large number of studies have contributed to the proposal and improvement of new geodiversity assessment methods (Benito-Calvo et al., 2009; Zwoliński, 2009; Hjort and Luoto, 2010; Pereira et al., 2013; Argyriou et al., 2016; Forte et al., 2018; Crisp et al., 2021; Gray, 2021). According to Zwoliński et al. (2018) there are three methods for assessing geodiversity: the qualitative approach, the quantitative one and the combination of the both (quali-quantitative approach). The qualitative approach relies primarily on the expertise and experience of a single or group of subject-matter experts (a descriptive method based on the expert assessment of geodiversity of a certain area) (e.g. Panizza, 2009; Seijmonsbergen et al., 2014). Results

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https://doi.org/10.1016/j.geomorph.2024.109298
Received 15 November 2023; Received in revised form 1 June 2024; Accepted 4 June 2024
Available online 9 June 2024

are graphically represented by maps, which in turn are based on a very good knowledge of the same area, by both field studies, remote sensing and a thorough study of the literature (Zwoliński and Stachowiak, 2012; Seijmonsbergen et al., 2018; da Silva and do Nascimento, 2020; Jankowski et al., 2020). However, this makes the qualitative approach somewhat subjective, and leads to a number of problems, such as the difficulty in standardising a unique method, and suitability with only nominal data (Zwoliński et al., 2018; Crisp et al., 2021).

Quantitative approach is based on the numerical analysis of a group of variables typically used to calculate geodiversity indexes, such as the number of geological unit or the number of soil types. These are intended to numerically reflect and map the spatial variability of various abiotic components of geodiversity within a certain area (Datta, 2022). With respect to the qualitative approach, the quantitative one is considered less subjective and therefore capable of improving the comparability of results with other areas, which is an important aspect of geodiversity estimation (Serrano et al., 2009; Hjort and Luoto, 2010; Pereira et al., 2013; Santos et al., 2017; Araujo and Pereira, 2018; Forte et al., 2018; da Silva et al., 2019; Fernández et al., 2020; Ahmadi et al., 2021).

Within literature, few studies discussed the overall value and general applicability of geodiversity assessment, mostly recognising that some methods are more appropriate in some situations than others (Gonçalves et al., 2022; Najwer et al., 2022). However, the best method can be difficult to determine, because it depends on the specific conditions, such as the geology and available geospatial data (Gonçalves et al., 2020). According to Zwoliński et al. (2018), the best method is somewhere in between the qualitative and quantitative approaches. In this perspective, the quantitative assessment of geodiversity has to be supplemented with new data from the initial expert evaluation; therefore, elements with qualitatives value such as aesthetic, scientific, and educational values can be taken into account (Zakharovskyi and Németh, 2021a). Nevertheless, the assessment, quantification and mapping of geodiversity still have some limitations, mostly because there are no uniform standards or assessment methods (Soms, 2017; Ibáñez et al., 2019). Further, it remains unclear if the gap between methodology and concepts has been bridged in recent studies. Indeed, the numerous gediversity assessment methods present mutual inconsistencies, highlighting the many ways in which the basic concept can be interpreted and applied (Crisp et al., 2021). In order to achieve a meaningful assessment of geodiversity, it could be recommended to focus on standardising the criteria to be included in the assessment, as well as developing a common methodology and a model that includes the interaction of all geodiversity-related variables (Perotti et al., 2019).

Several studies aimed to highlight the importance of the assessing geodiversity, showing the influences of abiotic elements on biotic elements in the natural environment (Kärnä et al., 2018; dos Santos et al., 2019; Zarnetske et al., 2019; Fernández et al., 2020; Datta, 2022), and concerning the provided services to society (Fox et al., 2020). Some authors also stressed the importance of assessing geodiversity to evaluate geoheritage and consequently foster geoconservation (Bétard and Peulvast, 2019; Najwer et al., 2023), but only a little attention has been paid to the need of establishing a robust and unambiguous conceptual framework for fully developing the potential of the geodiversity index map.

This study aims to investigate the relationship between the geodiversity richness in the area and the presence of geoheritage, discussing whether the areas with the greatest geodiversity are the ones with the most relevant geoheritage. This led to question the potential use of the geodiversity index map. While geoheritage and geodiversity have been defined in the literature, the multiplicity of definitions given to these two concepts, particularly for geoheritage (see Brocx and Semeniuk, 2007; Mantovani, 2024), makes it difficult to establish an unambiguous relationship between them. Based on semantic-ontological studies (Mantovani and Lombardo, 2022; see Section 3), our study aims to investigate this relationship in the field by using maps in an attempt to reduce this ambiguity within the concepts. Our investigation delves into the understanding of the complex connections between geodiversity and geoheritage within Alagna Valsesia (NW Italy, Fig. 1), a region recognized for its significant scientific and cultural importance located within the Sesia Val Grande UNESCO Global Geopark (http://www.sesiavalgrandegeopark.it/index.php/it/). Through the parallel production of maps of geodiversity and geosites, our study aims to support policy makers, geopark staff and tourism planners in promoting responsible geotourism practices and sustainable development in the Sesia Val Grande UNESCO Global Geopark.

2. Study Area

For this work we chose Alagna Valsesia as case study area. Alagna Valsesia is a municipality with a territory that ranges from 1140 to 4554 m a.s.l., and located in the upper part of the Sesia main Valley, in Piedmont Region (NW Italy) (Fig. 1), where the Sesia river flows through. From there, five tributary valleys extend: to the west lies Val Vogna, Val d'Otro, Valle d'Olen and Valle di Bors, while Valle di Mud lies to the east. The landscape comprises some of the highest peaks of the Monte Rosa Massif, that surround the valley basin and are significant for international alpinism. The highest of these peaks is Punta Gnifetti, at 4554 m above sea level. From a geological point of view, Alagna Valsesia is located at the boundary between *Austroalpine* and *Pennidic Domains* (nappes) of the Alpine chain (Dal Piaz et al., 2015; Piana et al., 2017). The *Pennidic Domain* is composed of continental crust units, which were derived paleogeographically from the distal margin of Europe, as well as oceanic crust units that originated from the Piedmont-Ligurian Ocean (Dal Piaz et al., 2003). Particularly, the continental crust is represented by the *Monte Rosa Unit*, in which micaschists and ortogneiss outcrop; while the oceanic crust is represented by two different Units: the *Piedmontese Zone Combin type*, in which calceschists and metabasites outcrop, and the *Piedmontese Zone Zermatt-Saas type*, characterized by metabasites and serpentinites (Servizio Geologico Italiano, 1951; Dal Piaz, 2001). Finally, *Austroalpine Domain* is represented by the *Sesia-Lanzo Zone*, that emerges only in the southernmost part of the study area and is composed of gneiss (Fig. 2).

The geological richness of the area is complemented by its significant geoheritage sites (Viani et al., 2020), making it the proper place to investigate and clarify the meanings of important terms like geodiversity, geoheritage and geosites. The basic shape of the Monte Rosa Massif and the valleys within Alagna Valsesia is the result of endogenous and exogenous geological processes, such as the Alpine orogenesis (which set the litho-structural and tectonic conditions) and morphoclimatic variations (e.g., glacial pulsation). Particularly, during the Quaternary, the glaciers were the main morphogenetic agent in the area, and even today the dominant processes at higher altitudes (above 2600 m a.s.l.) are glacial and periglacial (Carraro and Giardino, 2004; Smiraglia and Diolaiuti, 2015). Nevertheless, at lower altitudes there is a proglacial environment whose actual surface shape results from active processes, where the main morphogenetic agents are currently fluvial (with the presence of the Sesia river) and especially gravitational ones (Giardino et al., 2017) (Fig. 3).

Additionally, in Alagna Valsesia is present the Walser people. The Walsers are a local community established in Alagna Valsesia since the Middle Ages following long migrations and known for maintaining their centuries-old traditions and their resilience in the face of climate changes (Dal Negro, 2004; Lenz, 2007; Rizzi and Gianoglio, 2023). Their culture and traditions adds another layer of cultural significance to the area.

Due to the geological diversity, geomorphological significance, and cultural importance of Alagna Valsesia, it has gained acknowledge among scientific community on an international level, being included in the Sesia Val Grande UNESCO Global Geopark, aiming to develop informal education, geoconservation and geotourism strategies (Henriques and Brilha, 2017); by receiving the European Heritage - Europa

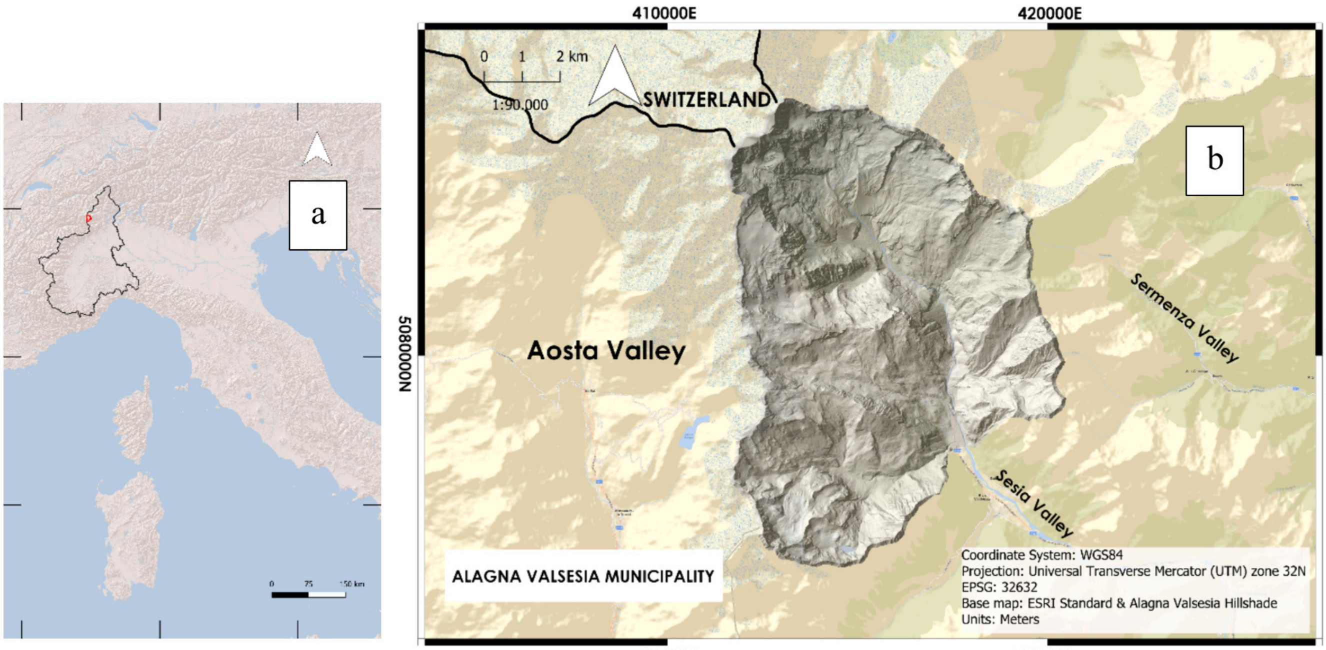

Fig. 1. a) Geographic location of Alagna Valseisa municipality, within the Piemonte Region, Italy. **b)** Overview map and detailed hillshade of Alagna Valsesia municipality, located at the end of the Sesia valley, at the border with the Aosta valley and Switzerland.

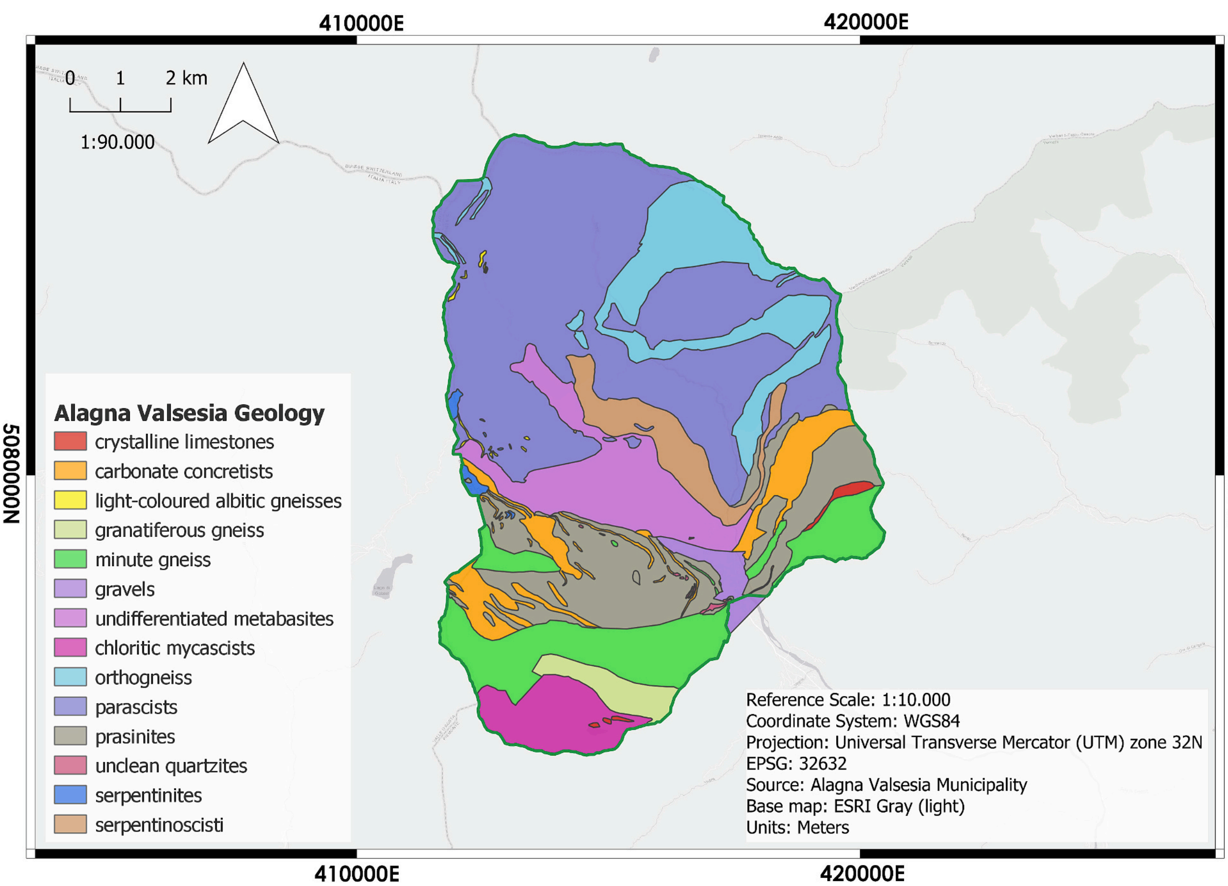

Fig. 2. Simplified geolithological map of the Alagna Valsesia municipality. The original map was made with the land use plan purpose.
(Modified from Bartolini et al. (2023a, 2023b))

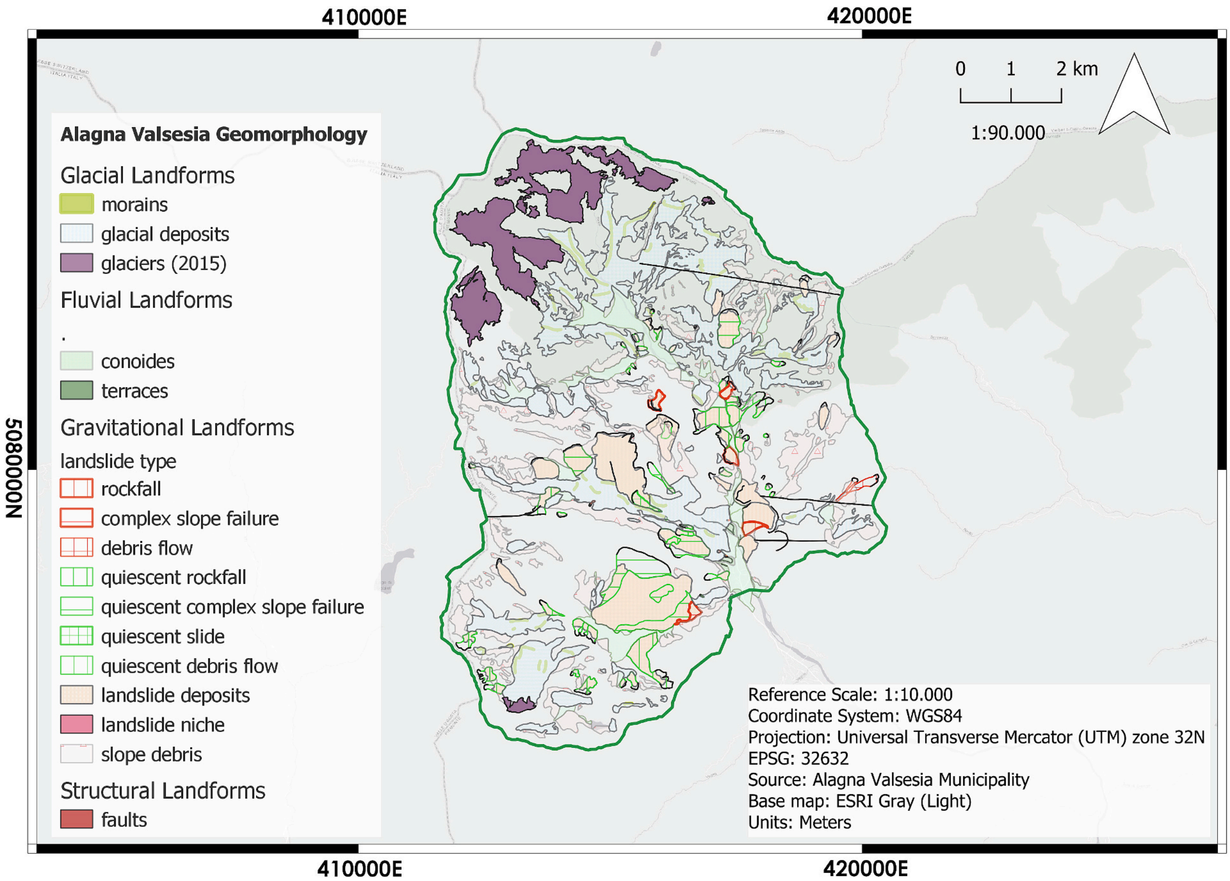

Fig. 3. Geomorphological map of Alagna Valsesia including glacial, gravitational, fluvial and structural landforms. The original map was made with the land use plan purpose.
(Modified from Bartolini et al. (2023a, 2023b))

Nostra Awards in 2014 for the conservation of traditional architecture (https://www.europanostra.org/winners-2014-eu-prize-cultural-heritageeuropa-nostra-awards-announced/); and being designed by the H2020 Arctic Hub project as a learning study area in the Alps reflects its remarkable diversity and cultural heritage, as well as its importance on a European scale (https://projects.luke.fi/arctichubs/). Moreover Alagna Valsesia was the subject of several research, such as the study of geosystem services in mountain areas (Tognetto et al., 2021), works aimed at studying the impacts of climate change on natural elements of geodiversity (Colombo et al., 2019; Giardino et al., 2020; Quaglia et al., 2020), and an important site for geotourism (Perotti et al., 2020) and geoeducational activities (Giardino et al., 2022). Together, these elements make Alagna Valsesia a suitable case study for advancing our knowledge on geodiversity and geoheritage of the region, how they relate to one another, and the consequences of these relationships for promoting sustainable development and geotourism.

3. Teorethical background

The assessment of geodiversity is an important issue which is still under debate. Indeed, there are different methods for the assessment that have been applied for different purposes and different types of areas. In order to support a more coherent study on the field concerning both a geodiversity assessment and the relation of the geodiversity richness with the occurrence of geoheritage, we propose a summary of the definitions of these concepts based on the semantic and ontological studies (see Mantovani and Lombardo, 2022). Especially, these approaches focus on formalizing concepts within a given knowledge domain and make their relationships explicit (Gruber, 1993). Specifically, some of the concepts considered in our work are described in literature with many different definitions (Brocx and Semeniuk, 2007) that can be different and mutually incoherent. Accordingly, ontological and semantic studies allow to reduce ambiguities among the considered concepts and served as the core basis for our field assessments and analyses focused on understanding the correlation between geodiversity and geosites within our study area.

3.1. Geodiversity

Over the past 30 years, several definitions of the concept of geodiversity have been proposed. According to Boothroyd and Henry (2019), the many definitions can be grouped into two main schools of thought according to the affinity of the concepts within them. The first school of thought follows the definition first suggested by Gray (2013) and Gray et al. (2013); while the second school of thought follows a definition proposed by Brocx and Semeniuk (2007) after Semeniuk (1997) (Mantovani, 2024). Upon analyzing the definitions, the main difference lies in the relation to a territory. Brocx and Semeniuk's (2007) definition suggests a limited use of the concept to a well-defined area, while Gray (2013) describes geodiversity at a global scale and specifies how it can be considered at both global and local levels. According to Boothroyd and Henry (2019) 88 % of authors use Gray's definition or similar versions. Consequently, our work is based on this definition of geodiversity. Therefore, in the context of our study, we considered as elements of geodiversity the ones listed in this definition, many of which are already encoded in the OntoGeonous ontology (Lombardo et al., 2016, 2018; Mantovani et al., 2020a, 2020b), an ontology for the geosciences based on GeoScienceML international standard (http://geos ciml.org/). Specifically, these elements are the geological features in the whole, considering the materials (rocks, minerals, fossils, soils, but also water); in which shape they appear on the surface (landforms, structures and topography); and the presence of processes that act on the surface or the evidence of subsurface processes.

3.2. Geoheritage

As for geodiversity, the concept of geoheritage has several definitions in literature (see Mantovani, 2024). All of these definitions highlight the deep relationship between geoheritage and the elements of geodiversity. Moreover, all of these definitions share the attribution of a value to the elements of geodiversity as a requirement for geoheritage status. All these definitions are well summarized in the definition suggested by Sharples (2002). Indeed, it encompasses all the other definitions when considering the relationship with the geodiversity elements and values. However, looking at definitions and works in the literature lists of values to define geoheritage are not fully shared (Sharples, 2002; Brilha, 2018; Georgousis et al., 2021; National Park Service, 2021). For example, all the authors accept the scientific value as a condition for an element of geodiversity to be considered as geoheritage, but not all of them accept the recreational or economic values (see Mantovani, 2024). An example of this issue is Uluru/Ayers Rock, located in Uluru-Kata Tjuta National Park, Australia. Although its scientific value has been established (Twidale, 1978, 2010; Twidale and Wopfner, 1981), this geosite is often associated with its high cultural value (e.g. Brilha, 2018). However, cultural value alone is not generally accepted for attribution of geoheritage status. As the values that comprise the geoheritage only partially overlap, we have adopted the Sharples (2002) definition because it avoids constraints on given values and allows for the inclusion of all other definitions, so being supportive for decision-makers.

3.3. Geosites

Despite also the term geosite present multiple definitions in literature (see Mantovani, 2024), all these definitions highlight that a geosite is a delimited area in which significant geodiversity elements are present. According to some definitions (García-Cortés et al., 2013; Brilha, 2016) the geosites have a direct connection with the geoheritage (i.e., geosites are the in situ occurrence of geoheritage), while others identify in the geosite the presence of geological interest (Wimbledon, 1995; Brilha, 2018). However, also in the latter definitions, the link between geosites and geoheritage is established by relating geological interest and values (that are condition for an element of geodiversity to be considered geoheritage), as investigated by Diaz Martinez and Fernandez Martinez (2015) and by others ongoing studies. For instance, the geosite of the Vajont Landslide could be examined: in the Vajont Valley, in Northern Italy, a massive landslide occurred in 1963. It is a geosite of international relevance, characterized on the one hand by the geomorphologic interest due to the exposition of the sliding surface and of the crown, that can be linked to a scientific value for the landslide study; on the other hand by the historical and educational interest for the significance of that event in the history of the region, giving cultural and educational values (Hilario et al., 2022). For the purposes of our study, we consider the geosites in the field as areas in which geoheritage occur, and all of the reviewed definitions allow to link the geosites to the geoheritage. Thus, it is possible to investigate the relationship in the field between geodiversity richness and geoheritage, through its occurrence in the identified geosites.

4. Methods

The present study entails the identification and mapping of geodiversity and geosites within Alagna Valsesia, and the spatial correlation between these two elements. Additionally, the potential utility of the geodiversity assessment map for identify geosites is discussed. In particular, geotourism is increasingly gaining interest (Herrera-Franco et al., 2020), and Alagna Valsesia, as mountain tourist area within a UNESCO Global Geopark, is an important place where to plan geotourism activities for sustainable development. To address these research questions we created the geosites map and the quantitative geodiversity index map; then we overlapped them and applied non-parametric correlation tests to investigate their correlation.

First, we identified the geosites that represent the main attraction of the Geoparks (Brilha et al., 2018). The identification of geosites was conducted by analyzing the geoscience literature related to the most important study area and then completed by photo interpretation and some relevant field trips. Secondly, by means of spatial analysis using geographic information system (GIS) with an open source software QGIS (version 3.28.13, https://www.qgis.org/en/site/), we assessed geodiversity and mapped the geodiversity index in the study area using a revised version of the method previously described in Forte et al. (2018). The method was adapted to also consider elements such as quarries and mines, and the natural processes active in the study area during the geodiversity assessment (further addressed as energy relief). Subsequently, in an attempt to understand the correlation between geodiversity and geoheritage, we overlaid the geodiversity index map and the geosites map, and applied some correlation tests using RStudio software, version 2023.12.1 + 402 (https://posit.co/download/rstudio-desktop/). Finally, to better understand the type of relationship describing the spatial relationship between these two variables, we performed some non-linear regression models.

4.1. Geosites selection

The method of identifying and selecting the geosites of Alagna Valsesia was based on a two-step approach. First, we consulted the existing literature on the local geosites. Perotti et al. (2020) provided a foundational inventory of geosites within the Sesia Val Grande UNESCO Global Geopark, serving as a key reference for Alagna Valsesia geosites. Additionally, in order to identify more geosites in the study area, we investigated through the Sesia Val Grande geopark's archives, which listed sites of particular geological interest in Alagna Valsesia; the "Inventario Nazionale dei Geositi", the official inventory of all geosites catalogued in Italy provided by the Italian Institute for Environmental Protection and Research (ISPRA-Servizio Geologico d'Italia, 2023); and other articles about the geosites of the Sesia Val Grande UNESCO Global Geopark (Perotti et al., 2019; Guerini et al., 2023). Second, through photointerpretation and field trips, we completed the selection of geosites by adding to those identified in the literature some geosite that, following the criteria outlined in Section 3.3, have similar level of interest. During the field trips we also meticulously recorded geographic coordinates of the geosites, enabling accurate spatial representation of each geosite in GIS environment.

4.2. Geodiversity assessment

Geodiversity assessment is difficult due to its complexity, and it is impossible to consider the diversity of all the abiotic elements (Marceau, 1999). Therefore, it was necessary to make a selection based on the purpose of the study. Among the geodiversity elements listed in the definition by Gray (2013), geology, geomorphology, soils, and hydrography were considered. According to Bollati et al. (2023), these are relevant elements of geodiversity, mainly because Alagna Valsesia is a mountainous area, and geodiversity of proglacial areas depends on water, rocks, landforms and soils. In addition, we also considered the quarries and mines and energy-relief. The former increase the diversity of an area by ensuring the inclusion in the index of minerals, stones and metals present in the area. Indeed, quarries and mines expose a range of rock types that would not otherwise be visible (British Geological Survey, 2024). Moreover, they have also been considered an element of geodiversity and are often linked to the geological heritage of the area

(Gajek et al., 2019; Kubalíková and Balková, 2023). The latter make it possible to highlight places where processes, which are part of the definition of geodiversity (Gray, 2013), may be most intense. A geodatabase was created for each of these types of elements.

For our study we crossed information coming from many different geodatabases:

- Lithology: contains the information included in the geolithogical map of Alagna Valsesia (Bartolini et al., 2023a), naming all the different lithological units;
- Geomorphology: contains the following elements selected from the geomorphology map made for the land-use plan of Alagna Valsesia (Bartolini et al., 2023b): glaciers, moraines, glacial deposits, faults, landslide landforms (niches, body and deposits), slope debris, alluvial deposits, and terraces. In addition, this dataset includes energy relief information, which contains the polygons where energy relief was considered maximum (from five classes, only the highest was selected because it includes areas where there is more energy and therefore it is more likely to have active natural processes);
- Hydrography: includes information about the river network classified according to the Strahler method for hierarchization of fluvial channels within a drainage system (Strahler and Archibold, 2011). In addition, it includes information about other elements linked to the hydrographic network: conoids, springs and lakes;
- Soils: contains the soil types;
- Quarry and mines: contains information on mineral, stone and metal resources within Alagna Valsesia, both active and inactive.

The Municipality of Alagna Valsesia provided the geolithogical and geomorphological maps at 1:10,000 scale (Bartolini et al., 2023a, 2023b). From Piedmont Geoportal (https://www.geoportale.piemonte.it/cms/) we retrieved the 5-meter resolution Piedmont DTM (for extraction of Alagna DTM and for calculation), and both the hydrographic map at 1:10,000 scale and the soil map at 1:250,000 scale for regional framework of local soil types. The mineral data were provided by the Sesia Val Grande UNESCO Global Geopark archive. All these maps, except for DTM, were obtained in shapefile format and have been checked and validated in QGIS as a means of avoiding any topological error such as superimposition.

Each of the databases was loaded into QGIS in shapefile format, some in point and some in polygonal format (see Table 1). In order to carry out the geodiversity assessment, all polygons were converted to point features using the centroid tool in QGIS (thus getting one point for each polygon). Later on, all the punctual shapefiles were merged together, thus providing a single shapefile in which each point represent one element of the geodiversity. Eventually, we performed the kernel analysis on this shapefile that outcome in a final raster file. Indeed, this method avoids the use of the cells which can be difficult to apply to small areas, such as the one under study, and can depend on numerous tests (Lopes et al., 2023). Thereafter we classified the resulted raster into 5 classes of geodiversity (from very low to very high) according to the Jenks Natural Breaks method (Jenks, 1967). These characterization of geodiversity is relative to the study area and should not be understood as absolute values (Gonçalves et al., 2020). Thereby, the values of the kernel density are directly the values of the geodiversity index. To obtain the more accurate result we conducted several tests in the kernel analysis changing the radius value. By doing tests with 100 m, 250 m, and 500 m radius, we were able to choose the 250 m radius as the optimum value for our case study, also in accordance to Forte et al. (2018).

Table 1
Number of the elements and format type of the datasets resulted from the data collection of the geodiversity elements in Alagna Valsesia. E.g., Lithology dataset contains the polygons of the specific geological lithostratigraphy unit.

Dataset	Number of elements	Type of shapefile
Lithology	112	Polygons
Geomorphology (+ energy relief)	682	Polygons
Soils	18	Polygons
Hydrology	250	Points and Polygons
Quarry and Mines	7	Points

4.3. Geodiversity and Geoheritage correlation

To achieve the aim of our research understanding the links between geoheritage and geodiversity by testing their spatial correlation, the geodiversity index map and the geosites (point feature) map were overlaid. By using the Point Sampling Tool QGIS plugin (version 0.5.4 https://plugins.qgis.org/plugins/pointsamplingtool/) we identified the geodiversity value at the locations of each selected geosite. Then, we reclassified the values as we previously did for the geodiversity assessment, and assessed to which geodiversity class each geosite belongs.

The final statistical analysis has been performed by using Rstudio open source software and considered the count of geosites in each geodiversity class. Standard Pearson correlation test (Lee Rodgers and Wander, 1988) were not applicable due to the quantitative nature of the geosite variable and the ordinal and qualitative nature of the geodiversity class variable. Moreover, the Shapiro-Wilk normality test (Shapiro and Wilk, 1965), applied to the geosite number variable, resulted $W = 0.93017$, with a p-value $= 0.5975$, indicating that it is not possible to assume the normality distribution, that is required for the significance of the Pearson test.

Non-parametric correlation tests were conducted to ascertain the absence of a positive linear correlation between the number of geosites and the geodiversity class. We applied both the Spearman and Kendall rank correlation tests (Spearman, 1904; Kendall, 1938; Dodge, 2008) because these non-parametric tests take into account the different characteristics of our ordinal qualitative and quantitative data, allowing us to examine the relationship between variables while avoiding the assumptions of linearity and normality (Siegel, 1957). Finally, having acknowledged the non-linear relationship, an attempt was made to find the best non-linear regression model to appropriately determine the relationship between these variables. This involved examining numerous non-linear regression models to identify the model that best represented the complex relationship between geodiversity class and geosite quantity.

4.4. Limitations of the method

The complexity of the mountain environment, which is rich in geodiversity, poses challenges. As a mountainous area, with altitudes ranging from 1140 to 4554 m above sea level, the region has experienced rapid climate change, with the transition from the Little Ice Age (from about 1250 to 1860 CE) to a period of warming, which has intensified geomorphological processes (Giardino et al., 2017, 2020). Due to the resulting complex topography and geological processes, it may be difficult to directly correlate geomorphological elements with the structural pattern (such as faults and folds). In addition, automated techniques in GIS software are not able to fully capture this complexity and have to make compromises. To address these limitations, future research should include comparative analyses in areas where correlations are more evident. Such efforts provide relevant background information and clarify the connections between geoheritage and geodiversity in less complex situations than our study area.

Moreover, concerning the scale of the maps, for consistency with the size of our study area, we chose to consider maps with 1:10,000 scale. By doing this, we were able to conduct an accurate assessment of geodiversity at local scale and compare the geodiversity classes location in the area with the position of the selected geosites. It is recognized that the soil map in the source datasets is not at 1:10,000 scale but at 1:250,000. Although it would be better to have all maps at the same scale to have the same detail in all features considered, it was not possible to obtain a soil map at a larger scale. For this reason, we decided that including the 1:250,000 in the assessment was rather better for the final result than not including the soil elements.

Finally, while we rigorously followed established protocols for identifying geosites and consulted widely accepted literature, and always relied on the definition of a geosite (see Section 3.3), the final selection included some subjectivity inherent in the selection process. This is because it is difficult to streamline the geological value and interest included in the definition of geosite, and there is no fully shared opinion in the literature on what values allow an element of geodiversity to be given geoheritage status (see Section 3.2).

5. Results

Although it is generally accepted that the assessment and mapping of geodiversity is useful for land-use planning, nature conservation and landscape management to promote geoconservation and sustainable development (Brilha et al., 2018; Zwoliński et al., 2018), not many studies refer to the spatial correlation between geodiversity assessment and geosites on the basis of the concepts. As described above, in order to have a strong teorethical background, we selected definitions of geodiversity, geoheritage, and geosite based on semantic and ontological studies (see Section 3). On the basis of these definitions, aiming to establish whether areas with the greatest geodiversity are the ones with the most relevant geoheritage (and consequently if the geodiversity intex map could be a useful tool to identify geosites in the area), we have mapped the geodiversity and geosites of Alagna Valsesia and analysed their spatial correlation in the field. Table 1 shows the results of the data collection. In order to assess the geodiversity of Alagna Valsesia, we created 5 geodatabases containing the geodiversity elements of the area in polygonal and point format. The resulted shapefile including the 1069 points representing all the selected geodiversity elements is shown in Fig. 4. In our study, the geodiversity index map corresponds to the application of kernel density analysis; the values score between 0 and 20.56 and were divided into 5 classes of geodiversity according to Jenks natural breaks, from very low (< 0.5009) to very high (> 7.1935), as can be observed in Fig. 5.

Generally, the higher values of geodiversity are recorded in the central and western part of the study area. In fact, the landscape of Alagna Valsesia is exceedingly complex since there is no precise correspondence between the geomorphological features and the structure pattern, due to the multiple geomorphological processes functioning on the area. Therefore, it seems that the regions with higher geodiversity coincide with those where the geological exogenous processes are more intense. Concerning the central part, the concentration of high geodiversity follows the main valley, where deposits and accumulation landforms are mostly present and gravitational and fluvial processes are pronounced. The presence of a large number of geological and hydrological elements is more likely to explain the high values recorded in the western part. Conversely, low and very low geodiversity are observed in the northern region of the research area, which is situated at the highest elevations where predominantly only glacial and periglacial processes are active.

Fig. 6 shows that the identification of geosites in Alagna Valsesia resulted in the recognition of 25 geosites (also present in Table 2). Unlike the geodiversity index, the selected geosites are approximately evenly distributed throughout the study area. Concerning the primary scientific interest, four interests were recognized: geomorphology (GM), structural geology (ST), georesources (GRS), hydrology (HYD) and geohistorical (GS). Table 3 shows that the majority of geosites are related to geomorphological interest (68 %). Although the local study led us to choose a small study area, it is appreciable that we recorded 3 geosites of international importance (12 %), mainly related to georesources and structural geology interests, testifying to the relevant geoheritage and the geotouristic potential of the area. However, the most represented importance is the regional one, comprising 48 % of the geosites.

Consistent with previous research (Chrobak et al., 2021; Gonçalves et al., 2022), no correlation was found between the presence of geosites and the geodiversity index score (Fig. 6). This lack of correlation was also observed in the aforementioned studies, despite the use of a different method to create the geodiversity map. As can be seen in Table 4, in Alagna Valsesia only a minimal number of geosites occurs on the areas of high geodiversity (12 %), while the most of the geosites are associated with areas of moderate geodiversity. Notably, no geosites are recorded in areas characterized by a high level of geodiversity. Based on these results, the correlation tests strongly confirmed no linear correlation between the number of geosites and the class of the Geodiversity Index. Specifically, the results of the Spearman and Kendall tests are −0.462 and − 0.316, respectively (Table 5). Moreover, for both of the tests, an alpha of 0.05 was chosen and in both cases the *p*-value is significantly higher than alpha. This means that the tests are not

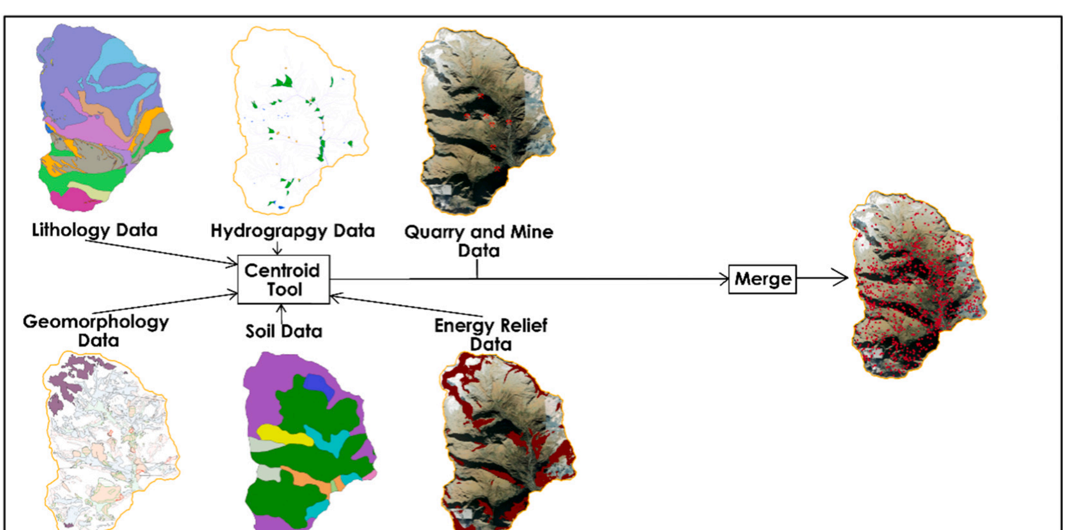

Fig. 4. Illustrative procedure of the creation of the final dataset collecting all the geodiversity elements of Alagna Valsesia. According to Forte et al. (2018), the polygonal elements of each geodiversity unit were converted in punctual features (centroids tool) and merged together with the other punctual features in a final shapefile containing 1069 geodiversity elements.

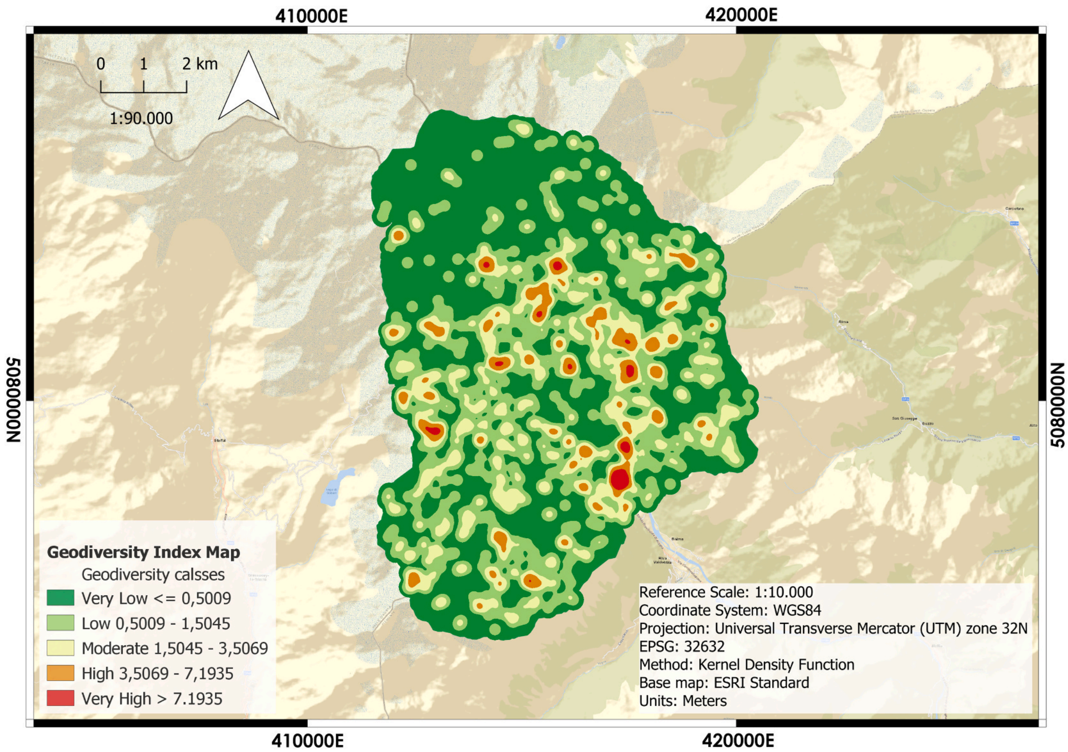

Fig. 5. Quantitative geodiversity index map of the municipality of Alagna Valsesia. The lithology, geomorphology, soil, hydrography and quarry and mine data were considered to produce this map by applying the kernel density function (Forte et al., 2018). The geodiversity classes have been divided according Jenks Natural break (Jenks, 1967).

significant and it is essentially impossible to accept the null hypothesis of a correlation.

Having acknowledged the non-linear relationship between geodiversity class and number of geosites, we applied numerous non-linear regression models in RStudio in an attempt to find the best model representing the relationship between these variables. The evidences suggest that the regression model which better represent the relation between geodiversity class and number of geosites is the polynomial regression model (2nd degree polynomial) (Fig. 7).

Using this model results in a correlation coefficient r^2 of 0.6454, but the *p*-value is still the most important value for this test. In fact, the p-value of 0.1773 is above the threshold alpha of 0.05 (Table 6), indicating that the test is not significant, as with the other tests we conducted. Our study was unable to find a significant regression model describing the relationship between geodiversity richness and geoheritage occurrence in the field. This confirms that there is no predictable correlation between the two variables.

6. Discussion

This study provide a comprehensive investigation of the correlation between geoheritage and geodiversity in terms of both concepts and fieldwork. There is a gap in the literature between these two concepts and methodologies (Crisp et al., 2021), and it is still not fully acknowledged what the potential uses of the geodiversity map are (Santos et al., 2017; Gray, 2021; Gonçalves et al., 2022), partly due to the lack of a robust and unambiguous conceptual framework. As previously described (see Section 3), based on semantic and ontological studies, in this paper geodiversity is considered according to Gray (2013; see Mantovani, 2024), which is in good agreement with 88 % of the researchers (Boothroyd and Henry, 2019); whereas geoheritage is considered according to Sharples (2002) (see Mantovani, 2024), because it does not impose restrictions on specific values and allows for the inclusion of all other definitions, thus supporting decision makers. These two concepts describe different features of the natural environment. Eventually, on the basis of these definitions, we can establish a theoretical framework for understanding their relationship.

Geodiversity includes the totality of natural abiotic elements within a given area. It is worth noting that geodiversity concept comprises a wide range of natural elements; however, their intrinsic value is not expressly addressed in its definition. Whereas the geosites are a delimited areas in which significant geodiversity elements are present, and geoheritage is a subset of geosites that only includes features that have a value and are considered to be of significant importance, as already observed by other works (Ólafsdóttir and Dowling, 2014; Williams et al., 2020; Zakharovskyi and Németh, 2021b). We were able to consider the geosites in the field as areas in which geoheritage occur by linking interest and values (Diaz Martinez and Fernandez Martinez, 2015). Although these definitions make the relationship between geodiversity and geoheritage clear, they do not in themselves clarify their spatial correlation. We based on these theoretical considerations to produce the geodiversity index map of Alagna Valsesia by following a revised version of the method proposed by Forte et al. (2018). Indeed, this quantitative approach makes it possible to create a geodiversity map that represents the spatial distribution and the variety of geodiversity elements, according to the definition by Gray (see Mantovani, 2024), avoiding to include their values, which are features of the geoheritage, and decreasing subjectivity in the process (Fernández et al., 2020). Then, after a literature review and field trips, 25 geosites were selected and mapped in the same study area. By overlaying the geodiversity index map with the geosite map no particular spatial correlation between geodiversity and geoheritage was shown. In particular, only 12 % of the geosites are located in areas of high geodiversity and none in areas of very high geodiversity. This result shows that some geosites may occur in areas of low geodiversity. Specifically, this study finds that, in the field, the geoheritage occurrence increase only up to the "moderate geodiversity" class, while then the number of geosites decreases as the geodiversity class increases. However, given the significant difference of

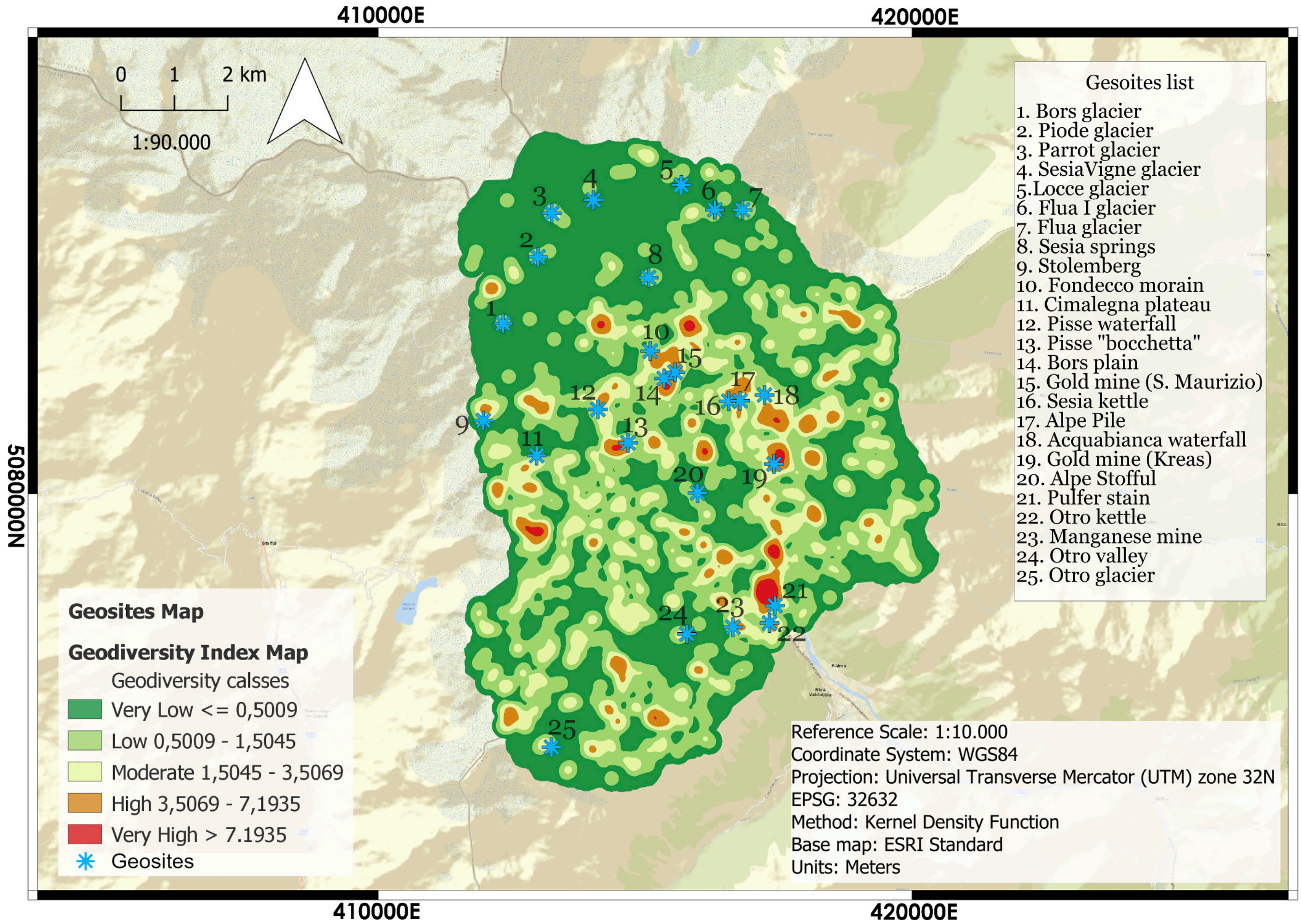

Fig. 6. Overlay of the geosites map with the geodiversity index map in Alagna Valsesia. In green are the "very low geodiversity" class areas, in red "very high geodiversity".

Table 2
List and location of selected geosites in Alagna Valsesia. Primary interests: structural geology (ST), georesources (GRS), hydrology (HYD), geomorphology (GM), Geohistorical (GS). Importance: International (I), national (N), regional (R), local (L). The geodiversity index indicates the value of quantitative geodiversity at the location of the geosite.

Geosite	Primary interest	Importance	Latitude (N)	Longitude (E)	Geodiversity Index
Stolemberg	ST	I	45.867	7.866	1.25
Alpe stofful	GRS	R	45.867	7.918	0.49
Flua I glacier	GM	R	45.916	7.921	0.74
Acquabianca waterfall	GM	L	45.885	7.933	1.67
Locce sud glacier	GM	R	45.920	7.912	0.01
Pisse waterfall	GM	L	45.882	7.893	2.56
Sesia-Vigne glacier	GM	R	45.918	7.891	0.02
Sesia kettle	GM	L	45.884	7.25	2.97
Piode glacier	GM	R	45.907	7.878	0.96
Sesia springs	HYD	R	45.905	7.905	1.52
Flua glacier	GM	R	45.916	7.927	1.50
Parrot glacier	GM	R	45.914	7.883	1.88
Bors glacier	GM	R	45.896	7.870	0.97
Otro glacier	GM	R	45.826	7.883	1.30
Cimalegna plateau	GM	N	45.874	7.876	1.18
Fondecco Moraine	GM	R	45.867	7.918	1.66
Pulfer stein	GM	L	45.850	7.937	2.46
Otro valley	GS	R	45.843	7.915	0.95
Golden mine (Kreas)	GRS	I	45.874	7.936	4.99
Golden mine (S. Maurizio)	GRS	I	45.889	7.912	4.24
Manganese mine	GRS	L	45.846	7.926	2.54
"Bocchetta" of Pisse	GRS	L	45.877	7.901	3.97
Alpe Pile	GM	L	45.884	7.927	2.15
Bors Plain	GM	L	45.888	7.909	3.49
Otro kettle	GM	L	45.847	7.935	2.55

Table 3
Percentages of selected geosites in Alagna Valsesia divided by type of interest and importance. Type of interests: structural geology (ST), georesources (GRS), hydrology (HYD), geomorphology (GM). Importance: International (I), national (N), regional (R), local (L).

Type of interest	Number of geosites	%	Level of importance	Number of geosites	%
GM	17	68	I	3	14
GRS	5	20	N	1	9
HYD	1	4	R	12	48
ST	1	4	L	9	29
GS	1	4			

Table 4
Number and percentage of geosites occurring on the areas of the different geodiversity classes in Alagna Valsesia. geodiversity classes were calculated using a quantitative method (Forte et al., 2018) and range from very low to very high. Geosites were identified through literature review and fieldwork.

Geodiversity class	Number of geosites	Geosites %
Very Low	3	12
Low	8	32
Moderate	11	44
High	3	12
Very high	0	0

Table 5
Results of the correlation tests applied during the fieldwork in Alagna Valsesia. The considered variables were "number of geosites" and "geodiversity class".

Type of value	Kendall test	Spearman test
Correlation coefficient	−0.316	−0.462
Parameters	Z = -0.758	S = 29
P-value	0.449	0.434

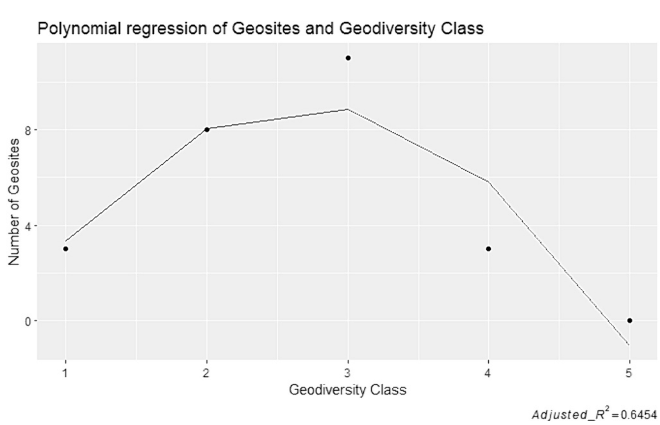

Fig. 7. Result of the second-degree polynomial regression model. This model resulted as the more accurate for describing the spatial relationship between geodiversity class and number of geosite in Alagna Valsesia; but the *p*-value higher than the alpha threshold makes the test not statistically significant proving that in our case study area there is not predictable spatial relationship between these two variables.

geosites number in the five geodiversity classes, even when taking into account that "high geodiversity" and "very high geodiversity" classes are less widespread than the other classes, it is not possible to admit that there is a spatial correlation between geodiversity and geoheritage. This is particularly true for the results of the correlation tests.

The two correlation tests applied, the Kendall and Spearman ones, show no spatial linear correlation between the variables "geodiversity class" and "number of geosites". In particular, the correlation

Table 6
Statistical results of the application of the second-degree polynomial model between the variables geodiversity class and geosites number in Alagna Valsesia.

Type of value	values
Degree	2nd
Residual standard error	2.63
Multiple r^2	0.8227
Adjusted r^2	0.6454
f-statistic	4.64
p-value	0.1773

coefficients of the Spearman and Kendall tests are −0.462 and − 0.316, respectively, with a p-value that is much higher than the alpha (0.05) in both cases. Indeed, it was already clear from the scatterplot (Fig. 7) that there is no clear monotonic relationship between the two variables, neither negative nor positive, rendering the two tests void of significance. Hence, our study shows that in Alagna Valsesia the areas with the greatest geodiversity are not the ones with the most relevant geoheritage. Notably, this result is in accord with previous studies that show that areas of high geodiversity are not necessarily related to the presence of geosites, while areas of low geodiversity may contain sites of geological interest (Brocx and Semeniuk, 2007; Santos et al., 2017; Chrobak et al., 2021; Gray, 2021; Gonçalves et al., 2022), but our work confirms this in an innovative way, with fieldwork based on a semantic and ontological study of definitions (Mantovani and Lombardo, 2022). Furthermore, even all other non-parametric regression models tested were not significant, indicating that there is no predictable relationship between geodiversity and geoheritage in our study area. This field result is crucial because it imply that the geodiversity index map, created with the quantitative methods, could not be a useful tool for geosites recognition and tourism promotion. Indeed, geodiversity and geoheritage are different features of the abiotic environment (Gray, 2019), and for this reason the methodologies used to assess geodiversity and to perform a geological inventory are different (Gonçalves et al., 2022). Moreover, this supports the idea that any environmental management focused on geoconservation and geotourism planning requires the recognition of what can be considered geoheritage in the area, that is, the selection, mapping and promotion of the geosites (Brilha, 2018; Selmi et al., 2019; Crofts et al., 2020), while the quantitative geodiversity map could be only a complementary tool.

However, the knowledge of geodiversity is the backbone of geoheritage (as the geoheritage are elements of the geodiversity with a particular value) and of geoconservation (Gray, 2018). Previous studies have shown that different approaches give different results (Gonçalves et al., 2022), and the relationship between geodiversity and geoheritage is usually shown in geodiversity assessment studies using a qualitative approach (Brilha et al., 2018). Thus, the qualitative map becomes a useful tool for recognition (Zakharovskyi et al., 2023) and management (Najwer et al., 2023) of geosites. Nevertheless, qualitative maps can have some drawbacks: this approach involves assigning numerical values to geodiversity elements based on their qualitative value, which introduces a degree of subjectivity into the process (Crisp et al., 2021). Although this makes it more functional for certain purposes, there is a risk that it moves away from the definition of geodiversity, which only includes the diversity of elements and not their values, which is what geoheritage is all about. In addition, the results of this work are in support of previous research that has shown that recognition of geoheritage is somewhat subjective (Fernández et al., 2020). In fact, the selection of geoheritage in the past may have been based on criteria that favored cultural aspects (e.g., common wisdom of local communities) over scientific ones, and for this reason spatial correlation may not occur. Therefore, there is a clear need to rationalize indicators and values that would allow the attribution of geoheritage status to geodiversity elements (Pereira et al., 2010).

Nonetheless, as highlighted in earlier research (Hjort and Luoto, 2010; Santos et al., 2017), the quantitative geodiversity map provides a direct and effective approach to evaluate the richness of the physical environment. Therefore, this method may be helpful in other scenarios, such as identifying abiotic ecosystems and the ways that geodiversity affects biodiversity. Previous studies comparing geodiversity and biodiversity have shown that they are distinct elements of the natural environment: both are capable of providing services to humans, and together, they make up all the elements of the natural environment (Gray, 2019; Frisk et al., 2022; Herrera-Franco et al., 2022). Nevertheless, although geodiversity–biodiversity relationship can be very complex and still needs more evidence (Alahuhta et al., 2019), it is now acknowledged that geodiversity can affect and underpin biodiversity (Tukiainen et al., 2017a; Ren et al., 2021). Particularly, geodiversity and biodiversity relationships have been demonstrated by highlighting the significant influence of abiotic heterogeneity on habitat richness (Jačková and Romportl, 2012), vegetation (dos Santos et al., 2019), species richness (Salminen et al., 2023), and presence of ecosystem services (Alahuhta et al., 2018; Garcia, 2019; Queiroz and Garcia, 2022). Thus, the quantitative geodiversity map could be important in providing more information about a landscape's potential for biodiversity conservation (Anderson and Ferree, 2010; Lawler et al., 2015), and it would be considered an important tool in defining protected areas (Tukiainen et al., 2017b; Fernández et al., 2020). Therefore, the quantitative geodiversity map can be a useful surrogate of biodiversity, and should be incorporated into biodiversity research and conservation (Hjort et al., 2012; Lawler et al., 2015). Furthermore, climate change is another important factor that can impact the geodiversity and the geosites, thus impacting both the biodiversity and the services the geodiversity provides to humans (Gordon et al., 2022).

7. Conclusions

This study aimed to investigate the relationship between the geodiversity richness and the presence of geoheritage in Alagna Valsesia (Sesia Val Grande UNESCO Global Geopark, Italian Western Alps), discussing whether the areas with the greatest geodiversity are the ones with the most relevant geoheritage, thus questioning the potential use of the geodiversity index map. Upon a strong theoretical framework based on semantic and ontological studies, by using the geosites and the quantitative geodiversity index maps, our study showed that there is no spatial correlation between the geodiversity class and the number of geosites, proving that some geosites may occur in areas of low geodiversity, and the greatest geodiversity areas are not the ones with the most relevant geoheritage. An accurate statistical analysis confirmed this result: the Kendall and Spearman correlation tests showed the impossibility to admit the correlation between the geodiversity richness and the geoheritage occurrence in the field. Moreover, all the other non-parametric regression models tested were not significant, indicating that there is no predictable relationship between geodiversity and geoheritage in our study area. For that reason, the quantitative geodiversity map could not be a useful tool for geosites recognition and tourism promotion, while for this purpose should be better use a qualitative geodiversity map. However, the potential use of quantitative geodiversity map was discussed highlighting its role for geoconservation and the strong influence of geodiversity on biodiversity. Finally, the potential use of the geodiversity map depends on the study's purpose and the approach used to produce it. As previously noted (Gonçalves et al., 2022), the two approaches may be complementary. It is recommended that future studies focus on applying these approaches in a complementary manner to develop land management that considers both the influence of geodiversity on biodiversity and the significance of geoconservation and geotourism promotion.

Data availability statement

Data available via the Zenodo Digital Repository doi:https://doi.org/10.5281/zenodo.10636050 (Guerini et al., 2024).

CRediT authorship contribution statement

Michele Guerini: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alizia Mantovani:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization. **Rasool Bux Khoso:** Visualization, Resources, Data curation. **Marco Giardino:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank the entire staff of the Sesia Val Grande UNESCO Global Geopark and of the Monterosa2000 s.p.a. for the support during the field trips and the data collection. The authors also thank the Municipality of Alagna Valsesia in the person of the mayor Roberto Veggi for the fruitful cooperation, especially during the phase of data collection. Finally, the authors thank the three reviewers. This study was funded by the European Commission Horizon 2020 ArcticHubs-project (Global drivers, local consequences: Tools for global change adaptation and sustainable development of industrial and cultural Arctic "hubs") - Grant Agreement No 869580.

References

Ahmadi, M., Mokhtari, D., Khodadadi, M., Shahabi, H., 2021. Geodiversity evaluation and geoconservation using grid analysis: case study, north of Ilam Province. Appl. Geomat. 13, 537–553. https://doi.org/10.1007/S12518-021-00377-0/FIGURES/8.

Alahuhta, J., Ala-Hulkko, T., Tukiainen, H., Purola, L., Akujärvi, A., Lampinen, R., Hjort, J., 2018. The role of geodiversity in providing ecosystem services at broad scales. Ecol. Indic. 91, 47–56. https://doi.org/10.1016/J.ECOLIND.2018.03.068.

Alahuhta, J., Toivanen, M., Hjort, J., 2019. Geodiversity–biodiversity relationship needs more empirical evidence. Nat. Ecol. Evol. 4, 2–3. https://doi.org/10.1038/s41559-019-1051-7.

Anderson, M.G., Ferree, C.E., 2010. Conserving the stage: climate Change and the Geophysical Underpinnings of Species Diversity. PLoS One 5, e11554. https://doi.org/10.1371/JOURNAL.PONE.0011554.

Araujo, A.M., Pereira, D.Í., 2018. A new methodological contribution for the geodiversity assessment: applicability to Ceará State (Brazil). Geoheritage 10, 591–605. https://doi.org/10.1007/S12371-017-0250-3/FIGURES/11.

Argyriou, A.V., Sarris, A., Teeuw, R.M., 2016. Using geoinformatics and geomorphometrics to quantify the geodiversity of Crete, Greece. Int. J. Appl. Earth Obs. Geoinf. 51, 47–59. https://doi.org/10.1016/j.jag.2016.04.006.

Bartolini, R., Biasetti, E., Biasetti, M., 2023a. Piano Regolatore Generale Comunale. Geological Map.

Bartolini, R., Biasetti, E., Biasetti, M., 2023b. Piano Regolatore Generale Comunale. Geomorphological Map.

Benito-Calvo, A., Pérez-González, A., Magri, O., Meza, P., 2009. Assessing regional geodiversity: the Iberian Peninsula. Earth Surf. Process. Landf. 34, 1433–1445. https://doi.org/10.1002/ESP.1840.

Bétard, F., Peulvast, J.P., 2019. Geodiversity hotspots: concept, method and cartographic application for geoconservation purposes at a regional scale. Environ. Manag. 63, 822–834. https://doi.org/10.1007/S00267-019-01168-5.

Bollati, I.M., Viani, C., Masseroli, A., Mortara, G., Testa, B., Tronti, G., Pelfini, M., Reynard, E., 2023. Geodiversity of proglacial areas and implications for geosystem services: a review. Geomorphology 421, 108517. https://doi.org/10.1016/J.GEOMORPH.2022.108517.

Boothroyd, A., Henry, M.M., 2019. Old processes, new movements: the inclusion of geodiversity in biological and ecological discourse. Diversity 11, 216. https://doi.org/10.3390/D11110216.

Brilha, J., 2016. Inventory and quantitative assessment of geosites and geodiversity sites: a review. Geoheritage 8, 119–134. https://doi.org/10.1007/S12371-014-0139-3/TABLES/9.

Brilha, J., 2018. In: Reynard, E., Brilha, J. (Eds.), Geoheritage: Inventories and Evaluation. Assessment, Protection, and Management. Elsevier, Geoheritage, pp. 69–85. https://doi.org/10.1016/B978-0-12-809531-7.00004-6.
Brilha, J., Gray, M., Pereira, D.I., Pereira, P., 2018. Geodiversity: an integrative review as a contribution to the sustainable management of the whole of nature. Environ. Sci. Pol. 86, 19–28. https://doi.org/10.1016/J.ENVSCI.2018.05.001.
British Geological Survey, 2024. Quarrying and geodiversity [WWW Document]. URL https://www2.bgs.ac.uk/mendips/aggregates/geodiversity.html (accessed 2.5.24).
Brocx, M., Semeniuk, V., 2007. Geoheritage and geoconservation - history, definition, scope and scale. J. R. Soc. West. Aust. 90, 53–87.
Brocx, M., Semeniuk, V., 2019. The '8Gs'—a blueprint for Geoheritage, Geoconservation, Geo-education and Geotourism. Aust. J. Earth Sci. 66, 803–821. https://doi.org/10.1080/08120099.2019.1576767.
Brocx, M., Semeniuk, V., 2020. Geodiversity and the '8Gs': a response to Gray & Gordon (2020). Aust. J. Earth Sci. 67, 445–451. https://doi.org/10.1080/08120099.2020.1722966.
Carraro, F., Giardino, M., 2004. Quaternary glaciations in the western Italian Alps – a review. Dev. Quat. Sci. 2, 201–208. https://doi.org/10.1016/S1571-0866(04)80071-X.
Chrobak, A., Novotný, J., Struś, P., 2021. Geodiversity assessment as a first step in designating areas of geotourism potential. Case study: western Carpathians. Front. Earth Sci. 9, 919. https://doi.org/10.3389/FEART.2021.752669/BIBTEX.
Colombo, N., Salerno, F., Martin, M., Malandrino, M., Giardino, M., Serra, E., Godone, D., Said-Pullicino, D., Fratianni, S., Paro, L., Tartari, G., Freppaz, M., 2019. Influence of permafrost, rock and ice glaciers on chemistry of high-elevation ponds (NW Italian Alps). Sci. Total Environ. 685, 886–901. https://doi.org/10.1016/J.SCITOTENV.2019.06.233.
Crisp, J.R.A., Ellison, J.C., Fischer, A., 2021. Current trends and future directions in quantitative geodiversity assessment. Prog. Phys. Geogr. 45, 514–540. https://doi.org/10.1177/0309133320967219/FORMAT/EPUB.
Crofts, R., Gordon, J.E., Brilha, J., Gray, M., Gunn, J., Larwood, J., Santucci, V., Tormey, D., Worboys, G.L., 2020. Guidelines for geoconservation in protected and conserved areas. Guidel. geoconservation Prot. Conserv. areas. https://doi.org/10.2305/IUCN.CH.2020.PAG.31.EN.
da Silva, M.L.N., do Nascimento, M.A.L., 2020. Ecosystem services and typology of urban geodiversity: qualitative assessment in natal town. Brazilian Northeast. Geoheritage 12. https://doi.org/10.1007/s12371-020-00479-y.
da Silva, M.L.N., do Nascimento, M.A.L., Mansur, K.L., 2019. Quantitative assessments of geodiversity in the area of the Seridó Geopark Project, Northeast Brazil: grid and centroid analysis. Geoheritage 11, 1177–1186. https://doi.org/10.1007/s12371-019-00368-z.
Dal Negro, Silvia, 2004. The Decay of a Language: The Case of a German Dialect in the Italian Alps. Peter Lang, Bern.
Dal Piaz, G.V., 2001. Geology of the Monte Rosa massif: Historical review and personal comments. Swiss J. Geosci. Suppl. 81, 275–303.
Dal Piaz, G.V., Bistacchi, A., Massironi, M., 2003. Geological outline of the Alps. Episodes 26, 175–180. https://doi.org/10.18814/epiiugs/2003/v26i3/004.
Dal Piaz, G.V., Bistacchi, A., Gianotti, F., Monopoli, B., Passeri, L., Schiavo, A., 2015. Note illustrative del F. 070 Monte Cervino della Carta Geologica d'Italia alla scala 1: 50.000, Vol. 101. ISPRA-Servizio Geologico d'Italia, pp. 88–218.
Datta, K., 2022. Does geodiversity correlate with land use/land cover diversity? A case study of Birbhum district, West Bengal. India. Proc. Geol. Assoc. 133, 589–602. https://doi.org/10.1016/J.PGEOLA.2022.07.004.
Diaz Martinez, E., Fernandez Martinez, E., 2015. El valor del patrimonio geológico: fundamentos y significado. Patrim. geológico y geoparques, Av. un camino para todos 13–18.
Dodge, R., 2008. Kendall rank correlation coefficient. Concise Encycl. Stat. 278–281 https://doi.org/10.1007/978-0-387-32833-1_211.
dos Santos, D.S., Mansur, K.L., de Arruda, E.R., Dantas, M.E., Shinzato, E., 2019. Geodiversity mapping and relationship with vegetation: a regional-scale application in SE Brazil. Geoheritage 11, 399–415. https://doi.org/10.1007/S12371-018-0295-Y/FIGURES/18.
Fernández, A., Fernández, T., Pereira, D.I., Nieto, L.M., 2020. Assessment of geodiversity in the southern part of the central Iberian Zone (Jaén Province): usefulness for delimiting and managing natural protected areas. Geoheritage 12, 1–16. https://doi.org/10.1007/S12371-020-00447-6/FIGURES/10.
Forte, J.P., Brilha, J., Pereira, D.I., Nolasco, M., 2018. Kernel density applied to the quantitative assessment of geodiversity. Geoheritage 10, 205–217. https://doi.org/10.1007/S12371-018-0282-3/FIGURES/11.
Fox, N., Graham, L.J., Eigenbrod, F., Bullock, J.M., Parks, K.E., 2020. Incorporating geodiversity in ecosystem service decisions. Ecosyst. People 16, 151–159. https://doi.org/10.1080/26395916.2020.1758214.
Frisk, E.L., Volchko, Y., Sandström, O.T., Söderqvist, T., Ericsson, L.O., Mossmark, F., Lindhe, A., Blom, G., Lång, L.O., Carlsson, C., Norrman, J., 2022. The geosystem services concept – what is it and can it support subsurface planning? Ecosyst. Serv. 58, 101493 https://doi.org/10.1016/J.ECOSER.2022.101493.
Gajek, G., Zgłobicki, W., Kołodyńska-Gawrysiak, R., 2019. Geoeducational value of quarries located within the Małopolska Vistula River Gap (E Poland). Geoheritage 11, 1335–1351. https://doi.org/10.1007/S12371-019-00395-W/FIGURES/8.
Garcia, M. da G.M., 2019. Ecosystem Services provided by Geodiversity: preliminary Assessment and Perspectives for the Sustainable use of Natural Resources in the Coastal Region of the State of São Paulo, Southeastern Brazil. Geoheritage 11, 1257–1266. https://doi.org/10.1007/S12371-019-00383-0/TABLES/2.
García-Cortés, Á., Carcavilla, L., Díaz-Martínez, E., Vega, J., 2013. DOCUMENTO METODOLÓGICO PARA LA ELABORACIÓN DEL INVENTARIO ESPAÑOL DE LUGARES DE INTERÉS GEOLÓGICO (IELIG). Madrid.
Georgousis, E., Savelidi, M., Savelides, S., Holokolos, M.-V., Drinia, H., 2021. Teaching geoheritage values: implementation and thematic analysis evaluation of a synchronous online educational approach. Heritage 4. https://doi.org/10.3390/heritage.
Giardino, M., Mortara, G., Chiarle, M., 2017. The glaciers of the Valle d'Aosta and Piemonte regions: records of present and past environmental and climate changes. World Geomorphol. Landsc. 77–88 https://doi.org/10.1007/978-3-319-26194-2_6.
Giardino, M., Montani, A., Tamburini, A., Calvetti, F., Borghi, A., Alberto, W., Villa, F., Martelli, D., Salvalai, G., Perotti, L., 2020. Climate change and cryosphere in high mountains: preliminary results of field monitoring at Capanna Margherita hut, Punta Gnifetti (Monte Rosa, Pennine Alps). EGU2020. doi:https://doi.org/10.5194/EGUSPHERE-EGU2020-20375.
Giardino, M., Justice, S., Olsbo, R., Balzarini, P., Magagna, A., Viani, C., Selvaggio, I., Kiuttu, M., Kauhanen, J., Laukkanen, M., Perotti, L., 2022. ERASMUS+ strategic partnerships between UNESCO Global geoparks, schools, and research institutions: a window of opportunity for geoheritage enhancement and geoscience education. Heritage 5, 677–701. https://doi.org/10.3390/HERITAGE5020038/S1.
Gonçalves, J., Mansur, K., Santos, D., Henriques, R., Pereira, P., 2020. A discussion on the quantification and classification of geodiversity indices based on GIS methodological tests. Geoheritage 12, 1–20. https://doi.org/10.1007/S12371-020-00458-3/FIGURES/20.
Gonçalves, J., Mansur, K., Santos, D., Henriques, R., Pereira, P., 2022. Is it worth assessing geodiversity numerically? A comparative analysis between quantitative and qualitative approaches in Miguel Pereira Municipality, Rio de Janeiro. Brazil. Geosci. 12 https://doi.org/10.3390/geosciences12090347.
Gordon, J.E., Tormey, D., Wignall, R., Brazier, V., Crofts, R., 2022. Climate change will challenge the management of geoheritage in protected and conserved areas. Park. Steward. Forum 38. https://doi.org/10.5070/P538156119.
Gray, M., 2013. Geodiversity: Valuing and Conserving Abiotic Nature, 2nd ed. Wiley - Blackwell, Chichester, UK.
Gray, M., 2018. In: Reynard, E., Brilha, J. (Eds.), Geodiversity: the backbone of geoheritage and geoconservation. Assessment, Protection, and Management. Elsevier, Geoheritage, pp. 13–25. https://doi.org/10.1016/B978-0-12-809531-7.00001-0.
Gray, M., 2019. Geodiversity, geoheritage and geoconservation for society. Int. J. Geoheritage Park 7, 226–236. https://doi.org/10.1016/j.ijgeop.2019.11.001.
Gray, M., 2021. Geodiversity: a significant, multi-faceted and evolving, geoscientific paradigm rather than a redundant term. Proc. Geol. Assoc. 132, 605–619. https://doi.org/10.1016/J.PGEOLA.2021.09.001.
Gray, M., Gordon, J.E., 2020. Geodiversity and the '8Gs': a response to Brocx & Semeniuk (2019). Aust. J. Earth Sci. 67, 437–444. https://doi.org/10.1080/08120099.2020.1722965.
Gray, M., Gordon, J.E., Brown, E., 2013. Geodiversity and the ecosystem approach: the contribution of geoscience in delivering integrated environmental management. Proc. Geol. Assoc. 124, 659–673.
Gruber, T.R., 1993. A translation approach to portable ontology specifications. Appear. Knowl. Acquis. 5, 199–220.
Guerini, M., Khoso, R.B., Negri, A., Mantovani, A., Storta, E., 2023. Integrating cultural sites into the Sesia Val Grande UNESCO Global Geopark (North-West Italy): methodologies for monitoring and enhancing cultural heritage. Heritage 6, 6132–6152. https://doi.org/10.3390/HERITAGE6090322/S1.
Guerini, M., Mantovani, A., Khoso, R.B., Viani, C., Giardino, M., 2024. Geodiversity and geoheritage data from Alagna Valsesia, Sesia Val Grande UGGp (NW Italy) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10636050.
Henriques, M.H., Brilha, J., 2017. UNESCO Global Geoparks: a strategy towards global understanding and sustainability. Episodes 40, 349–355. https://doi.org/10.18814/EPIIUGS/2017/V40I4/017036.
Herrera-Franco, G., Montalván-Burbano, N., Carrión-Mero, P., Apolo-Masache, B., Jaya-Montalvo, M., 2020. Research trends in geotourism: a bibliometric analysis using the scopus database. Geosciences 10, 1–29. https://doi.org/10.3390/GEOSCIENCES10100379.
Herrera-Franco, G., Caicedo-Potosí, J., Carrión-Mero, P., 2022. Geodiversity and biodiversity for conceptual synthesis, in: WIT Transactions on Ecology and the Environment. WITPress, pp. 383–392. doi:https://doi.org/10.2495/SDP220321.
Hilario, A., Asrat, A., Vries, B., Mogk, D., Lozano Otero, G., Zhang, J., Brilha, J., Vegas, J., Lemon, K., Carcavilla, L., Finney, S., 2022. The First 100 IUGS Geological Heritage Sites. International Union of Geological Sciences.
Hjort, J., Luoto, M., 2010. Geodiversity of high-latitude landscapes in northern Finland. Geomorphology 115, 109–116. https://doi.org/10.1016/J.GEOMORPH.2009.09.039.
Hjort, J., Luoto, M., 2012. Can geodiversity be predicted from space? Geomorphology 153–154, 74–80. https://doi.org/10.1016/J.GEOMORPH.2012.02.010.
Hjort, J., Heikkinen, R.K., Luoto, M., 2012. Inclusion of explicit measures of geodiversity improve biodiversity models in a boreal landscape. Biodivers. Conserv. 21, 3487–3506. https://doi.org/10.1007/S10531-012-0376-1/FIGURES/5.
Hjort, J., Gordon, J.E., Gray, M., Hunter, M.L., 2015. Why geodiversity matters in valuing nature's stage. Conserv. Biol. 29, 630–639. https://doi.org/10.1111/COBI.12510.
Ibáñez, J.J., Brevik, E.C., Cerdà, A., 2019. Geodiversity and geoheritage: detecting scientific and geographic biases and gaps through a bibliometric study. Sci. Total Environ. 659, 1032–1044. https://doi.org/10.1016/J.SCITOTENV.2018.12.443.
ISPRA-Servizio Geologico d'Italia, 2023. Inventario Nazionale dei Geositi [WWW Document]. Ital. Geosites Invent. URL http://sgi.isprambiente.it/GeositiWeb/default.aspx?ReturnUrl=%2Fgeositiweb%2F (accessed 11.10.23).
Jačková, K., Romportl, D., 2012. The relationship between geodiversity and habitat richness in Šumava National Park and Křivoklátsko PLA (Czech Republic): a

quantitative analysis approach. J. Landsc. Ecol. 1, 23–38. https://doi.org/10.2478/V10285-012-0003-6.
Jankowski, P., Najwer, A., Zwoliński, Z., Niesterowicz, J., 2020. Geodiversity assessment with crowdsourced data and spatial multicriteria analysis. ISPRS Int. J. Geo-Information 9. https://doi.org/10.3390/ijgi9120716.
Jenks, G., 1967. The data model concept in statistical mapping. Int. Yearb. Cartogr. 7, 186–190.
Kärnä, O.M., Heino, J., Grönroos, M., Hjort, J., 2018. The added value of geodiversity indices in explaining variation of stream macroinvertebrate diversity. Ecol. Indic. 94, 420–429. https://doi.org/10.1016/J.ECOLIND.2018.06.034.
Kendall, M.G., 1938. A new measure of rank correlation. Biometrika 30, 93. https://doi.org/10.2307/2332226.
Kubalíková, L., Balková, M., 2023. Two-level assessment of threats to geodiversity and geoheritage: a case study from Hády quarries (Brno, Czech Republic). Environ. Impact Assess. Rev. 99, 107024 https://doi.org/10.1016/J.EIAR.2022.107024.
Lawler, J.J., Ackerly, D.D., Albano, C.M., Anderson, M.G., Dobrowski, S.Z., Gill, J.L., Heller, N.E., Pressey, R.L., Sanderson, E.W., Weiss, S.B., 2015. The theory behind, and the challenges of, conserving nature's stage in a time of rapid change. Conserv. Biol. 29, 618–629. https://doi.org/10.1111/COBI.12505.
Lee Rodgers, J., Wander, Alan Nice, 1988. Thirteen ways to look at the correlation coefficient. Am. Stat. 42, 59–66. https://doi.org/10.1080/00031305.1988.10475524.
Lenz, P.C., 2007. I Walser a sud delle Alpi. Provincia Verbania Cusio Ossola, Verbania.
Lombardo, V., Piana, F., Fioraso, G., Irace, A., Mimmo, D., Mosca, P., Tallone, S., Barale, L., Morelli, M., Giardino, M., 2016. The classification scheme of the Piemonte geological map and the OntoGeonous initiative. Rend. Online Soc. Geol. Ital. 39, 117–120. https://doi.org/10.3301/ROL.2016.61.
Lombardo, V., Piana, F., Mimmo, D., 2018. Semantics–informed geological maps: Conceptual modeling and knowledge encoding. Comput. Geosci. 116, 12–22. https://doi.org/10.1016/j.cageo.2018.04.001.
Lopes, C., Teixeira, Z., Pereira, D.I., Pereira, P., 2023. Identifying optimal cell size for geodiversity quantitative assessment with richness. diversity and Eevenness indices. Resources 12, 65. https://doi.org/10.3390/RESOURCES12060065/S1.
Mantovani, A., 2024. Definitions of geodiversity, geoheritage, geosite. Zenodo. https://doi.org/10.5281/ZENODO.10663974.
Mantovani, A., Lombardo, V., 2022. Toward a semantic representation of geoheritage (short paper), in: Artificial Intelligence for Cultural Heritage 2022, November 28th. Udine. doi:ceur-ws.org/Vol-3286/10_paper.pdf.
Mantovani, A., Piana, F., Lombardo, V., 2020a. Ontology-driven compilation of geological map database. Rend. Online Soc. Geol. Ital. 52, 62–68. https://doi.org/10.3301/ROL.2020.20.
Mantovani, A., Piana, F., Lombardo, V., 2020b. Ontology-driven representation of knowledge for geological maps. Comput. Geosci. 139 https://doi.org/10.1016/j.cageo.2020.104446.
Marceau, D.J., 1999. The scale issue in the social and natural sciences. Can. J. Remote. Sens. 25, 347–356. https://doi.org/10.1080/07038992.1999.10874734.
Najwer, A., Jankowski, P., Niesterowicz, J., Zwoliński, Z., 2022. Geodiversity assessment with global and local spatial multicriteria analysis. Int. J. Appl. Earth Obs. Geoinf. 107, 102665 https://doi.org/10.1016/J.JAG.2021.102665.
Najwer, A., Reynard, E., Zwoliński, Z., 2023. Geodiversity assessment for geomorphosites management: Derborence and Illgraben, Swiss Alps. Geol. Soc. London Spec. Publ. 530 https://doi.org/10.1144/SP530-2022-122.
National Park Service, 2021. Geoheritage Values [WWW Document]. URL https://www.nps.gov/articles/series.htm?id=29E0CA29-A137-25A5-51554A2D50C99586 (accessed 2.2.24).
Ólafsdóttir, R., Dowling, R., 2014. Geotourism and geoparks-a tool for geoconservation and rural development in vulnerable environments: a case study from Iceland. Geoheritage 6, 71–87. https://doi.org/10.1007/S12371-013-0095-3/FIGURES/7.
Panizza, M., 2009. The geomorphodiversity of the Dolomites (Italy): a key of geoheritage assessment. Geoheritage 1, 33–42. https://doi.org/10.1007/S12371-009-0003-Z/FIGURES/10.
Pereira, D.I., Pereira, P., Brilha, J., Santos, L., 2013. Geodiversity assessment of Paraná State (Brazil): an innovative approach. Environ. Manag. 52, 541–552. https://doi.org/10.1007/S00267-013-0100-2/FIGURES/8.
Pereira, P., Brilha, J., Pereira, D., Carcavilla, L., Amrikazemi, A., Bajada, S., Marden Barreto, J., Bollati, I., Braga, N., Canilho, S., Carvalhido, R., Casinhas, P., Castro, I., Cumbe, Â., Dias, N., Erhart, B., Fraga Pereira, R., Gaidzik, K., Guimarães, R., Ghiraldi, L., Kozina, K., Lima, E., Lopes, E., Loureiro, C., Mantesso, V., Martin, S., Nekouie-Sadry, B., Pereira, S., Rocha, J., Sá Lemos, H., Schilling, M., Sousa, M., Tomsa, A.M., Torres, M., Welc, E., Zanoletti, E., 2010. Subjectivity and uncertainty in geological heritagequantitative assessment: results from fieldwork using a predefinednumerical methodology. Schriftenr. der Dtsch. Gesellschaft für Geowissenschaften 66, 114–115. https://doi.org/10.1127/SDGG/66/2010/114.
Perotti, L., Carraro, G., Giardino, M., De Luca, D.A., Lasagna, M., 2019. Geodiversity evaluation and water resources in the Sesia Val Grande UNESCO Geopark (Italy). Water 11, 2102. https://doi.org/10.3390/W11102102.
Perotti, L., Bollati, I.M., Viani, C., Zanoletti, E., Caironi, V., Pelfini, M., Giardino, M., 2020. Fieldtrips and virtual tours as geotourism resources: examples from the Sesia Val Grande UNESCO Global Geopark (NW Italy). Resources 9, 1–34. https://doi.org/10.3390/RESOURCES9060063.
Piana, F., Fioraso, G., Irace, A., Mosca, P., D'Atri, A., Barale, L., Falletti, P., Monegato, G., Morelli, M., Tallone, S., Vigna, G.B., 2017. Geology of Piemonte region (NW Italy, Alps–Apennines interference zone). J. Maps 13, 395–405. https://doi.org/10.1080/17445647.2017.1316218/SUPPL_FILE/TJOM_A_1316218_SM2251.PDF.
Quaglia, E., Ravetto Enri, S., Perotti, E., Probo, M., Lombardi, G., Lonati, M., 2020. Alpine tundra species phenology is mostly driven by climate-related variables rather than by photoperiod. J. Mt. Sci. 17, 2081–2096. https://doi.org/10.1007/S11629-020-6079-2/METRICS.
Queiroz, D.S., Garcia, M. da G.M., 2022. The "hidden" geodiversity in the traditional approaches in ecosystem services: a perspective based on monetary valuation. Geoheritage 14, 1–13. https://doi.org/10.1007/S12371-022-00676-X/TABLES/4.
Ren, Y., Lü, Y., Hu, J., Yin, L., 2021. Geodiversity underpins biodiversity but the relations can be complex: implications from two biodiversity proxies. Glob. Ecol. Conserv. 31 https://doi.org/10.1016/J.GECCO.2021.E01830.
Rizzi, E., Gianoglio, M., 2023. I Walser e le Alpi. Ultimi Studi, Grossi, Domodossola.
Salminen, H., Tukiainen, H., Alahuhta, J., Hjort, J., Huusko, K., Grytnes, J.A., Pacheco-Riaño, L.C., Kapfer, J., Virtanen, R., Maliniemi, T., 2023. Assessing the relation between geodiversity and species richness in mountain heaths and tundra landscapes. Landsc. Ecol. 38, 2227–2240. https://doi.org/10.1007/S10980-023-01702-1/FIGURES/5.
Santos, D.S., Mansur, K.L., Gonçalves, J.B., Arruda, E.R., Manosso, F.C., 2017. Quantitative assessment of geodiversity and urban growth impacts in Armação dos Búzios, Rio de Janeiro. Brazil. Appl. Geogr. 85, 184–195. https://doi.org/10.1016/J.APGEOG.2017.03.009.
Schrodt, F., Bailey, J.J., Kissling, W.D., Rijsdijk, K.F., Seijmonsbergen, A.C., Van Ree, D., Hjort, J., Lawley, R.S., Williams, C.N., Anderson, M.G., Beier, P., Van Beukering, P., Boyd, D.S., Jość, J., Brilha, J., Carcavilla, L., Dahlin, K.M., Gill, J.C., Gordon, J.E., Gray, M., Grundy, M., Hunter, M.L., Lawler, J.J., Monge-Ganuzas, M., Royse, K.R., Stewart, I., Record, S., Turner, W., Zarnetske, P.L., Field, R., 2019. To advance sustainable stewardship, we must document not only biodiversity but geodiversity. Proc. Natl. Acad. Sci. 116, 16155–16158. https://doi.org/10.1073/PNAS.1911799116.
Seijmonsbergen, A., de Jong, M.G.G., de Graaff, L.W.S., Anders, N.S., 2014. Geodiversität von Vorarlberg und Liechtenstein. Haupt, Bern.
Seijmonsbergen, A.C., De Jong, M.G.G., Hagendoorn, B., Oostermeijer, J.G.B., Rijsdijk, K.F., 2018. Geodiversity mapping in alpine areas. In: Hoorn, C., Perrigo, A., Antonelli, A. (Eds.), Mountains. Climate and Biodiversity, Wiley Blackwell, pp. 155–171.
Selmi, L., Coratza, P., Gauci, R., Soldati, M., 2019. Geoheritage as a tool for environmental management: a case study in northern Malta (central mediterranean sea). Resources 8. https://doi.org/10.3390/resources8040168.
Semeniuk, V., 1997. The linkage between biodiversity and geodiversity. In: Eberhard, R. (Ed.), Pattern & Processes: Towards a Regional Approach to National Estate Assessment of Geodiversity. Pattern & Processes: Towards a Regional Approach to National Estate Assessment of Geodiversity, Canberra, Australia, pp. 51–58.
Serrano, E., Ruiz-Flaño, P., Arroyo, P., 2009. Geodiversity assessment in a rural landscape: Tiermes-Caracena area (Soria, Spain). Mem. Descr. Cart. Geol. d'It. LXXXVII 173–179.
Servizio Geologico Italiano, 1951. CARTA GEOLOGICA D'ITALIA 1:100.000, Foglio 29 Monte Rosa.
Shapiro, S.S., Wilk, A.M.B., 1965. An analysis of variance test for normality (complete samples). Biometrika 52, 591–611. https://doi.org/10.1093/BIOMET/52.3-4.591.
Sharples, C., 2002. Concepts and Principles of Geoconservation, 3rd ed. Tasmanian Parks & Wildlife Service.
Siegel, S., 1957. Nonparametric Statistics. Am. Stat. 11, 13–19. https://doi.org/10.1080/00031305.1957.10501091/ASSET//CMS/ASSET/54FD5ADA-C9ED-47CD-91C5-41C6F1776296/00031305.1957.10501091.FP.PNG.
Smiraglia, C., Diolaiuti, G., 2015. Il nuovo Catasto dei Ghiacciai Italiani. EvK2CNR, Bergamo.
Soms, J., 2017. Assessment of geodiversity as tool for environmental management of protected nature areas in south-eastern Latvia. Environ. Technol. Resour. Proc. Int. Sci. Pract. Conf. 1, 271–277. https://doi.org/10.17770/etr2017vol1.2581.
Spearman, C., 1904. The proof and measurement of association between two things. By C. Spearman, 1904. Am. J. Psychol. 100, 441–471. https://doi.org/10.2307/1422689.
Strahler, A.H., Archibold, O.W., 2011. Physical Geography: Science and Systems of the Human Environment, 5th ed. Wiley.
Tognetto, F., Perotti, L., Viani, C., Colombo, N., Giardino, M., 2021. Geomorphology and geosystem services of the Indren-Cimalegna area (Monte Rosa massif–Western Italian Alps). J. Maps 17, 161–172. https://doi.org/10.1080/17445647.2021.1898484.
Tukiainen, H., Alahuhta, J., Field, R., Ala-Hulkko, T., Lampinen, R., Hjort, J., 2017a. Spatial relationship between biodiversity and geodiversity across a gradient of land-use intensity in high-latitude landscapes. Landsc. Ecol. 32, 1049–1063. https://doi.org/10.1007/S10980-017-0508-9.
Tukiainen, H., Bailey, J.J., Field, R., Kangas, K., Hjort, J., 2017b. Combining geodiversity with climate and topography to account for threatened species richness. Conserv. Biol. 31, 364–375. https://doi.org/10.1111/COBI.12799.
Twidale, C.R., 1978. On the origin of Ayers Rock, central Australia. Z. Geomorphol. (Suppl. Band 31), 177–206.
Twidale, C.R., 2010. Uluru (Ayers Rock) and Kata Tjuta (the Olgas): Inselbergs of Central Australia. In: Migon, P. (Ed.), Geomorphological Landscapes of the World. Springer, Netherlands, Dordecht, pp. 321–332. https://doi.org/10.1007/978-90-481-3055-9_33/COVER.
Twidale, C.R., Wopfner, H., 1981. Aeolian landforms of Central AustraliaA discussion. Z. Geomorphol. 25, 353–358. https://doi.org/10.1127/ZFG/25/1981/353.
Viani, C., Bollati, I.M., Perotti, L., Zanoletti, E., Caironi, V., Pelfini, M., Gentilini, S., Giardino, M., 2020. Geosites and geotrails of the Sesia Val Grande UNESCO Global Geopark: inventory and potential implementations. In: Oxford Geoheritage Virtual Conference, 25–28 May 2020. Oxford Geoheritage Virtual COnference, Online.

Williams, M.A., McHenry, M.T., Boothroyd, A., 2020. Geoconservation and geotourism: challenges and unifying themes. Geoheritage 12, 1–14. https://doi.org/10.1007/S12371-020-00492-1/FIGURES/4.

Wimbledon, W.A.P., 1995. National site selection, a stop on the road to a European Geosite list. Geol. Balc. 26, 15–27.

Zakharovskyi, V., Németh, K., 2021a. Quantitative-Qualitative Method for Quick Assessment of Geodiversity. Land 10. https://doi.org/10.3390/LAND10090946.

Zakharovskyi, V., Németh, K., 2021b. Qualitative-quantitative assessment of geodiversity of Western Samoa (SW Pacific) to identify places of interest for further geoconservation, geoeducation, and geotourism development. Geographies 1, 362–380. https://doi.org/10.3390/GEOGRAPHIES1030020.

Zakharovskyi, V., Kósik, S., Li, B., Németh, K., 2023. Geosite determination based on geodiversity assessment utilizing the volcanic history of a near-sea-level explosive eruption-dominated volcanic island: Tūhua/Mayor Island, New Zealand. Geol. Soc. London Spec. Publ. 530, 127–140. https://doi.org/10.1144/sp530-2022-90.

Zarnetske, P.L., Read, Q.D., Record, S., Gaddis, K.D., Pau, S., Hobi, M.L., Malone, S.L., Costanza, J., Dahlin, K.M., Latimer, A.M., Wilson, A.M., Grady, J.M., Ollinger, S.V., Finley, A.O., 2019. Towards connecting biodiversity and geodiversity across scales with satellite remote sensing. Glob. Ecol. Biogeogr. 28, 548–556. https://doi.org/10.1111/GEB.12887.

Zwoliñski, Z., 2009. The routine of landform geodiversity map design for the Polish Carpathian Mts. Landf. Anal. 11, 77–85.

Zwoliński, Z., Stachowiak, J., 2012. Geodiversity map of the Tatra National Park for geotourism. Quaest. Geogr. 31, 99–107. https://doi.org/10.2478/v10117-012-0012-x.

Zwoliński, Z., Najwer, A., Giardino, M., 2018. Methods for assessing geodiversity. Geoheritage assessment. Prot. Manag. 27–52. https://doi.org/10.1016/B978-0-12-809531-7.00002-2.