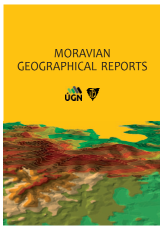

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Geodiversity and land cover diversity from coast to mountains in Northern Albania

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Abstract

The present study explores the relationship between geodiversity and land cover diversity in northern Albania, near Shkodra, covering approximately 1,400 km^2. Using open-source GIS tools, we analyse the diverse geographical features, including coastal, agricultural, urban, riverside, and mountainous terrains. Geodiversity is assessed through geological, soil, morphometric, paleontological, and mineral data, while land cover diversity is determined using Copernicus Global Land Cover 2019 data. Our analyses, conducted at both low and medium altitudes (< 850 m a. s. l.) and high altitudes, reveal a positive correlation between geodiversity and land cover diversity in lower regions but a negative correlation in higher elevations. The connectivity in the study area shows low values in low-altitude areas with high land cover diversity, characterised as cultural landscapes. Our results highlight the importance of taking geodiversity into account in conservation efforts, as areas rich in geodiversity and land cover diversity offer potential for geotourism but also deserve attention due to human activities. Consistent with previous research, our results confirmed that there is a relationship between geodiversity and land cover diversity. However, the negative correlation at high altitudes is a new finding. Overall, our research underscores the intricate interplay between geodiversity, land cover diversity, and connectivity in shaping ecological patterns and emphasises the need for coordinated conservation strategies in diverse landscapes.

Keywords: Geodiversity, land cover diversity, geotourism, connectivity, coordinated strategies

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1. Introduction

The evaluation of land cover diversity supports ecological analyses and has long been present in scientific research. Studies typically use indicators such as the Shannon diversity index to measure the diversity of surface vegetation cover within a given unit area (Uuemaa et al., 2009). Although diversity is a scale-dependent measure and the definition of classes is challenging, the classes defining land cover diversity are well defined within the CORINE programme, and the CORINE surface cover map, which is constructed from remotely sensed data and regularly updated, is freely available and allows their analysis using GIS tools (Büttner, 2014).

Vegetation cover is defined as the average leaf area per unit of land area, and different vegetation cover types (such as open or closed forest, shrubland, cropland, etc.) contribute to different land cover types (Martin et al., 2021). The diversity or homogeneity of the vegetation cover has an impact on the fauna and flora that live in it. Different land cover categories mean different habitats. Some organisms prefer homogeneous habitats, others prefer contact zones, and population size is related to habitat size. For groups of organisms, it is important to be able to move between habitats that suit their living conditions, so connectivity of land cover categories is an important measure alongside diversity (Taylor et al., 1993; Debinski & Holt, 2000).

The diversity of vegetation cover and the size of contiguous homogeneous areas are most affected by human expansion. In general, an increase in land cover categories in an area represents an increasing intensification of urbanisation and agriculture, and tends to be more pronounced in the vicinity of inhabited areas (Alados et al., 2004). Although some species are well adapted to human proximity, increasing habitat fragmentation leads to a reduction in the size of populations that prefer homogeneity and become more vulnerable on the long run (Tilman et al., 1994).

Under natural conditions vegetation cover depends on climatic, topographic and soil characteristics (Florinsky & Kuryakova, 1996). It has long been known that climate and altitude are the primary factors influencing vegetation cover, but the relief, slope steepness and soil quality (i.e. the parent rock) also influence the vegetation cover of a given area (Florinsky & Kuryakova, 1996; Cantón et al., 2004). These variables are also being investigated by a relatively new subdiscipline of earth sciences, known as geodiversity studies.

Geodiversity, if assessed in a quantitative way, can usually be interpreted in a similar way to land cover, i.e. as a measure per unit area (e.g., Zwoliński et al., 2018 and references therein). Geodiversity usually includes geomorphological, hydrological, geological and soil diversity (Gray, 2018). Since several of the defining variables are common, it is therefore logical that land cover

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and geodiversity are interrelated and to better understand the nature of the relationship, studies are needed that are sufficiently broad and cover a large enough area to provide statistical evidence of the association observed.

In the present study, the area of Shkodra (Shkodër) municipality in northern Albania is investigated, which has diverse topography and rich of natural values within its boundaries (Fig. 1). With an area of 953.64 km^2, Shkodra municipality is relatively large in Albania and one of the richest geosite areas in the country, featuring 25 geo-related and 10 living natural monuments, such as forests and habitats, listed in the national geoportal (State Authority for Geospatial Information – ASIG, 2023). The geosites include mainly caves, glacial lakes, waterfalls, springs, and geomorphological features (canyons, rock formations, glacial features). The area includes Lake Shkodra, the largest in the Balkans, the Adriatic coast and the North Albanian Alps, reaching an altitude of 2,694 m a. s. l. The region also includes three major rivers (Buna, Drini, Kiri), and nature reserves like Albanian Alps National Park formed from the merge of the Theth National Park and the Valbona Valley National Parks in 2022, and the Maranai Park. Situated in the Eastern Alpine Mediterranean Belt, the area has diverse geological formations, including Mesozoic marine sediments (Triassic dolomites, limestones, shales, Jurassic limestone, marl, and Cretaceous carbonates), along with Late Permian and Cenozoic sediments (Meço & Aliaj, 2000).

Focusing on this diverse landscape, the research sought to answer the questions:

1. Can a relationship between geodiversity and vegetation cover diversity be demonstrated in this area?
2. Is the nature of the relationship (if any) linear?
3. Is there a spatial variation?

Since the area under study is already partly protected, and its geoscientific diversity is high, it is very suitable to become a geopark, which would enable the region to exploit the growing tourism in the area in a sustainable way (Dollma, 2019; Serjani, 2020). A previous geodiversity study in the area confirmed this assumption by noting that geodiversity hot-spots in the area coincide with areas already partly exploited for tourism (Kraja & Albert, 2023). Therefore, in the present study, parameters that represent both geotourism and local business aspects (e.g., fossil sites, raw materials) are taken into account. The results are particularly discussed in the light of the ecological implications of the exploitation of high geodiversity sites for geotourism purposes when designing the infrastructure of a possible geopark.

2. Theoretical background

The structure of the land cover of an area is a key determinant of biodiversity, and its distinct components, the 'patches', can be considered as elements of the landscape, the spatial characteristics and relationships of which can be studied using landscape metrics (Walz, 2011). The techniques of landscape metrics use indices and primarily measure characteristics of landscape elements such as: composition, configuration (or structure) and function (Lausch et al., 2015). Methods that include remotely sensed data and GIS are the most useful way to determine the composition (e.g., diversity) and structure (e.g., connectivity) of patches of land cover (Herold et al., 2002; Lang & Blaschke, 2007).

Landscape element diversity at this level (i.e. the level of satellite images), although a determinant of biodiversity, does not automatically represent species diversity (Walz, 2011), so no conclusions on biodiversity can be drawn from the analysis of land cover alone. It appears that a close relationship exists between them, although this may change over time. For example,

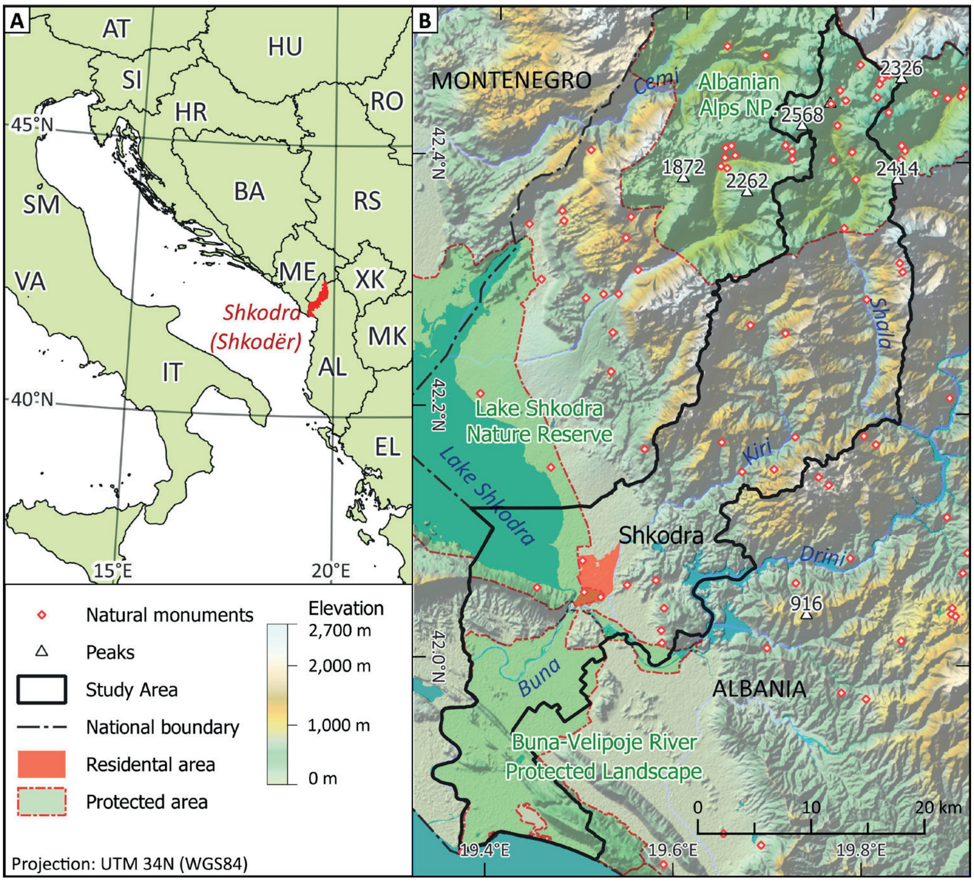

Fig. 1: Location (A) and geographical settings (B) of the study area
Source: Authors' elaboration

the diversity of land cover leads to an increase in the number of species in the short term, as more habitat types appear in a unit area (e.g., Honnay et al., 2003). However, as diversity increases, the size of habitats decreases, and the same habitat types become more distant from each other, resulting the reduction of species diversity (Debinski & Holt, 2000). Furthermore, anthropogenic impacts may temporarily increase both diversity, but in the longer term lead to a decline in species numbers (Tilman et al., 1994; Martin et al., 2021).

The diversity of vegetation is usually expressed by the Shannon diversity index and the Simpson diversity index (Forman, 1995). The former measures the inequality and richness of the classes under study, while the latter characterises the proportion of dominant categories. The scale of the area under study determines the appropriate distinction to be made between the different vegetation cover groups. For regional and smaller scales, vegetation cover categories are determined based on satellite data. The CORINE Programme (Co-ordination of Information on the Environment), initiated by the European Commission, has developed a well-defined categorisation system over decades of operation (Büttner, 2014; Buchhorn et al., 2020). The processing of multispectral satellite imagery has resulted in the production of free-use land cover maps (European Environment Agency, 2019; Büttner et al., 2021).

Landscape metrics include not only composition (variety of categories, i.e. diversity), but configuration as well. Configuration refers to the geographical distribution of patches. A common metric of configuration is the edge length calculation and the connectivity index. As the diversity of surface cover increases, the length of the edges of individual habitat patches also increases, making communities more vulnerable to expanding species (Saunders et al., 1991). The effects of fragmentation are not the same for all species, but in general, the connections that remain between patches can help link populations and thus reduce vulnerability (Debinski & Holt, 2000; Riitters et al., 2000). Connectivity is the ratio of actual to potential connectivity between habitats of the same type and is a measure of the extent to which organisms have the potential to move between habitats in a way that maintains their preferred living conditions (Taylor et al., 1993; Nikolakaki, 2004). Connectivity is a number between 0 and 1; the closer it is to 1, the more mobility there is for the species living there, i.e. the more homogeneous the area.

While in the case of vegetation cover the categories that form the basis for measuring diversity are well defined, in the case of geodiversity it is more complex and, as a relatively young sub-discipline, there is no consensus on the metrics. The most widely used method for estimating geodiversity is the quantitative approach, which can be quickly implemented using a geographic information system based on maps, surveys or data derived from a geodatabase (Zwoliński et al., 2018). There are two subtypes of this approach, one is map-algebra based and the other is indicator based, and both basic types are common, as well as their combinations (Serrano & Ruiz-Flaňo, 2007; Pál & Albert, 2023). Quantitative analysis is achieved by quantifying the elements that play a role in geodiversity and then summarising them over the area under study (e.g., Pereira et al., 2013; Argyriou et al., 2016). The elements of geodiversity are usually derived from the available data: geological diversity is defined by the categories of the geological map, soil diversity by the categories of the soil map and geomorphological diversity by the categories of the geomorphological map. In the case where there is no categorisable map, only point data on geodiversity elements (e.g., cave dataset), diversity is defined by the number of points per unit area (e.g., Stojilković, 2022). Given the large number of methods available, the geodiversity estimate should therefore be chosen primarily on the basis of the basic data available, the size of the study area and the purpose of the study (Zwoliński et al., 2018; Crisp et al., 2021).

For medium and small-scale (i.e. regional) analyses, there are often edited geological, soil and geomorphological maps of the area, as well as a digital terrain model (DEM) that can be used to calculate morphometric indicators. These can be used to calculate geodiversity values along a regular grid using a map-algebraic method. If a geomorphological map is not available, DEM-derived maps of morphological classes can be used, typically based on geomorphons or Topographic Position Index (TPI) classes (Chrobak et al., 2021; Nasiri et al., 2022; Zakharovskyi & Németh, 2022). The hydrographic elements at this scale can also be implemented from a global database (e.g., OpenStreetMap) or derived from the DEM (Pál & Albert, 2021a). By combining maps with specific geodatabases (e.g., karst features cadastre, fossil sites, etc.), the geodiversity calculation can be fine-tuned to a specific theme.

The relationship between geodiversity and vegetation cover has been established by several studies (Jačková & Romportl, 2008; Hjort et al., 2012; Dos Santos et al., 2019). It was concluded that geodiversity underpins biological diversity, as all organisms rely on the abiotic elements of their environment. Consequently, a decline in geodiversity will negatively impact biodiversity. For example, plant species diversity benefits from higher geodiversity, but only in areas away from human influence (Tukiainen et al., 2017). At the regional scale, a positive correlation between geodiversity and land use/cover diversity has been shown (Datta, 2022), but the spatial variability of this relationship has not been investigated to our knowledge.

3. Data and methods

3.1 Study area

Albania, located in Southeastern Europe on the Balkan Peninsula, boasts a distinctive and very diverse landscape, shaped by geological activity and the Mediterranean climate. The study area lies in the northern part of the country, where around 80% of the Shkodra region consists of mountainous terrain, including the Albanian Alps (Fig. 1). It is also abundant in water resources, with rivers such as the Drini, Buna, Shala, Kiri, and Cemi, as well as Lake Shkodra, the largest lake in the Balkans. This tectonic-karstic lake spans the border between Albania and Montenegro.

Northern Albania has an exceptionally rich and diverse natural environment, thanks to its varied topography and proximity to the Adriatic Sea. Landscapes from the high mountains to the coast vary considerably in terms of flora, fauna and climate. The climate is characterised by a combination of mediterranean and continental influences, modified by the diversity of topography (Metaj, 2007). The coastal areas are characterised by warm, dry summers and mild, wet winters with 650–1,060 mm/year of precipitation and average annual temperatures of 14–17 °C, while in the mountains the temperature decreases and the precipitation increases with increasing altitude. In the hilly and mountainous areas, the average annual temperature is around 7–11 °C, and the average annual precipitation can reach 2,100–3,100 mm/year (Kopali et al., 2013). However, the effects of climate change are evidenced by an increasing temperature and a decreasing precipitation year on year (Gjoni et al., 2023).

Thanks to the varied climatic conditions, the region has a relatively rich flora (Shuka et al., 2017). The coast is covered with Mediterranean evergreen shrubs and forests, dominated by acorn oaks, olive trees and myrtle. In the lower parts of the mountains, deciduous forests have developed, with beech, oak and ash being the main tree species. In the higher regions, coniferous forests, followed by subalpine and alpine meadows, replace deciduous forests (Fig. 2A).

The landscape has been shaped by human activity for thousands of years (Dyczek et al., 2020). Deforestation, agriculture and urbanisation have resulted in the loss of many natural habitats. Grazing and fires have also contributed to vegetation change, but the higher regions of the area have low population densities and better-preserved natural habitats due to the sparse road network. In order to preserve the natural vegetation cover, increased attention has recently been paid to the creation of national parks and the expansion of protected areas (Fig. 1).

The geological diversity of the region also affects its morphology and soils (Hoxha, 2021), so an overview of the formations and evolutionary history of the area is given in the following. The study area lies at the junction of the Albanides and Dinarides mountain ranges, separated by the Scutari-Pec transverse zone between the High Karst Nappe tectonic unit in the north and the Mirdita ophiolites in the south (Speranza et al., 1995; van Hinsbergen et al., 2020). Its unique geological history is shaped by tectonic activity from the convergence of the African and European plates during the Alpine orogenesis. The Cretaceous and Cenozoic orogenic phases created a stacked nappe structure with folded and thrusted sequences.

The geological formations in the Shkodra region show significant variation in age and type (Fig. 2B). Although Mesozoic carbonates form the bulk material of the Albanian Alps, the oldest sediments date back to the Permian, consisting of fossiliferous limestones, sandstones, conglomerates, and shales. The Lower Triassic features terrigenous-carbonate rocks, while the Middle Triassic marks the development of a carbonate ramp transitioning into a marine basin filled with cherty limestones and tuffaceous sediments (Gaetani et al., 2015). At the beginning of the Late Triassic the carbonate platform sediments of the Adriatic region started to develop (Vlahović et al., 2005; Gawlick & Schlagintweit, 2019). The Jurassic and Cretaceous sequence in the area consists of shallow-marine neritic limestones and pelagic limestones transitioning to deep-marine turbiditic deposits in the Paleogene (Meço & Aliaj, 2000; Robertson & Shallo, 2000). From the Cretaceous period onwards, the Alpine orogenesis has induced a series of nappe thrusts, resulting in a variety of marine- and terrestrial sediments being overthrusted by and folded under the Albanian Alps zone (Meshi et al., 2014). The folded succession includes Cretaceous shallow marine carbonates, evaporites, Paleocene bauxite, and Middle Eocene nummulitic limestones, followed by Oligocene turbidites (Schmitz et al., 2020). East of Shkodra, on the southern side of the Scutari-Pec transform zone, the Mirdita ophiolites expose oceanic crust with volcanic rocks from the Triassic to Late Jurassic (Dilek et al., 2005). Recent tectonic activity, marked by SW–NE shortening and reactivated thrust faults, leads to frequent earthquakes, including the 1905 Shkodra earthquake (magnitude 6.6) (Biermanns et al., 2019).

The geomorphology of the area is mainly the result of tectonic uplift and the action of fluvial waters, and the precursors of the deep river valleys were already formed in the Neogene (Lenaerts et al., 2013). A series of Quaternary glaciations around the Last Glacial Maximum (LGM) produced glacial and periglacial landforms in the area (Milivojević et al., 2008). The border region between northern Albania and Montenegro is covered by Quaternary sediments, creating broad alluvial plains stretching

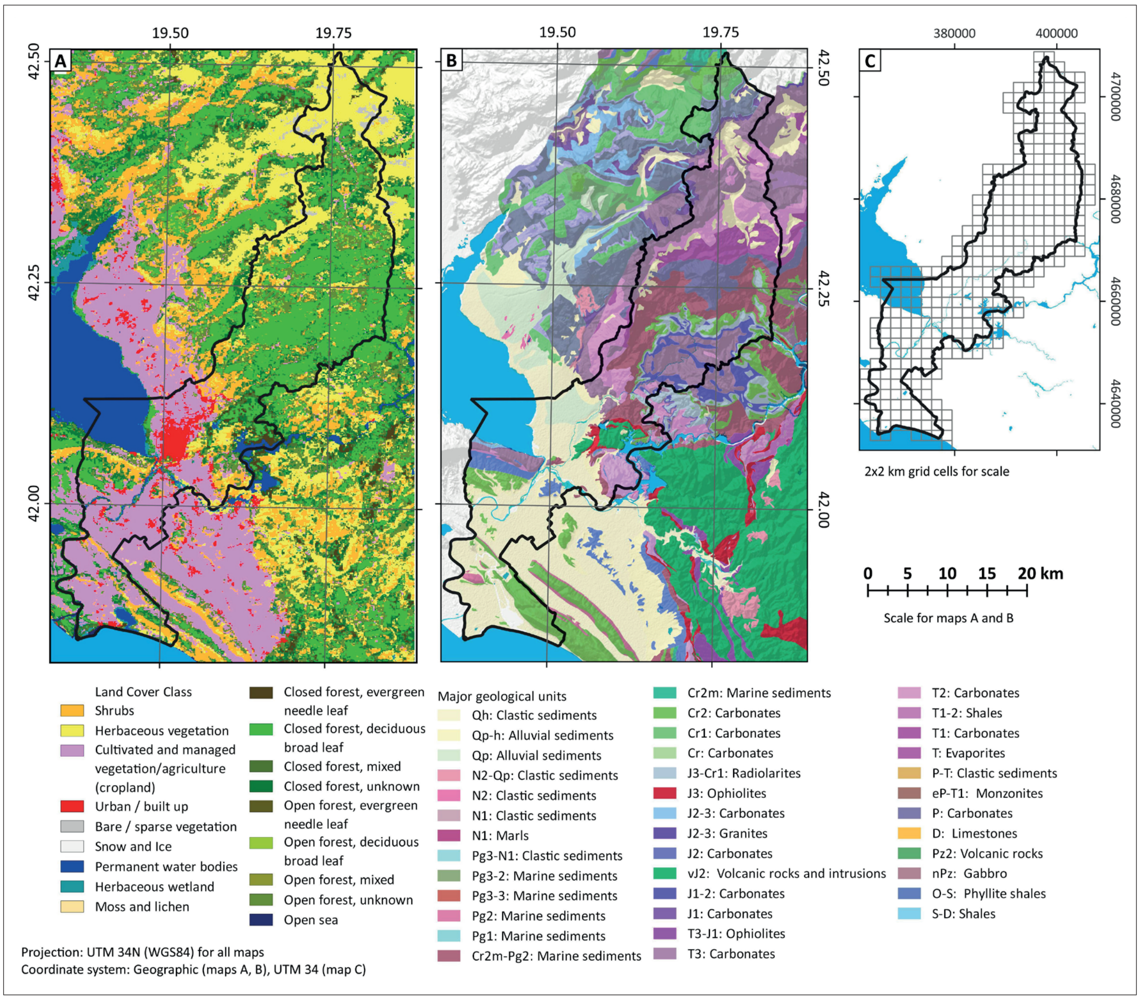

Fig. 2: Land cover map (A) and geological map (B) of the study area based on the Copernicus Global Land Cover 2019 data for vegetation (Buchhorn et al., 2020), and the geological map of Albania (Xhomo et al., 2002). Adjacent map (C) shows the 2 × 2 km grid resolution
Source: Authors' elaboration

from the city of Shkodra to the coast. This area is dominated by Lake Shkodra, a relatively young freshwater lake, around 6,000 years old, surrounded by marshlands, with evidence of human activity dating back to prehistoric times (Mazzini et al., 2016). On the plains and on the shores of Lake Shkodra, accumulation landforms developed. These were modified by man throughout history to regulate flooding (Hoxha, 2021).

The varied geology, topography and climate of the area around Lake Shkodra and the Albanian Alps has resulted in a wide variety of soils. The soils around Lake Shkodra are mainly alluvial and hygromorphic (wetland) soils and near the Adriatic coastline halomorphic soils are present, which are exposed to saline groundwater (Kraradžić et al., 2020). The alluvial soils are formed by sediments deposited by rivers and the marshy soils are formed by frequent flooding. Throughout the High Karst Nappe of the Dinarides-Albanides mountain ranges the soils were formed by karstification, weathering and erosion. The most common soil types are rendzina, which is a thin layer of humus overlying limestone bedrock, cambic soil types, which is a fertile soil with a deeper layer of humus, and skeletal soils of high mountain areas, which are stony, rocky soils where humus formation is limited (Zdruli, 2005; Kraradžić et al., 2020).

3.2 Methodology

To answer the research questions, we calculated and compared diversity indices. For the calculation we used partly open data available online and partly published maps. Due to the size of the study area, the maps were on a medium scale and the indices were calculated on a 2 × 2 km grid, which is a common dimension for regional analyses (Elkaichi et al., 2021; Manosso et al., 2021; Pál & Albert, 2023). The source material was digitised and analysed using QGIS (v.3.24.1) and SAGA (v.9.6.1) open-source geospatial software in UTM34N Cartesian coordinate system (WGS84 datum). In this coordinate system the extent of the area was: 361,500 min. easting; 407,500 max. easting; 4,630,800 min. northing; 4,708,800 max. northing (Fig. 2C). When analysing diversity grids, we display this coordinate system on our maps, where the grid cells can also be used as scales. The analysed area covered 1,464 km^2. The analysis was carried out using established methods, which have already been described in the literature review and are further detailed below.

3.2.1 Data

The free-use data included a digital elevation model (DEM) of the area, which was the MERIT (Multi-Error-Removed Improved-Terrain) model (Yamazaki et al., 2017). This model does not include the height of vegetation and built features but has a relatively poor resolution (3 arc second, which corresponds to about 70 × 90 m at this latitude). The resolution was converted to square pixels of 50 m edge length by bicubic interpolation due to the use of a rectangular coordinate system. Also free-use data was the hydrography of the area, which was extracted from the OpenStreetMap database (OSM, 2024). To calculate the geodiversity index, we used the freely available European Geological Data Infrastructure (EGDI) mineral raw material database (EGDI, 2024), which contained five object types for the area as point data: 1) precious minerals, gemstones; 2) metallic minerals; 3) industrial minerals and dimension stones; 4) geological energy sources; 5) mineral waters and springs. For vegetation cover analysis, we used the Copernicus Global Land Cover 2019 data for vegetation with 100 m resolution raster data, which distinguishes 22 land cover types (Buchhorn et al., 2020).

The geological and soil map of the area was not freely available, but published data were obtained. The scale of the geological map was 1:200,000 (Xhomo et al., 2002); the map had to be converted into a vector format, with polygons containing the rock types and characteristic fossils of each geological category as attributes. The soil map was at a scale of 1:250,000 (Zdruli, 2005) and its categories corresponded to the World Reference Base for Soil Resources database (IUSS Working Group, 2006). The maps represented the categories in a generalised way due to their scale.

3.2.2 Calculating the land cover diversity and the connectivity indices

The great variety in the vegetation cover of the area is shown by the fact that in the area of the Shkodra municipality 18 of the 22 possible cover types are found. The 18 categories included 14 vegetation categories, three water surface, and one urban cover category (Fig. 2A). The diversity was expressed using the Shannon diversity index for each 2 × 2 km edge length cell, which were parallel to the coordinate system and covered the entire area of Shkodra municipality. The Shannon Diversity Index is a commonly used metric in ecology and other fields that measures the richness and distribution of a given community (Pielou, 1969). The higher the value of the index, the more diverse the community. The formula for calculating the index is as follows (Shannon, 1948):

$$H = -\sum(p\_i * \ln(p\_i))$$

where *p_i* is the relative abundance of the ith group (i.e. land cover category) in the community. The value of the Shannon diversity index is usually between 0 and ln(S), where *S* is the number of groups. The index is largest when all groups occur with equal frequency.

When comparing the diversity of various communities of different composition, the normalised value is commonly used (Ramezani, 2012). In normalisation, the index value is divided by the maximum possible diversity value, which is usually equal to the natural logarithm of the number of possible groups, but in our case this is not a realistic scenario, as no 2 × 2 km cell contains all the 18 coverage categories. For this reason, the cells were divided into groups by altitude and normalised to these groups. The groups were subdivided along terciles: cells with an average elevation over 850 m (126 cells), cells with an average elevation between 80 and 850 m (115 cells), and cells with an average elevation of less than 80 m (126 cells). Thus, for each cell a value between 0 and 1 was obtained, where 1 represents the maximum diversity.

The calculation was performed on the 100 m resolution raster Copernicus-2019 data by examining the base data pixel-by-pixel in a 20-pixel square kernel, which resulted in a "Shannon index raster" also with 100 m resolution. The values of the resulting raster data layer were further examined within each 2 × 2 km cell and its maximum within a cell was recorded in a geodatabase.

In addition to the Shannon Index, we also calculated the connectivity. Since we did not focus on the migration of specific species or other taxonomic groups in the present study, we used the most general approach to the calculation, which is implemented in the SAGA GIS (Conrad et al., 2015) and was developed as an image processing algorithm (Burger & Burge, 2008). In this sense connectivity is defined as the number of pixel-connections within a search radius where fields of the same type are considered to be neighbours and is used for general analyses of landscape connectivity (e.g., Gupta & Pandey, 2020). Connectivity was calculated by the 'Diversity of Categories' SAGA tool using the same kernel geometry as for the Shannon Index and the queen's case principle was followed without distance weighting, i.e. diagonal pixels were considered to be neighbours in the same way as adjacent pixels. The connectivity index can take values between 0 and 1 and the degree of connectivity varies depending on the value. A higher value indicates a stronger and more extensive connectivity.

3.2.3 Calculating the geodiversity index

The Geodiversity Index aims to represent all geoscientific aspects in a balanced manner, without prioritising any specific geodiversity element (Gray, 2018). To achieve this, we analysed geological, paleontological, pedological (soil), mineral, and geomorphological (hydrological and relief) data for the Shkodra region using a quantitative methodology based on studies by Pereira et al. (2013) and Pál and Albert (2021b). The resulting geodiversity index is calculated from the combined values of the identified sub-indices. Since the five sub-indices have different ranges of values a normalisation of the values was performed in each case. Normalisation is a common operation in the calculation of the components of the geodiversity index, and in almost all cases the aim is to bring the basic data with different variability to the same scale and thus to give them the same weight in the computation (Bétard & Peulvast, 2019; Pál & Albert, 2021b; Carrión-Mero et al., 2022).

The geological sub-index was calculated using the 1:200,000 scale geological map of Albania (Xhomo et al., 2002). This sub-index was derived by counting the number of different lithological and stratigraphic units within each grid cell.

To calculate the palaeontological sub-index, no fossil site database or map was available. However, based on the geological map and the information provided in the explanatory book 'Geology of Albania' by Xhomo et al. (2002), it was possible to determine the number of fossil assemblages present in the various lithological and stratigraphic units depicted on the map. When digitising the map, these were recorded and the number of different fossil groups in each grid cell could be determined, which represents the value of the palaeontological sub-index. The groups cannot be linked to a specific taxonomic level, as the map did not follow this logic. The number of isolated groups was 21, consisting mainly of corals, ammonites, bivalves, and gastropods.

The mineral occurrences sub-index was calculated using European Geological Data Infrastructure (EGDI). For the study area, 12 occurrences or deposits were retrieved, indicating the location of quarrying of building material, ornamental stone and base metals. The sites were concentrated in the coastal region and therefore the diversity index could not be calculated for most of the cells.

The soil sub-index was calculated using a 1:250,000 scale soil map of Albania (Zdruli, 2005) following the same principle as for the geological sub-index, i.e. counting the number of different soil units within each grid cell.

The geomorphological sub-index consists of two components: hydrology and relief, for which sub-indices were calculated separately and then combined to obtain the geomorphological sub-index value using the method of Pál and Albert (2021b). For both components we used the MERIT elevation model and for hydrology we used the OpenStreetMap water course data. For the hydrology sub-index, the Strahler hierarchy level of watercourses (Strahler, 1957) was calculated first, which was done using the SAGA GIS program. The value of the sub-index in each cell is the highest hierarchical level divided by 2, rounded to the nearest integer. Cells with no watercourses were assigned a value of zero, while the index for larger rivers and lakeside areas was 4. For the relief sub-index, the classification method of geomorphological elements developed by Jasiewicz and Stepinski (2013) was used. This algorithm uses line-of-sight to classify relief elements from DEM and classifies cells of the relief model into 10 morphological types. The computation was performed in SAGA GIS using line tracing method from pixels as centre to 8 directions with radius of 500 m. To calculate the value of the sub-index, the diversity of the resulting geomorphic map was examined for the 2 × 2 km cells, where the range of values was 0–10. After calculating the hydrological and relief sub-indices, the next step was to sum them to obtain the geomorphological sub-index.

4. Results

The diversity of the study area is illustrated by the compiled maps (Fig. 3), and for comparison purposes, diagrams and tables were prepared. The spatial distribution of land cover diversity and connectivity is shown in Figures 3A and 3B. In the three altitude categories, we also examined these indicators separately to see if any difference in the distribution of diversity values could be observed (Fig. 4). In the low and medium altitude categories and in the regions above 850 m, both the Shannon diversity and the connectivity distribution function showed different patterns, but in the low altitude region, the histograms showed a greater difference than the other two. Here, the mean value of the Shannon diversity index was smaller and showed a larger standard deviation, and the mean value of the connectivity was larger than in the other two cases (Figs. 4A, 4D). In none of these ranges did the phenomena under study show a purely normal distribution, which was confirmed by the Shapiro-Wilk test performed in Excel at the alpha = 0.05 significance level (Shapiro & Wilk, 1965; Zaiontz, 2024). However, in almost all cases the distributions were unimodal, and the histograms were nearly bell-shaped.

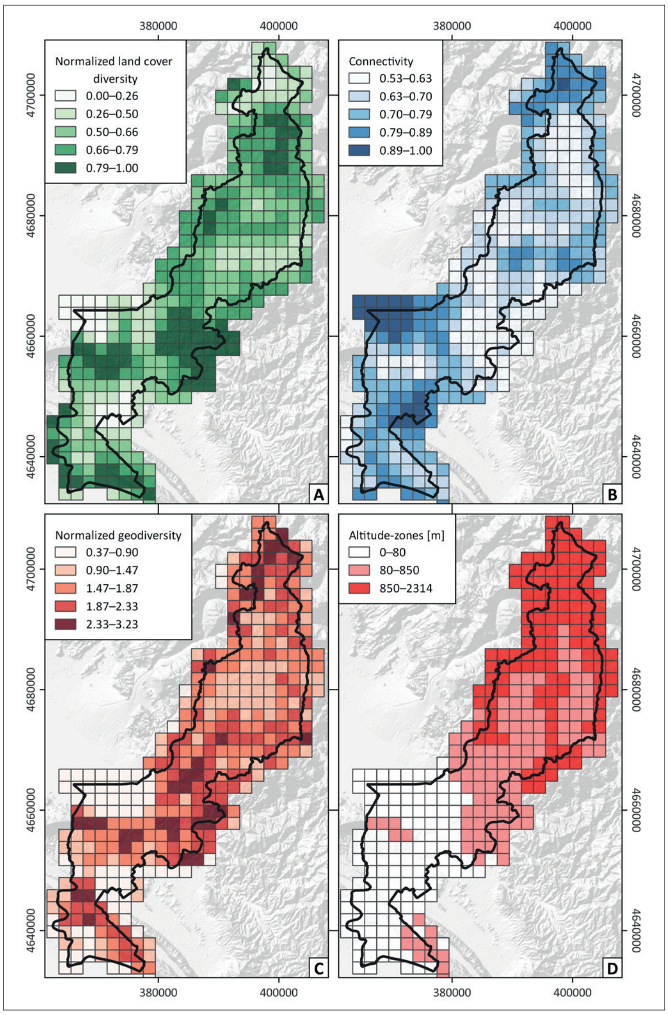

Fig. 3: Diversity maps of the study area: A) Normalised land cover diversity (Shannon-diversity); B) Connectivity; C) Normalised geodiversity; D) Map of the three height zones
Source: Authors' elaboration

The spatial distribution of geodiversity is shown in Figure 3C. In two of the three altitude ranges, medium and high, the geodiversity index was normally distributed according to both the histogram and the Shapiro-Wilk test. In the low altitude ranges, however, the conditions for a normal distribution (such as unimodality, symmetry and bell curve) were apparently not fulfilled, and the histogram had two distinct peaks (Fig. 4G).

Since most of the phenomena under study were not normally distributed, Pearson correlation tests could not be performed. However, the Spearman rank correlation is also suitable for examining the relationships between variables with a different distribution (Daniel, 1990). The aim of the correlation analysis

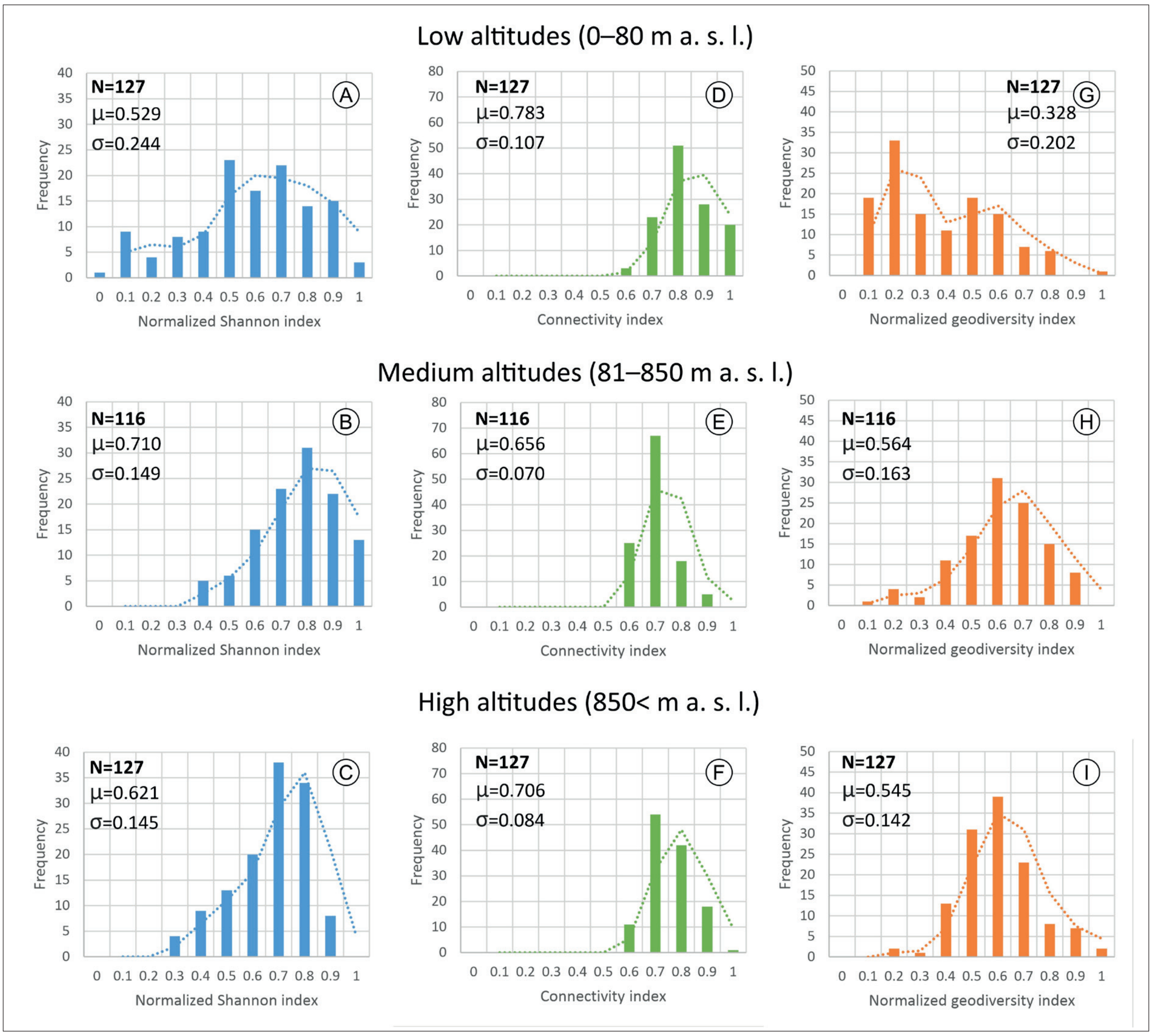

Fig. 4: Histograms and descriptive statistics (N = sample number, μ = mean, σ = standard deviation) of the examined indices for the three altitude zones: Low (0–80 m a. s. l.), Medium (81–850 m a. s. l.), and High (> 850 m a. s. l.). The dotted lines show the moving average. Panels A, B, C: the frequency distributions of the Normalised Shannon Index (land cover diversity) for Low, Medium, and High altitudes, respectively. Panels D, E, F: the frequency distributions of the Connectivity Index for Low, Medium, and High altitudes, respectively. Panels G, H, I: the frequency distributions of the Normalised Geodiversity Index for Low, Medium, and High altitudes, respectively
Source: Authors' calculations and elaboration

was to analyse the relationships between the three variables under study, but we also included the averaged values of altitude in the cells. In most cases, the correlation indicated a significant relationship between the variables (Tab. 1). For geodiversity and Shannon diversity, and for geodiversity and connectivity, only at medium altitudes was there no significant relationship.

An important result of the correlation analyses is the opposite relationship observed between geodiversity (GD) and Shannon diversity (i.e. land cover diversity = LCD) and between geodiversity and connectivity in low and high-altitude areas. Specifically, at low elevations, GD and LCD move together and connectivity moves opposite. Conversely, in high altitude areas, geodiversity and connectivity move together to a smaller extent, and the higher they are, the lower the LCD. It can also be seen that there is a strong negative correlation between connectivity and LCD at each altitude zone, which is not surprising since the greater the fragmentation of areas, the less the relationship between the same coverage types.

The relationship between elevation and the other variables shows a unique feature in all three cases. Elevation and geodiversity are positively correlated in low and high-altitude areas and negatively correlated in medium altitude areas. Elevation and land cover

Low	**GD**	**Conn.**	**LCD**	**Elev.**
GD	1	– 0.6326*	0.6146*	0.6371*
Conn.		1	– 0.8848*	– 0.4446*
LCD			1	0.268**
Elev.				1
Medium	**GD**	**Conn.**	**LCD**	**Elev.**
GD	1	– 0.048	0.1406	– 0.2765**
Conn.		1	– 0.77*	0.1327
LCD			1	– 0.4918*
Elev.				1
High	**GD**	**Conn.**	**LCD**	**Elev.**
GD	1	0.3314*	– 0.2323**	0.3167*
Conn.		1	– 0.8874*	0.7105*
LCD			1	– 0.5508*
Elev.				1

Tab. 1: Spearman rank correlation matrices of the different variables on the three elevation ranges (low, medium, high)
*Notes: GD = normalised geodiversity index, Conn. = connectivity index, LCD = normalised Shannon diversity index for land covers, Elev. = average elevations. *Correlations are significant at $p < 0.001$, **Correlations are significant at $p < 0.005$*
Source: Authors' calculations

diversity show a slight positive correlation in low elevation areas, which turns into a medium and then a medium-strong negative correlation in higher elevation areas. This means that coastal areas tend to have more diverse vegetation cover at higher levels (i.e. hill tops), while valley bottoms tend to have more diverse vegetation cover at the medium and high elevation zones. Finally, elevation and connectivity show a moderately negative correlation in low areas, a strong positive correlation in high areas and no significant relationship in medium elevation areas. This in turn implies that in the coastal areas the contiguous habitats are found at lower levels and in the high elevation areas on ridges and peaks.

In order to better understand the relationship between the geodiversity index and the other indices, the two main sub-indices of the geodiversity index, the geological and the geomorphological sub-indices, were also examined separately using Spearman's rank correlation. The results of the analysis (Tab. 2) show that the geomorphological sub-index plays generally a more dominant role in the relationship between the geodiversity index and the other variables, and this dominance is most pronounced in the high-altitude zone.

5. Discussion

In examining the diverse and in many ways outstanding natural assets of the Shkodra region, we sought to answer three main questions. Based on previous literature (e.g., Jačková & Romportl, 2008; Hjort et al., 2012; Dos Santos et al., 2019), a link between geodiversity and land cover diversity was assumed, which was our first research question, and one of our objectives was to confirm this with the analyses. This was successful, as our results also demonstrate a relationship between the two diversity indices. We can therefore say that there is a relationship between the two phenomena, as confirmed by the correlation studies.

5.1 Non-linearity of the relation

The success of the correlation test does not imply a causal relationship between the two phenomena. It is possible that a third factor is causing both phenomena to change simultaneously. This is particularly important in the present case, as we have examined indices that use several factors in their calculation, since it is possible that the factors have different roles (weights) in the correlation.

We have therefore formulated our working hypothesis with greater uncertainty about the linear or non-linear nature of the relationship. Both indices represent complex natural phenomena, which makes it logical to assume that the relationship between the indices cannot be modelled in a linear way. This was partly confirmed by the results, as the distribution of the indices was not unimodal in the low elevation zone and the Shannon diversity index of land cover and connectivity were not normally distributed in either elevation zone.

A linear relation requires that there is a relationship between the variables that can be approximated by a line. The points on the scatter plot then follow a straight line and the correlation test can be performed using Pearson's method. This also requires the variables to be normally distributed (Daniel, 1990), which in this case was only verified by the Shapiro-Wilk test for geodiversity values at medium and high altitudes. However, in these altitude zones, the other two variables (Shannon index and connectivity) were also bell-shaped, if not symmetric. These results suggest that the relationship between the variables cannot be approximated by a linear model in the present case, but that further areas should be investigated to understand whether this is the case in all circumstances, as the varying behaviour of the variables across areas is clearly demonstrated by our results.

5.2 The dynamics of the relationship between living and non-living nature

In a sense, the multi-area analysis was also carried out within the framework of the present research, as the study area was divided into three altitudinal ranges (Fig. 3). The study area was subdivided by altitudinal zones mainly because the composition of vegetation cover is different in the coastal and mountain areas, and nowhere (within the 2 × 2 km cells) does the number of cover categories reach the number of categories found in the whole area, so it was not possible to normalise the Shannon index to the whole area. These areas also have different climatic conditions due to the difference in altitude, which affects the vegetation cover (Kalajnxhiu et al., 2012).

The correlations between the investigated variables in the three areas showed three different dynamics. The tables (Tabs. 1, 2) can be interpreted in many ways and since causality cannot be proven, one can only speculate about the causes of the relationships, but the degree and direction of correlation is informative. The relationship was significant in most cases. The results suggest a complex relationship between geodiversity, land cover diversity, and connectivity. While geodiversity is generally positively correlated with land cover diversity in low elevation zones, this relationship can reverse in higher elevation areas. Conversely, geodiversity is negatively correlated with connectivity in low elevation zones but positively correlated in higher elevation areas. No significant relationship was detected in the medium elevation zones. In the low-altitude zone, the co-variation of geodiversity and land-cover diversity is probably related to the dominance of the cultural landscape in this zone, where agricultural land overlaps with natural habitats in the foothills, and where the extraction of minerals and building stones is most concentrated. In the high zone, however, the human influence is less pronounced, and natural processes (e.g., climate and mountain zonation) are more likely to induce the relationships.

This highlights the importance of interpreting results for specific environments and avoiding generalisations when examining the links between the living environment and geodiversity. In demonstrating the relationship between geodiversity and biodiversity, Hjort et al. (2012) and Tukiainen et al. (2017) have emphasised the boreal environment in their conclusions and have also demonstrated the important role of climate in their research.

	Low elevation zone			Medium elevation zone			High elevation zone		
	LCD	Conn.	Elev.	LCD	Conn.	Elev.	LCD	Conn.	Elev.
GD	0.6146*	– 0.6764*	0.6371*	0.1406	– 0.0475	– 0.2765**	– 0.2323**	0.3314*	0.3167*
Geom_si	0.5546*	– 0.6543*	0.6480*	0.3287*	– 0.119	– 0.4068*	– 0.3489*	0.3263*	0.2977*
Geol_si	0.5567*	– 0.5962*	0.5345*	0.2886**	– 0.2098	– 0.2378**	– 0.0419	0.0961	0.091

Tab. 2: Spearman rank correlations of the normalised geodiversity index (GD), and its geomorphological (Geom_si) and geological subindices (Geol_si) with the normalised Shannon-diversity index of the land cover (LCD), the connectivity index (Conn.) and the average elevations (Elev.) on the three elevation ranges
*Notes: Red colour: Negative correlation (as one variable increases, the other decreases); Blue colour: Positive correlation (as one variable increases, so does the other). *Correlations are significant at $p < 0.001$, **Correlations are significant at $p < 0.005$*
Source: Authors' calculations

Hjort et al. (2012) investigated the effects of several variables (e.g., precipitation, slope angle, elevation), of which elevation was the most relevant in our case due to the much smaller scale. Although there were no large differences in elevation in the area they studied, elevation showed a significant negative correlation with vegetation species diversity.

The results of the present study show that the relationship between land cover diversity and geodiversity was dominated by the morphological component of geodiversity, and that is more pronounced in the high-altitude zone. This could be explained by the fact that, in addition to linear erosion landforms and karstic landforms, glacial landforms also contribute to the geomorphological diversity in this zone. A relationship between land cover diversity and elevation can also be detected. At low altitudes, the diversity of vegetation cover increases with increasing altitude, but this relationship is reversed at medium and high altitudes, and a negative correlation is observed. This negative link is in line with the findings of the study (Hjort et al., 2012) on the relationship between biodiversity and altitude.

5.3 Implications for conservation strategies, geotourism, and human activities

Even though the reason for the relationship is not known, the awareness that there is a link between geodiversity and the diversity of living nature places much greater emphasis to the protection of non-living nature. In Albania, geoconservation efforts have included the collection of major geosites/geomorphosites (Serjani et al., 1998; Serjani, 2020) and detailed surveys have already been carried out in some areas (Braholli & Menkshi, 2021; Braholli et al., 2023). Geotourism also fits well into the state's rural development programme launched in 2018, which involves several villages in the study area (Ministres së Bujqësisë dhe Zhvillimit Rural, 2024).

The geodiversity of the study area (canyons, caves, waterfalls) makes it an ideal location for geotourism (Serjani, 2020), and there is already an infrastructure in place, which would be expanded with additional facilities in case the area is declared as a Geopark. Geosites, which are likely to occur in places with higher geodiversity (Pál & Albert, 2021b), are the tourist destinations of a geopark. If a geopark were to be created in the area, in addition to geosites, tourist infrastructure development (parking, buildings, roads, etc.) would also be implemented, especially in the more accessible low and medium elevation zones, which will affect the vegetation cover and its connectivity. The present study has shown that the vegetation cover at high geodiversity areas is already much more fragmented in the low altitude zone, which would be further amplified by such an intervention. In the high-altitude areas, high geodiversity areas are less fragmented and would be less impacted by infrastructure development.

The currently protected areas (Albanian Alps National Park, Shkodra Lake National Reserve, and part of the Buna Velipoje River Protected Landscape area) are typically low Shannon diversity, high connectivity areas. In these areas, infrastructure is therefore already in place in the high geodiversity hot-spot areas, and the chances of vulnerability of the living environment are also lower due to the existing control. Because of this, utilisation of the existing tourism infrastructure in these areas to showcase geodiversity would be most effective. Such geodiversity hot-spots can be found, for example, in the high mountain area of the Albanian Alps National Park and in the morphologically diverse parts of the Buna Velipolje River Protected Landscape. However, human-induced fires, for example, may pose a greater threat to contiguous forests in these regions, especially as the tourist season and the dry season coincide (Milenković et al., 2020).

6. Conclusion

Focusing on this diverse landscape, the research has demonstrated that there is a link between geodiversity and vegetation diversity, and found that the nature of the relationship is not linear. The large relief variation and size of the area made it possible to divide it into altitudinal zones and to investigate these indicators and the relationships between them on a zone-by-zone basis. The main result of the study can be derived from this, which to our knowledge has not been shown by other scholars.

We have shown that the relationship between geodiversity (GD) and land cover diversity (LCD) is different in different altitude zones:

- In low, coastal areas (< 80 m a. s. l.), GD and LCD show a strong positive correlation, i.e. the higher the geodiversity, the more fragmented the vegetation cover. This is also associated with a decrease in connectivity. In this zone, it was shown that GD increases with increasing altitude, and that the geomorphological subindex has only a slightly larger role than the geological subindex.
- At intermediate altitudes (between 80 and 850 m a. s. l.), there was no detectable relationship between GD and LCD, but both LCD and GD decreased with increasing altitude and the geomorphological subindex played a much greater role than the geological subindex.
- At high altitudes (above 850 m a. s. l.), there is a negative correlation between GD and LCD, i.e. the higher the geodiversity, the lower the vegetation cover fragmentation; this is associated with an increase in connectivity. In this zone, GD increases with altitude, but only the geomorphological subindex plays a role. LCD decreases with increasing altitude.

Underlying this zonality is, in our opinion, an increasing morphological variability towards the high relief areas, which can be traced back to diverse events in the geological past. Based on the results of the study, the policymakers, conservationists, and land managers of the future geopark in the area can design the geotourism infrastructure taking into account the different dynamics of the relationships between living and non-living natural assets. The potential impacts we have formulated, derived from the identified correlations, are not exhaustive, as this was not the scope of the study. However, our results can provide important support for impact studies to be carried out in the planning phase. This study presents a process for identifying potential geotourism hotspots characterised by high geodiversity and to estimate the potential impact of tourism activities on local natural values, considering land cover diversity and connectivity. However, the data employed are suitable only for broad, regional analyses and are not adequate for detailed assessments of ecotourism and geotourism impacts.

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