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Biogeographical regionalization of Kosovo: integrating vegetation, climate and topography

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Abstract. Kosovo, located at the intersection of continental, alpine and sub-Mediterranean climatic influences, represents a biogeographical transition zone with high ecological complexity. In this study, three different biogeographical regions are delineated - the continental, the alpine and the sub-Mediterranean region - using an integrative approach combining vegetation, climate and topography. By using updated vegetation mapping, standardized environmental data and K-means clustering, the study shows the spatial organization of vegetation alliances along altitudinal and climatic gradients. The continental region, which covers the widest area, is characterized by temperate deciduous forests and riparian ecosystems, while the alpine region has resilient high mountain vegetation adapted to extreme conditions. The sub-Mediterranean region, which is influenced by Adriatic-Ionian and Aegean climatic elements, is home to thermophilic forests and Mediterranean flora. The transition zones observed between the regions highlight the dynamic interplay of environmental factors that shape Kosovo's biodiversity. This research provides a fundamental framework for conservation planning and biogeographic studies in the Balkans and emphasizes the importance of integrating abiotic and biotic variables in regional classification.
Keywords: Biodiversity, natural habitats, Kosovo, Biogeography.

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Introduction

In the fields of biology, ecology and nature conservation, biogeographical data are of the utmost importance. They provide the conceptual framework for determining how different organisms and habitats are distributed over the Earth's surface (Olson & Dinerstein, 1998). Biogeographic regions are delineated areas that are characterized by particular ecological and evolutionary features and have a unique mix of flora and fauna (Cox, 2001; Morrone, 2018). The conceptual basis of these regions is rooted in the principles of historical biogeography, evolutionary biology and ecological dynamics (Parenti & Humphries, 2004; Cox *et al*., 2016). Various factors contribute to the formation and differentiation of biogeographical regions, including historical climatic events (Ye *et al*., 2021), geological processes (Liu *et al*., 2018), species dispersal ability and ecological interactions (Ottaviani *et al*., 2020). Understanding the intricate web of these factors is crucial for deciphering the origin and conservation of biodiversity (Buitenwerf & Higgins, 2016) on a global scale. The study of biogeographic regionalization has taken on new dimensions, particularly with the advent of tree-of-life reconstructions (Yessoufou *et al*., 2017; Hazzi, *et al*., 2018) and the increasing availability of species distribution data (Kreft & Jetz, 2010). Biogeographic regionalization has made considerable progress recently, using both quantitative methods with distribution and evolutionary data and qualitative methods with endemic taxa (Rueda *et al*., 2010). Regionalization analyzes based on quantitative techniques have so far proven to be far more objective and repeatable than qualitative methods (Ye *et al*., 2020). The selection of an appropriate dissimilarity index that calculates the pairwise distances between assemblages is essential for the development of a suitable quantitative biogeographic regionalization system.

Kosovo's central location on the Balkan Peninsula contributes to its significant biogeographic diversity. Located on the Balkan Peninsula, Kosovo is largely under continental climate influence, while the southeastern part is under Mediterranean influence (Peneva, 2023). Due to its diverse climate (Pllana, 2015), terrain and soil characteristics (Pruthi, 2013),

Kosovo is home to a wide range of plant and animal species (Millaku *et al*., 2013; Ibrahimi *et al*., 2019), including various geographical and migratory elements. This unique combination of factors allows for distinctive spatial and temporal ecosystem structures (Rexhepi, 1994; Krasniqi, 2013). Many species from different European regions have converged in this area of the Balkan Peninsula, interacting with the local flora and fauna to create a complex and exceptional biota. The succession of significant geotectonic and climatic disruptions and transitions that have taken place over time and across the country's landscape has in turn preserved a rich assemblage of Balkan endemic species. It has also produced important centers of speciation and divergence for various plant groups, including complex and aggregated species of vascular flora, as well as for various animal taxa. Historically, the most significant developments in the Balkan Peninsula took place during the Tertiary and Quaternary periods (Médail & Diadema, 2009; Feliner, 2011), when significant geotectonic and climatic shifts shaped the topography and geological structure of the region and permanently altered the biota. Over time, centuries of anthropogenic activities further altered the region's features, leading to a decrease in natural habitats and an increase in artificial surfaces (Bytyqi *et al*., 2024). The cumulative effects of these important factors can now be clearly observed in the current distribution of plant, animal and fungal species (Millaku *et al*., 2013; Ibrahimi *et al*., 2019; Berisha *et al*., 2020; Ramshaj *et al*., 2021) as well as in various aspects of ecosystems (Veselaj & Mustafa, 2015). The complexity of Kosovo's biogeography in this context is primarily due to its diverse orographic features, which are combined with numerous variations in basic climate types.

This process has led to a multitude of ecological relationships and interactions. Consequently, the biogeographical regionalization of Kosovo is notably intricate. It is undoubtedly more diverse than the large-scale biogeographical regions of Europe (EEA, 2017) suggest, which only designate the alpine and continental regions, which is also officially recognized by the Kosovo Agency for Environmental Protection (KAEP, 2016).

In the late 20th century, the prevailing view emphasized that zonal vegetation types ('*zonobiomes*') should serve as the basis for biogeographical classification. In this context, Matvejev and Puncer (1989) proposed a new framework for Yugoslavia based on the map of potential vegetation of the region developed by Fukarek and Jovanović (1983). This study examines the biogeographical characteristics of Kosovo, emphasizing its position as a transition zone with highly diverse ecosystems. While the complicated nature of these ecosystems presents a challenge in delineating smaller biogeographical units, the distribution of climax vegetation along environmental gradients (Hanz *et al*., 2022) provides a basis for broader classification efforts.

The aim of this study is to investigate the biogeographical regionalization of Kosovo by analyzing the interrelationship between vegetation, climate and topography. The study examines how climatic and topographic variations shape vegetation patterns, identifies the main vegetation zones along climatic and altitudinal gradients, and attempts to create a comprehensive classification of Kosovo's biogeographical regions. By synthesizing these factors, the research aims to highlight the ecological complexity of Kosovo's landscape and the central role of vegetation in defining biogeographical diversity.

Material and Methods

Data collection

In order to collect the necessary data for the biogeographical analysis of Kosovo, we first carefully analyzed the vegetation map of the former Yugoslavia (Fukarek & Jovanović, 1983), focusing on the territory of the Republic of Kosovo. This map provided basic insights into the historical vegetation patterns in the region. During this process, areas were identified that needed to be updated and corrected to more accurately reflect current vegetation conditions. Updates included revisions to the phytosociological naming of alliances to align with the modern classification system proposed by Mucina *et al.* (2016). These updates were incorporated into a revised map, which was then digitized to create a detailed vegetation dataset for Kosovo (Figure 1).

This vegetation dataset was then combined with current climate and topographic data to create a comprehensive dataset. The climate data was sourced from the WorldClim database (Fick & Hijmans, 2017), which provides high-resolution global climate datasets. The bioclimatic variables used included: BIO5: Maximum temperature of the warmest month representing the highest temperature conditions; BIO7: Annual temperature range, which captures the variability of temperature throughout the year and BIO12: Annual precipitation, which is a general measure of water availability in the region. For the biogeographical analysis, these three bioclimatic variables were selected due to their strong ecological significance for the distribution of vegetation in different biogeographical regions.

In addition to the *WorldClim* bioclimatic variables, the Water Retention (WR) index was included as a key variable to represent soil moisture availability. WR was derived by combining global soil moisture data and regional land cover classifications available through environmental data from Copernicus Land Monitoring Services. These data were processed in GIS and calibrated to the specific conditions of Kosovo by integrating information on regional soil types and vegetation cover.

Topographic data, including elevation and slope, were extracted from high-resolution digital elevation models (DEMs), providing a detailed representation of terrain variations. These datasets provided important insights into the elevation differences and slope characteristics that influence vegetation distribution and interactions with climate.

By integrating these datasets using GIS tools, we created a comprehensive geodatabase that depicts the complex interplay between vegetation, climate and topography across Kosovo. This dataset served as the basis for the subsequent cluster analysis and biogeographical regionalization and enabled a differentiated understanding of the ecological diversity of the region.

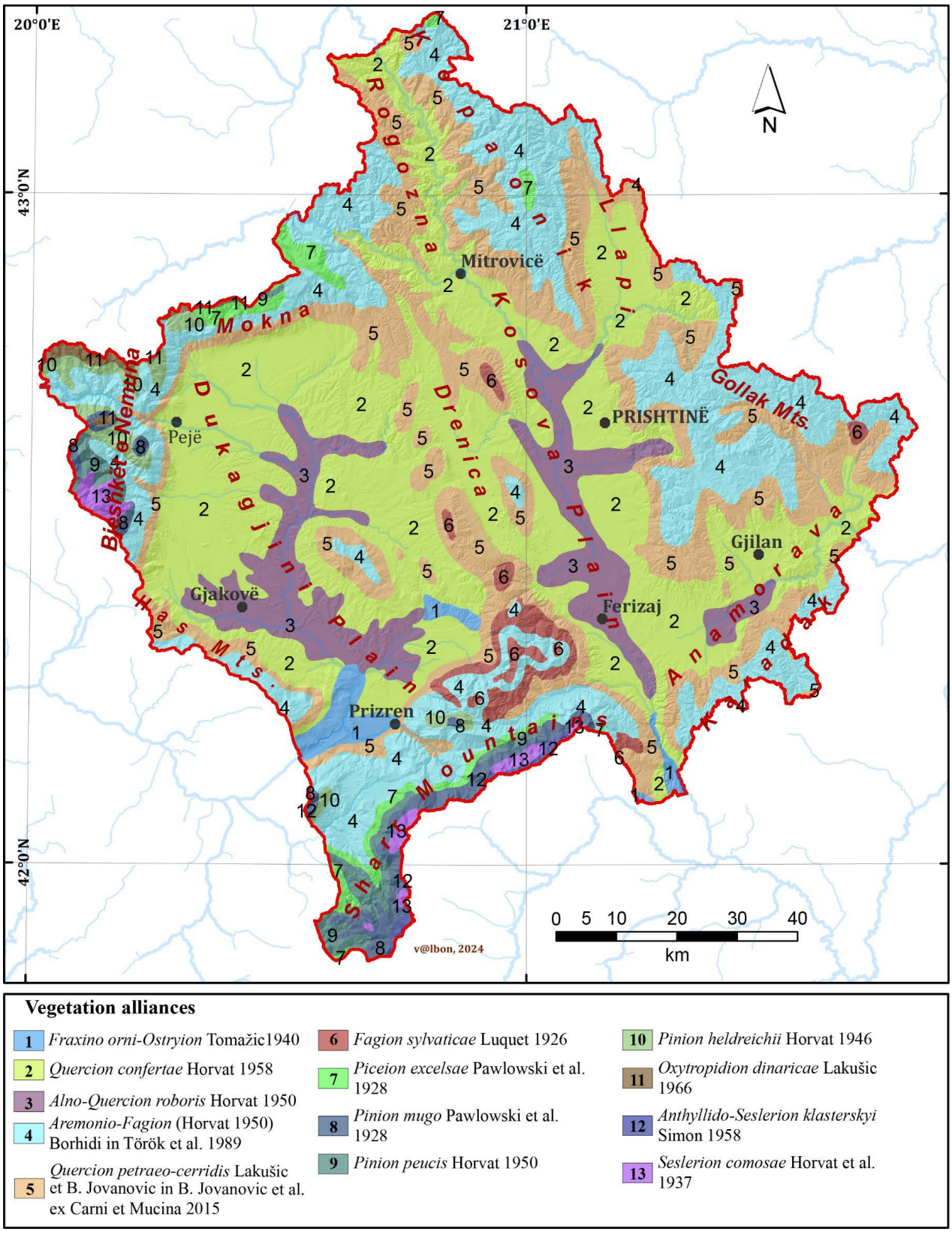

Figure 1. The distribution of main vegetation alliances in Kosovo (*after* Fukarek & Jovanović, 1983).

Data processing

The collected vegetation data formed the basis for the biogeographical regionalization of Kosovo. These data contained detailed information on indicator species (Rexhepi, 1994; Mucina *et al*., 2016) as well as endemic and rare species within each vegetation alliance. To ensure consistency and comparability, all variables (e.g. vegetation data, precipitation in mm, temperature in degrees Celsius, elevation in meters, and slope in degrees) were standardized using z-score normalization (James *et al*., 2021). This step was crucial as clustering analyzes are sensitive to differences in data scales.

Ellenberg indicator values (Ellenberg *et al*., 1991) were used to further characterize the

ecological preferences of vegetation alliances. They were assigned based on the diagnostic species of each vegetation alliance to ensure that the ecological preferences of each alliance were accurately represented in terms of climate and topography. These values, which quantify factors such as light, moisture and soil pH preferences, were combined with climatic data (e.g. temperature range and precipitation), topographic variables (elevation range and slope gradient) and vegetation composition data to create a comprehensive ecological profile for each alliance. This integrated approach (Mazel *et al*., 2018) ensured that the biogeographical regionalization captured the interplay between the vegetation and its environmental factors.

K-Means clustering

To identify biogeographical regions within Kosovo, we applied the K-means clustering algorithm to the standardized dataset. K-means is an unsupervised learning method that partitions data into a predefined number of clusters (MacQueen, 1967). Based on preliminary analysis and domain knowledge, we selected K = 3 clusters, representing distinct biogeographical zones (Figure 2). These clusters corresponded to varying vegetation types influenced by climate and topography.

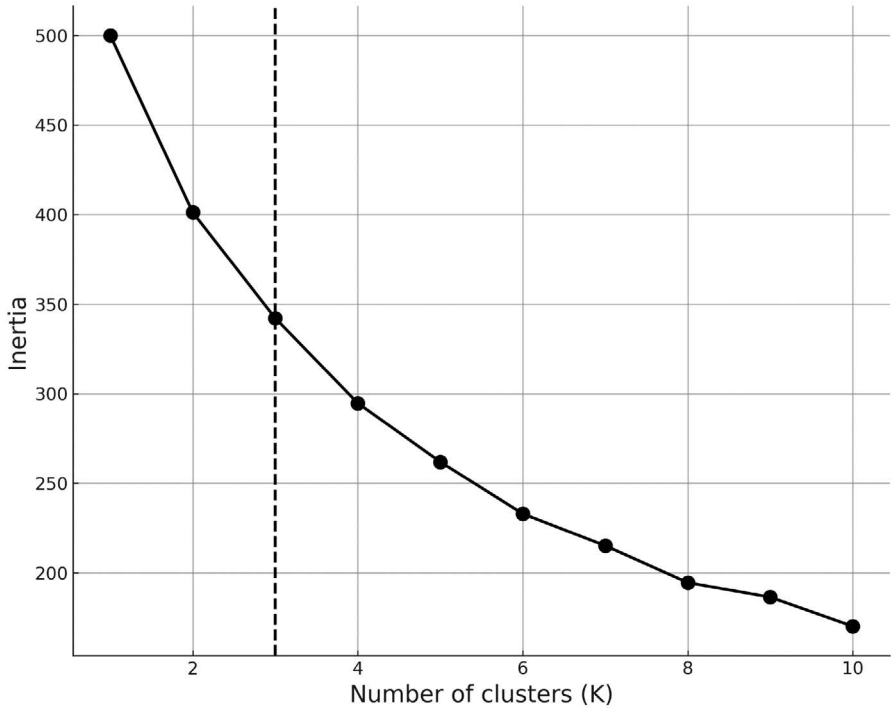

Figure 2. The optimal number of clusters (K) in biogeographical data analysis based on Elbow method.

Clustering execution and visualization

The clustering algorithm was applied to the dataset, resulting in three distinct clusters (Figure 3). To accurately reflect the national-level distribution of biogeographical regions, we adjusted the number of data points: 100 each for green and blue clusters, and 45 for red cluster, representing the less widespread Sub-Mediterranean biogeographical region. We then used Principal Component Analysis (PCA) to reduce the high-dimensional data to two principal components, allowing us to visualize the clusters in a 2D space. Each cluster was marked with a different color for clarity. To illustrate the spatial distribution and extent of each cluster, we calculated the covariance and center for each group and drew ellipses around them, representing their spread and orientation in the PCA plot. Using this data, we were able to create a self-organizing map (SOM) of Kosovo's three biogeographical regions (Figure 4) on a 5x5 km grids. This was achieved using the '*kohonen'* package in R for Self-Organizing Map (SOM) analysis (Wehrens & Buydens, 2007). By combining information, the clustering results gave us a clear and nuanced picture of how different zones are distributed across the country. This approach allowed us to highlight the unique features of each region and represent their spread across Kosovo with clarity and depth.

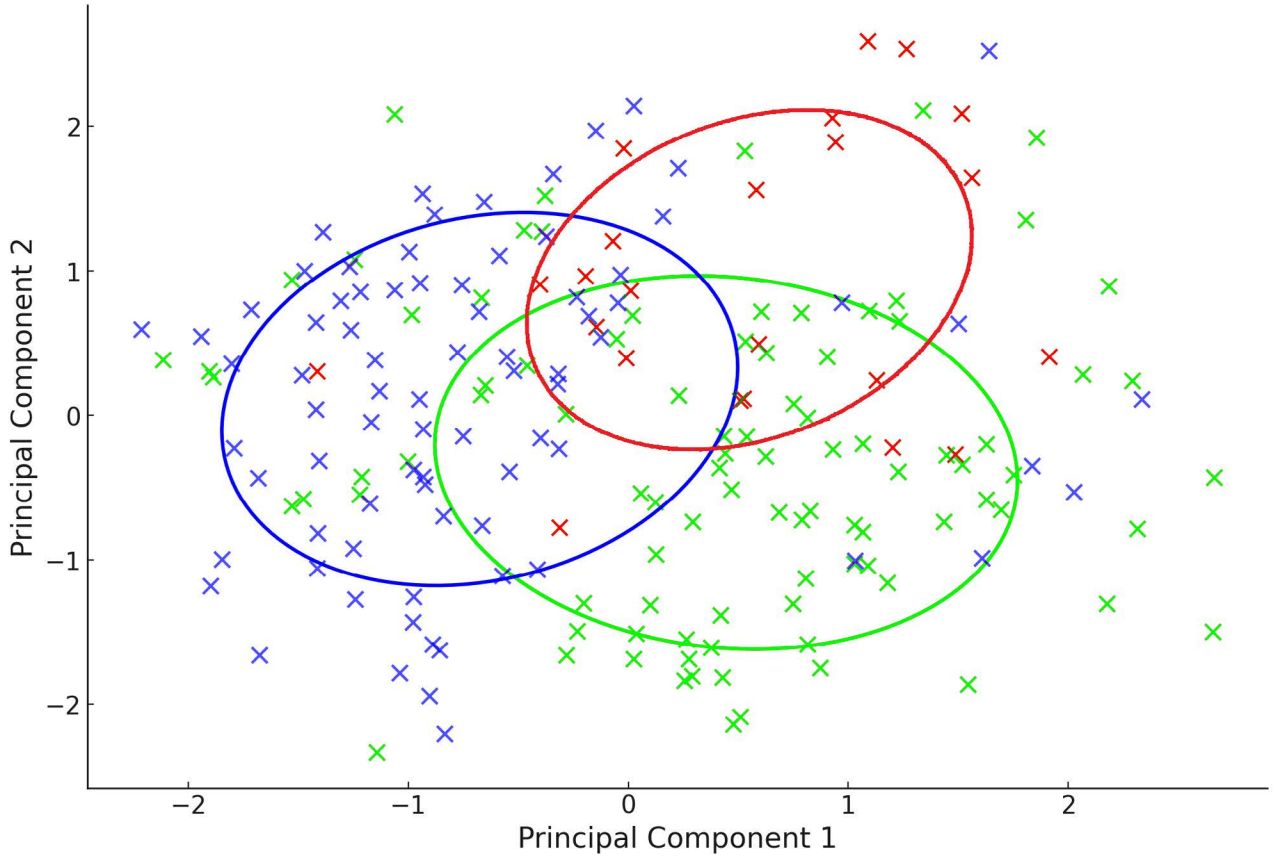

Figure 3. Scatter plot of K-Means clustering of Biogeographical data. Blue-x, represents the Alpine biogeographical region; red-x, the Sub-Mediterranean biogeographical region; green-x, the Continental biogeographical region.

Results and Discussion

The clustering plot, created using K-means clustering (Figure 3), reveals the distribution of three distinct biogeographical regions in Kosovo based on vegetation, climate, and topography. Each cluster, shown in blue, red and green, corresponds to a unique biogeographical region. Green cluster (Figure 3) represents the continental biogeographical region, that is the most widespread biogeographical region in Kosovo. It shows a relatively well-defined grouping in PCA, suggesting a homogenous area with consistent vegetation and environmental features. Anyhow, the slight overlap with the blue cluster as well as with green cluster, suggests transitional zones where environmental conditions and species composition gradually shift.

The continental biogeographical region of Kosovo is underpinned by a set of six principal vegetation alliances that collectively define the ecological framework and reflect the region's unique temperate climatic conditions (Table 1). These vegetation alliances, encompassing diverse forest types and characteristic species, form the backbone of the continental zone and are ecologically well-suited to the temperate conditions, moderate precipitation, and seasonality that define this area. Their specific compositions, structural features, and environmental preferences firmly affirm this biogeographical zonation. The vegetation distribution is mainly associated with the plains in Kosovo: Dukagjini, Kosova, Anamorava, Llapi and Drenica, but also in lower to medium altitudes, mostly with continental climate conditions, flat topography, including fluvial landforms. In these areas there are meadows and pastures, but they are not part of the potential (climax) vegetation, but rather secondary formations created by anthropogenic influences such as grazing and land use changes. The natural potential vegetation of the continental region consists primarily of deciduous forests, including alliances such as *Fagion sylvaticae*, *Quercion confertae* and *Alno-Quercion roboris*.

Fagin sylvaticae Luquet 1926 is a dominant alliance within this region, primarily comprising beech forests (*Fagus sylvatica* L.) that thrive in cooler, moist climates typical of mid-elevations in the continental zone. These forests are structurally complex, with dense canopies that support a shaded understory of ferns, mosses, and shade-adapted herbaceous plants. The presence of *Fagion sylvaticae* indicates a stable, temperate climate with well-distributed rainfall, making it a fundamental component of the continental region. The alliance's characteristic species composition and ecological requirements reinforce the region's classification, as it occupies areas where soil moisture and cool temperatures are sustained throughout the year. Another defining alliance, *Quercion confertae* Horvat 1958, primarily comprises oak forests where *Quercus cerris* L. and *Quercus frainetto* Ten. are dominant. These forests are often found in drier, warmer areas of the continental region, typically at lower elevations. The ecological preferences of *Quercion confertae* align with areas where soil moisture varies seasonally and temperature fluctuations are more pronounced,

Table 1. Climatic, topographical, and ecological characteristics of the Alpine, Continental, and sub-Mediterranean biogeographical regions of Kosovo.

Feature	Continental region	Alpine region	sub-Mediterranean region
Climate	Temperate with cold winters and warm summers	Cold, with long winters and short, cool summers	Mild, with dry summers and wet winters
Average temperature	Summer: ~20-23°C, Winter: ~0-5°C	Summer: ~10-15°C, Winter: -5 to -10°C	Summer: 23~25°C, Winter: ~0-5°C
Annual precipitation	Moderate (600–1,000 mm)	High (1,000–1,500 mm), often as snow	Moderate to low (600–850 mm), with seasonal drought
Elevation range	Mid to high (500–1,500 m)	High (1,500–2,658 m)	Low to mid (<500 m)
Topography	Rolling hills, plains, and plateaus with gentle slopes	Steep slopes, rugged terrain, with significant elevation gains	Valleys and foothills with moderate slopes
Vegetation and floral composition	Dominated by deciduous forests, mainly oak and beech (*Quercus petraea, Fagus sylvatica*), with meadow and pasture areas	Dominated by alpine grasslands, subalpine shrubs, and dwarf pines; includes species adapted to high-altitude conditions (e.g., *Juniperus communis*, *Pinus mugo, Helianthemum alpestre*)	Dominated by thermophilous and drought-tolerant species; characteristic species include *Quercus trojana*, *Pistacia terebinthus*, *Acer monspessulanum,* etc.
Main vegetation type(s)	Deciduous broadleaf forests, interspersed with grasslands (*Fagion sylvaticae, Quercion confertae, Aremonio-Fagion*, *Deschampsion cespitosae*)	Alpine grasslands and subalpine forests - (*Piceion excelsae*, *Pinion mugo*, *Pinion peucis*, *Pinion heldreichii*, *Oxytropidion dinaricae*, *Anthyllido-Seslerion klasterskyi*, and *Seslerion comosae)*	Mixed thermophilous woodlands and sclerophyllous shrubs – (*Fraxino orni-Ostryion*)
Soil types	Rich, moderately fertile soils	Thin, nutrient-poor soils, often rocky	Calcareous, well-drained soils, often rocky
Key adaptations	Tolerance for moderate cold and warm seasonal variation	Cold resistance, low-growing habit, slow growth	Drought and heat resistance, sclerophyllous leaves

indicating a high degree of adaptability within the continental zone. This alliance also highlights the transition between mesophytic and thermophilous species, as it serves as a bridge between more temperate beech forests and drier oak woodlands. *Quercion petraeo-cerridis* Lakušić & B. Jovanović in B. Jovanović et al. ex Čarni & Mucina 2015, represents a distinctive oak alliance with *Quercus petraea* (Matt.) Liebl. and *Quercus cerris* L. as prominent species, thriving in intermediate, well-drained soils. This alliance is particularly representative of the temperate, semi-dry areas within the continental region, where topography and microclimates create varying moisture and temperature conditions. The adaptability of *Quercion petraeo-cerridis* to these fluctuating conditions reinforces its relevance to the continental biogeographical classification, where seasonal moisture availability and mild temperatures are influential factors. *Alno-Quercion roboris* Horvat 1950, occupies riparian zones within the continental region, primarily along streams and river valleys where water availability is higher. Dominated by *Alnus* sp. (alder) and *Quercus robur* L. (pedunculate oak), this alliance thrives in areas with moderate flooding and high soil moisture. The presence of *Alno-Quercion roboris* supports the continental zonation by representing hydrologically unique ecosystems within a broader temperate framework. These riparian forests contribute to biodiversity by providing habitat for species that depend on stable moisture, thus enhancing the ecological diversity within the continental zone. *Aremonio-Fagion* (Horvat 1950) Borhidi in Török et al. 1989, includes mesophytic beech forests that exhibit characteristics of the continental zone's cool, temperate conditions. Similar to *Fagion sylvaticae*, this alliance occupies well-drained slopes and valleys with high soil moisture and moderate shade. However, it includes a broader array of mesophytic species in the understory, reflecting slightly more variable microclimates. The *Aremonio-Fagion* forests further confirm the continental zonation as they flourish under the stable temperate climate and structured seasonal rainfall typical of mid-elevation continental areas. Finally, *Deschampsion cespitosae* Horvatić 1930, is an herbaceous alliance commonly found in moist grasslands, particularly on flood-prone or poorly drained soils within the continental region. This alliance comprises *Deschampsia cespitosa* (L.)

P. Beauv., *Carex* spp., and other grasses that thrive in areas with high soil moisture and periodic flooding. *Deschampsion cespitosae* is essential in defining the continental region's ecological diversity, as it represents open habitats that are adapted to specific moisture regimes and seasonal waterlogging. Its presence emphasizes the variety of microhabitats that exist within the continental region, supporting a range of species adapted to both mesic and hydric conditions.

Together, these six alliances, spanning beech and oak forests, riparian woodlands, mesophytic zones, and floodplain grasslands, collectively characterize the continental biogeographical region of Kosovo. Each alliance's distinct ecological preferences and structural features provide a comprehensive foundation for understanding the region's biogeographical identity, confirming its classification through a well-defined balance of temperate climate adaptation and vegetation diversity.

Regarding the bioclimatic variables, this biogeographical region, at moderate elevations (500–800 m asl), this region shows hot summer temperatures, with BIO5 values rising to a maximum of 31°C. Temperature variability is also high, as indicated by BIO7 values ranging from 23°C to 29°C. Precipitation is moderate, with BIO12 between 600 mm and 1000 mm, and the WR index is somewhat lower (0.61–0.66), suggesting that water availability might be less consistent than in the Alpine region, possibly due to higher evaporation rates in warmer temperatures (Figure 5).

Blue cluster (Figure 3, Figure 4) represents another prominent biogeographical region in

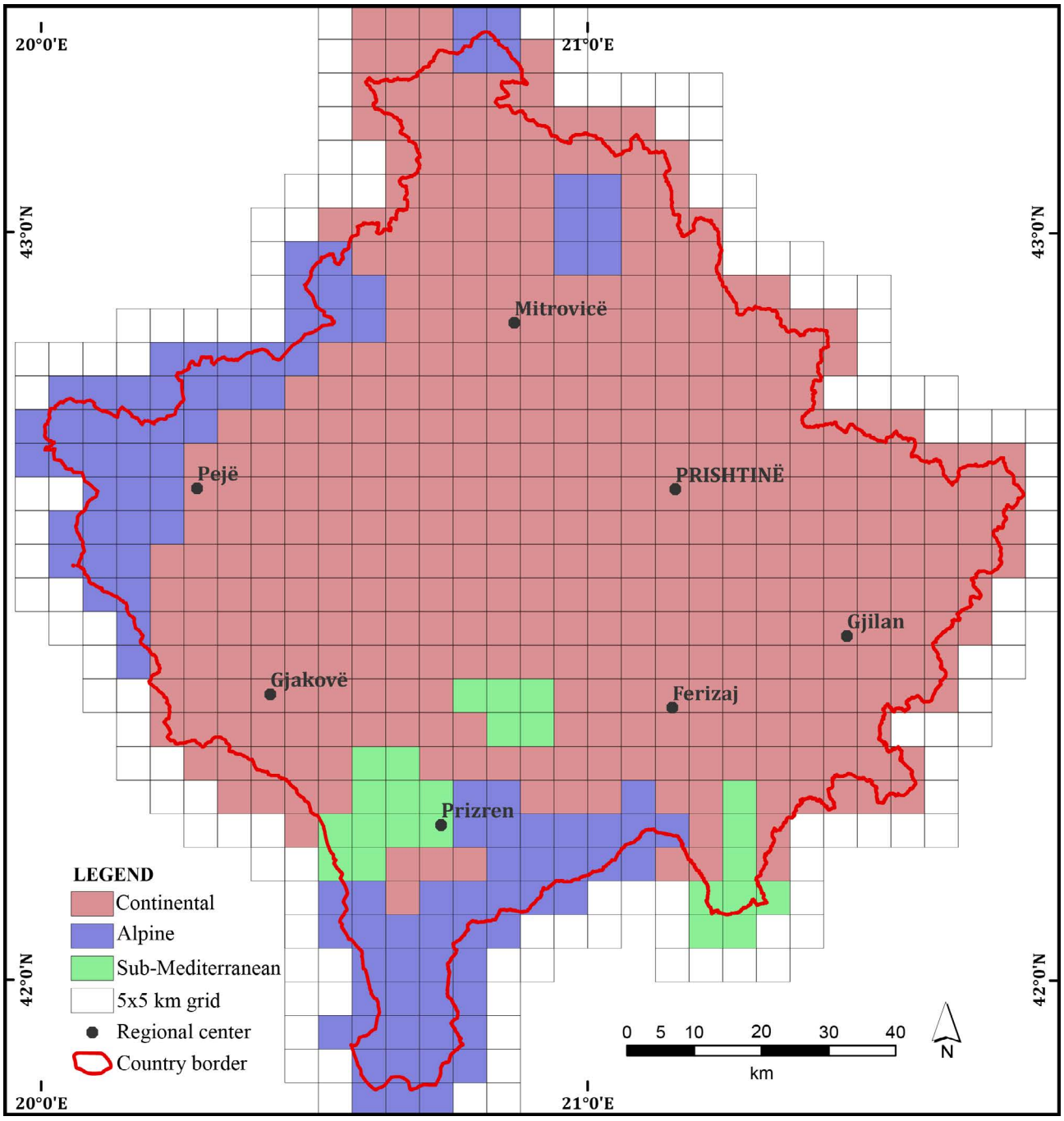

Figure 4. Map showing the distribution of three clusters representing the identified biogeographical regions of Kosovo.

Kosovo, the alpine one. It displays a broader spread in PCA space, indicating variability in elevation, microclimate and vegetation types (Table 1).

The alpine biogeographical region of Kosovo is distinctly characterized by a unique assemblage of vegetation alliances that are exceptionally adapted to the rigorous climate and terrain typical of high-altitude environments. This region is shaped by a combination of low temperatures, strong winds, a shorter growing season, and often extreme environmental conditions. The primary vegetation alliances in this region, including *Piceion excelsae*, *Pinion mugo*, *Pinion peucis*, *Pinion heldreichii*, *Oxytropidion dinaricae*, *Anthyllido-Seslerion klasterskyi*, and *Seslerion comosae*, together form the ecological backbone of Kosovo's alpine zone.

The *Piceion excelsae* Pawłowski et al. 1928 alliance, dominated by *Picea abies* (L.) H. Karst. (Norway spruce), is prevalent in montane to subalpine areas where cooler temperatures and high moisture levels favor the growth of spruce. This alliance is found at elevations where the tree line begins to shift into the subalpine zone, marking the transition between forested and open alpine environments. The ecological characteristics of *Piceion excelsae*, such as its tolerance for cold temperatures and ability to thrive on acidic, well-drained soils, align with the harsh conditions that define Kosovo's alpine region. The *Pinion mugo* Pawłowski et al. 1928 alliance, featuring *Pinus mugo* Turra (dwarf mountain pine), occupies exposed slopes and ridges at subalpine elevations, often on rocky or shallow soils. This low, shrubby pine community is highly adapted to strong winds, heavy snow cover, and intense solar radiation. *Pinion mugo* is emblematic of the alpine biogeographical zone due to its hardiness and its role in stabilizing soils in harsh, erosion-prone areas. It represents the upper limit of woody vegetation in this region, and in Kosovo is present predominantly in Bjeshkët e Nemuna National Park. The *Pinion peucis* Horvat 1950 alliance, which begins in the montane belt but extends into the subalpine zone, includes *Pinus peuce* Griseb. (Macedonian pine), a species well-suited to cool, moist conditions and poor soils. This alliance typically thrives in areas with relatively stable winter snow cover, which protects vegetation from the harshest climatic extremes. The presence of *Pinion peucis* confirms the alpine zonation, as it is found in ecotonal zones where montane species are replaced by those adapted to subalpine conditions. *Pinion heldreichii* Horvat 1946, another distinctive alliance, includes *Pinus heldreichii* Christ. (Bosnian pine) and is typically found on calcareous and ultramafic substrates. This alliance is unique to the Southern Balkans and Southern Apennines and is present in Kosovo's alpine region on steep, rocky slopes that experience limited soil development. Bosnian pine forests are relic communities, indicating ancient, stable habitats that have endured climatic shifts over millennia. The ecological preferences of *Pinion heldreichii*, including its tolerance for nutrient-poor soils and dry conditions, underscore its role in defining the rugged character of Kosovo's alpine zone. The *Oxytropidion dinaricae* Lakušić 1966 alliance represents alpine and subalpine grasslands characterized by hardy herbaceous species, such as *Oxytropis* species, that are adapted to high altitudes and strong climatic stressors. This alliance is primarily found on limestone substrates, where soils are often shallow and nutrient-poor. The vegetation within *Oxytropidion dinaricae* is well-suited to withstand strong winds, low temperatures, and a short growing season, making it a core component of the alpine landscape. The *Anthyllido-Seslerion klasterskyi* Simon 1958 alliance is another alpine grassland community, typically found on steep, sunny slopes and rocky areas. Comprising species such as *Anthyllis* sp. and *Sesleria* sp., this alliance is adapted to high light exposure, thin soils, and seasonal droughts. The drought tolerance and light requirements of this community emphasize its alignment with the alpine biogeographical region, where intense solar radiation and low precipitation limit vegetation to drought-resistant types. Lastly, *Seslerion comosae* Horvat et al. 1937 is a characteristic alliance of alpine grasslands that occur on acidic soils. This alliance includes grass species like *Sesleria* sp. that thrive in well-drained, rocky soils at high elevations. The vegetation in *Seslerion comosae* is finely attuned to the extreme conditions of the alpine zone, including prolonged snow cover in winter and rapid drying of soils in summer. Its ecological preferences further highlight the specificity of the alpine zone in Kosovo, as it occupies habitats where other vegetation types struggle to survive.

As concerning the bioclimatic variables, this biogeographical region, represented by higher elevations (1800–2500 m asl), exhibits relatively low temperatures, with BIO5 (mean warmest month temperature) ranging from 11°C to 17°C and BIO7 (temperature annual range) fluctuating between 18°C and 20°C. Precipitation levels (BIO12) are higher compared to the other regions, with values from 1220 mm to 1350 mm, reflecting a moist environment typical of high-altitude areas. The Water Retention (WR) index remains fairly high (0.82–0.88), indicating good water availability, likely due to lower evaporation rates in cooler conditions (Figure 5). These types of elevations are found in the Sharri Mountains (south), the Bjeshkët e Nemuna Mountains (west), and Kopaonik (north). The terrains are mostly rugged one with high slope gradient, intersected with peaks modeled in the past by the action of Pleistocene glaciers (Kuhlemann *et al*., 2004). Cirques, glacial valleys and moraines are found and serve as the growing environment of vegetation. The highest points of elevation are mostly peaks and mountain ridges, often without vegetation.

Red cluster (Figure 3) represents the sub-Mediterranean biogeographical region in Kosovo. The sub-Mediterranean biogeographical region in Kosovo is primarily characterized by low-altitude landscapes (<500 m asl), warm and dry summers and Mediterranean climatic influences, which gradually transition to the continental biogeographical region at higher altitudes. This region is influenced by Adriatic-Ionian and Aegean climatic elements, especially by the Drini i Bardhë and Lepenci river valleys, where warm air currents favor the presence of thermophilic and drought-resistant vegetation.

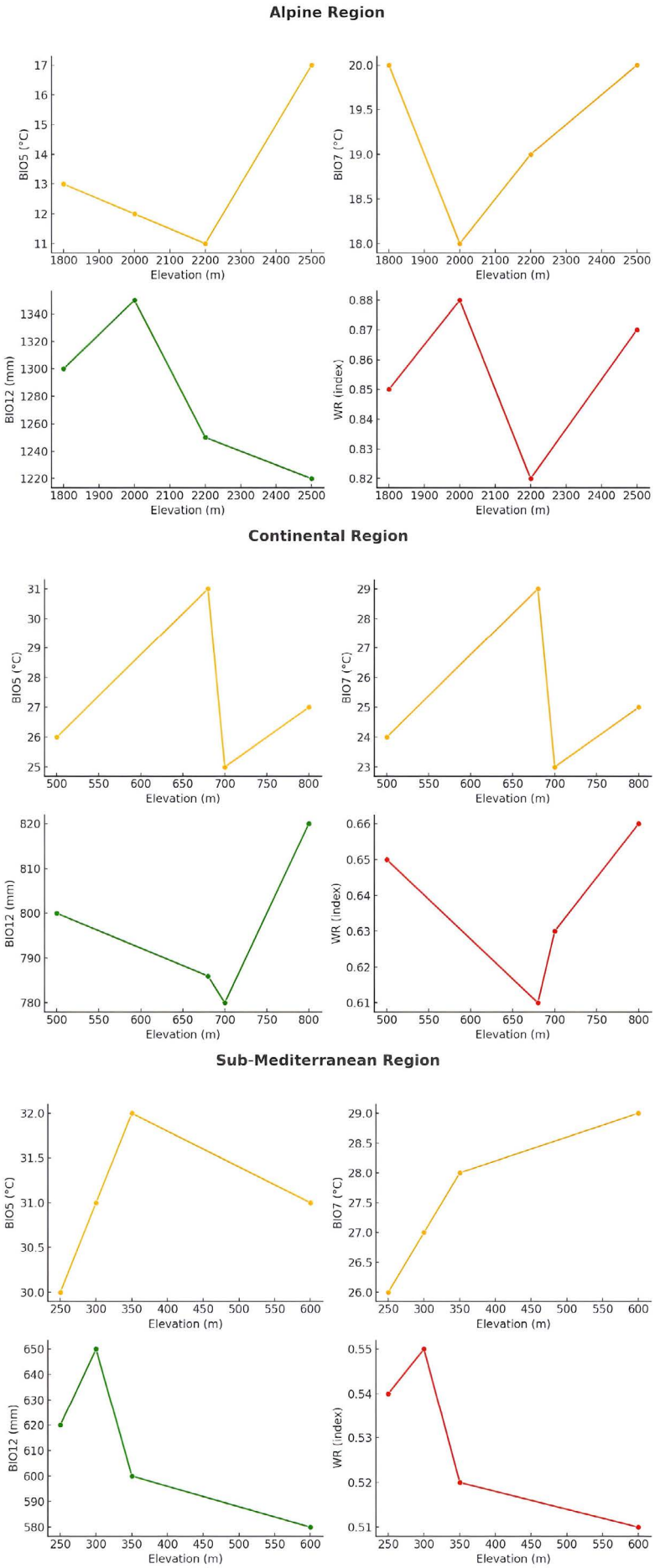

Figure 5. Comparison of four bioclimatic variables with altitude across the three biogeographical regions.

Together, these seven alliances define Kosovo's alpine biogeographical region, each bringing distinct ecological adaptations that enable survival in high-altitude, low-temperature environments. Their individual characteristics, such as adaptations to acidic or calcareous soils, tolerance for cold and drought, and resilience to wind and snow, confirm the alpine zonation and reinforce the uniqueness of this biogeographical zone.

In contrast to the continental region, which extends over medium altitudes (500–1,500 m asl) with a more temperate climate, moderate precipitation (600–1,000 mm) and the dominance of deciduous oak-beech forests (Quercus petraea, Fagus sylvatica), the sub-Mediterranean region is characterized by altitudes below 500 m asl, higher summer temperatures (BIO5: 30–32°C), lower precipitation (580–650 mm) and increased evapotranspiration due to longer dry periods. The vegetation of this region includes sclerophyllous forests and scrublands, especially *Fraxino orni-Ostryion* forests (*Quercus trojana*, *Pistacia terebinthus*, *Acer monspessulanum*), which are adapted to calcareous and well-drained rocky soils.

This distinction is also confirmed by the topographic and bioclimatic patterns in Table 1 and the supplementary Figures 2 and 5, which illustrate the marked contrast in altitude and climate between the continental and sub-Mediterranean regions. The transitional character of these biogeographical zones is evident where thermophilic elements extend into lower-altitude parts of the continental region, especially in areas with warm microclimatic conditions and calcareous substrates.

The Mediterranean and sub-Mediterranean biogeographical regions, as their names suggest, extend along the coastal areas and hinterlands of the Mediterranean Sea. In Kosovo, these regions are only slightly represented. Specifically, the Adriatic-Ionian influence, penetrating via the Drini i Bardhë River valley, is the most prominent, with less influence from the Aegean Sea in southeastern Kosovo. This latter influence reaches Kosovo through the Lepenci River valley, following its passage along the Vardar canyons and valleys throughout North Macedonia.

This biogeographical region is characterized by thermophilus forests and scrublands, primarily of the vegetation alliance *Fraxino orni-Ostryion* Tomažič 1940, which is very well differentiated from the previous two regions in terms of climate, vegetation composition, adaption and topography (Table 1, Figure 1, Figure 5). The dominant representatives of this region are Mediterranean to sub-Mediterranean plant species, such as *Quercus trojana* Webb, *Acer monspessulanum* L., *Pistacia terebinthus* L., *Carpinus orientalis* Mill. subsp. *orientalis*, etc. Notably, many of these floral elements extend further into the interior regions of Kosovo, where they establish on thermophilous limestone or serpentine substrates. The degradation of zonal forests due to human impact, along with the formation of pastures and warm, rocky terrains on calcareous and serpentine soils, facilitates the spread of sub-Mediterranean flora into more continental parts of Kosovo. The Amphiadriatic mesic calcareous sub-Mediterranean forests alliance (*Fraxino orni-Ostryion*) in Kosovo is represented by 4 plant associations: *Carpinetum orientalis scardicum* Krasniqi 1968*; Dioscoreo-Carpinetum orientalis* Blečić et Lakušić 1966; *Quercetum trojanae dukagjini* Rexhepi 1983 and *Ostryo-Quercetum pubescentis* (Ht.1950) Trinajstić 1974 (Rexhepi, 1994; Millaku *et al*., 2012; 2013; Berisha *et al*., 2020). They are distributed in confined and small areas in Kosovo, only on those parts where the influence of sub-Mediterranean climate (Horvat *et al*., 1974; Quézel & Medail, 2003) reaches the vegetation of Kosovo (Figure 1). They all combined, contain in total 28 plant taxa of Mediterranean origin (Millaku *et al*., 2012). With respect to the bioclimatic variables, this biogeographical region, defined by an elevation zone (250–600 m asl) has the warmest climate, with BIO5 values between 30°C and 32°C and BIO7 ranging from 26°C to 29°C, typical of a sub-Mediterranean climate with hot summers. Precipitation levels are relatively low (580–650 mm), and the WR index is the lowest among the regions (0.51–0.55), indicating limited water availability. This suggests a drier environment with potentially higher evaporation rates, consistent with the Mediterranean influence at these elevations (Figure 5).

The three biogeographical regions identified in Kosovo can also be analyzed in terms of their geological characteristics and differentiation (Figure S1). The Continental biogeographical region is predominantly characterized by clay sediments and conglomerate limestone, among other substrates. In contrast, the Alpine biogeographical region shows a notable presence of meta-sedimentary silicates, limestone schists, quartzites, and meta-conglomerate stones, reflecting the high-altitude, rugged terrain. The sub-Mediterranean region, on the other hand, is distinguished by deposits of alluvium, including gravel, sand, and silt, often interspersed with limestone. These geological distinctions emphasize the unique substrate and soil conditions that shape the vegetation and ecological dynamics within each region.

In terms of elevation (Figure S2) and slope (Figure S3), the differentiation between the regions is straightforward. The Continental biogeographical region is well-separated from the Alpine region by its lower elevation and gentler slopes, while the Alpine biogeographical region is defined by high altitudes, steep slopes, and rugged terrain, typical of its mountainous landscapes. The sub-Mediterranean region, however, shows similarities to the Continental region in both elevation and slope gradients, making differentiation based solely on these parameters more challenging. This overlap reflects the transitional nature of the Sub-Mediterranean zone, where the interplay between climatic influences and topography contributes to its complexity.

Regarding annual rainfall values (Figure S4), the Alpine region receives the highest precipitation levels, with areas such as the high mountains of Juniku and Deçani in the Bjeshkët e Nemuna National Park recording up to 1763 mm annually. This is significantly higher than the moderate precipitation observed in the Continental region and the relatively lower rainfall in the sub-Mediterranean region (Table 1). These patterns underscore the influence of elevation and orographic effects on precipitation distribution across the regions.

In terms of temperature patterns (Figure S5), the Continental region exhibits significant variability, with a clear distinction between the Kosovo Plain and Dukagjini Plain, the latter being on average 1.5–2.0°C warmer (Pllana, 2015). The sub-Mediterranean region shows even higher average temperatures, exceeding those of the Continental region by approximately 2.0°C. However, due to the limited spatial extent of this zone, such temperature differences are challenging to represent effectively on a map, highlighting the sub-Mediterranean region's narrow distribution and localized climatic influence.

The biogeographical regionalization of Kosovo, with its intricate blend of Continental, Alpine and sub-Mediterranean influences, underscores the region's unique ecological complexity within the Balkans. Kosovo's position at the convergence of these distinct biogeographical zones fosters a remarkable diversity of flora and fauna, which has evolved under the influence of both natural and anthropogenic factors (Millaku *et al*., 2013, 2016; Berisha *et al*., 2020). A significant challenge in biogeographical regionalization efforts, both in Kosovo and globally, lies in reconciling the hierarchical classifications of plant and animal distributions (Myers & Giller, 2012). Differences in reproductive strategies, ecological requirements, and dispersal mechanisms between flora and fauna often complicate efforts to create a cohesive spatial distribution framework, from broader divisions (e.g., floristic kingdoms) to more localized units (provinces and districts) (Parenti & Ebach, 2009; Myers & Giller, 2012; Wang *et al*., 2024). To address these challenges, many mid-20th-century attempts, including Matvejev's (1961) work in former Yugoslavia, emphasized zonal vegetation types, or '*zonobiomes'*, as a foundation for biogeographical classification, thereby reducing inconsistencies between phytogeographical and zoogeographical divisions (Loveland & Merchant, 2004).

In Kosovo's context, each biogeographical region is defined by distinct climatic conditions, vegetation types, and topographical features. The Alpine region, characterized by high altitudes, cold temperatures, and rigorous environmental conditions, is home to vegetation alliances such as *Piceion excelsae* and *Pinion mugo*, which reflect adaptations to extreme climates. The Continental region, in contrast, is marked by moderate elevations, temperate climates, and a diversity of forest types (e.g., *Quercion confertae* and *Fagion sylvaticae*), indicating an environment that supports broadleaf deciduous forests and meadow ecosystems. The sub-Mediterranean region, influenced by Adriatic-Ionian climatic factors, hosts thermophilous woodlands and sclerophyllous shrubs, including alliances like *Fraxino orni-Ostryion*, which contain species adapted to warmer, drier conditions and calcareous soils.

Applying an ecogeographical approach, Kosovo's biogeographical characteristics can be analyzed through the distribution of climazonal ecosystems. This framework aligns with Matvejev and Puncer's (1989) regionalization in Yugoslavia, which leveraged the natural potential vegetation map (Fukarek & Jovanović, 1983) to delineate regions. Kosovo's complex overlap of floral and faunal elements highlights the necessity of integrating historical and contemporary ecological dynamics to capture the area's biogeographical diversity. This nuanced approach reveals the region's sensitivity to both abiotic factors, such as temperature gradients and soil types, and biotic influences, including species interactions and historical biogeographic patterns.

Furthermore, anthropogenic factors play a critical role in shaping the current vegetation composition within Kosovo's sub-Mediterranean region. The degradation of zonal forests due to human activities has facilitated the spread of secondary species altering natural ecosystems and impacting biodiversity. Comparative analyses with neighbouring regions, like Serbia, further emphasize Kosovo's distinctiveness within the broader Balkan biogeographical context, where similar transitions occur but are modulated by localized ecological factors. Recognizing these diverse biogeographical zones within Kosovo is crucial for implementing targeted conservation strategies, as it allows for the prioritization of areas with high endemic species richness and ecological significance.

The results of our study, in which the continental, alpine and sub-Mediterranean biogeographical regions of Kosovo were delineated, are consistent with broader efforts in the Balkan Peninsula to understand regional biogeographical patterns. Similar approaches were applied in Albania (Malatesta *et al*., 2023), where a detailed bioregionalization revealed inconsistencies between floristic data and climate-based models. This result is consistent with our observation of transition zones in Kosovo, particularly between the continental and sub-Mediterranean regions, where vegetation and environmental gradients blur regional boundaries. Such overlaps reflect the complex interplay of biogeographical factors in small but ecologically diverse territories such as Kosovo and Albania. The study by Stevanović (2022) on the biogeography of Serbia emphasizes the richness and spatial heterogeneity of biodiversity on the Balkan Peninsula and highlights the role of both historical and current ecological processes. In Kosovo, a similar dynamic characterizes the differentiation of the three biogeographical regions. For example, the rugged Alpine region, with its glacial history and adaptation to extreme conditions, is comparable to other high mountain zones in the Balkans, which also serve as refuges for endemic species. In addition, Stevanović (2022), in his treatise on the biogeographical division of Serbia, maps the logical distribution of biogeographical regions across parts of the Balkan Peninsula based on oroclimatic ecosystems. His results clearly indicate the presence of sub-Mediterranean regions that extend across the Drini i Bardhë and Lepenci gorges into Kosovo. In the context of biogeographical regionalization of Kosovo, the structured approach of Chobanova *et al*. (2024) in North Macedonia demonstrates the effectiveness of integrating different ecological indicators and GIS-based methods for ecosystem assessment. Their emphasis on the application of the MAES framework confirms the use of comprehensive environmental datasets in the delineation of ecological zones, which is consistent with the identification of the three biogeographical regions in Kosovo. Our delineation

of biogeographical regions in Kosovo aligns with broader frameworks of biogeographical classification. Recent work by Loidi & Vynokurov (2024) highlights the importance of integrating floristic, evolutionary, and climatic criteria when defining biogeographical units at multiple scales.

In summary, the biogeographical regionalization of Kosovo reveals a complex interplay of natural and anthropogenic factors, underscoring the region's role as a biodiversity hotspot within the Balkans. By delineating the Alpine, Continental, and sub-Mediterranean regions through vegetation, climate, and topographical criteria, this study captures the distinct ecological identities of each zone. The eco-geographical approach allows for a cohesive understanding of Kosovo's biogeographical divisions and reflects broader patterns seen across the Balkan Peninsula. This framework not only highlights Kosovo's ecological diversity but also emphasizes the importance of ongoing refinement in regional classifications, as localized ecological factors and human impact continue to shape these unique landscapes. This analysis provides a foundation for more targeted conservation and ecological management strategies that can adapt to the evolving biogeographical landscape of Kosovo.

Conclusions

The biogeographical regionalization of Kosovo underlines the ecological diversity and complexity resulting from the interplay of climatic, topographic and vegetation factors. The delineation of the Continental, Alpine and sub-Mediterranean regions provide important insights into the different ecological identities of these zones. The Continental region is characterized by temperate climatic conditions that favor deciduous forests and riparian habitats, while the Alpine region reflects the resilience of vegetation to stress factors at high altitudes, such as cold temperatures and steep slopes. The sub-Mediterranean region, with its thermophilic vegetation, illustrates the extension of Mediterranean influences through certain geo-climatic corridors such as the Drini i Bardhë and Lepenci gorges.

This study is not only consistent with existing biogeographical frameworks in the Balkans but also provides a refined classification that captures transition zones and localized ecological nuances. The applied methodology, which integrates vegetation alliances with bioclimatic and topographic variables, demonstrates the value of a multidisciplinary approach to regionalization. The results emphasize the need for targeted conservation strategies that consider both the unique and transitional characteristics of Kosovo's biogeographical zones. Future research should expand this framework by incorporating temporal datasets and faunistic elements to gain a more comprehensive understanding of regional biodiversity patterns.

Author contribution

NB conceptualized the research idea, coordinated the study, gathered the data, performed the formal analysis, and led the research process. NB was primarily responsible for writing, revising, and supervising the manuscript preparation. EK contributed to data collection, provided comments on the conceptual framework, and authored portions of the manuscript. VB was responsible for data curation, refining the research objectives, and assisting with data collection. VB also handled software applications for mapping, analysis, and visualization, and contributed to writing and editing the manuscript. All authors read and approved the final version of the manuscript.

Conflict of interest disclosure

None.

References

Berisha, N., Krasniqi, E. & Millaku, F. 2020. A quantitative approach for conservation of endangered and endemic plants from Kosovo, SE Europe. Folia Oecol. 47(1):52–63. doi: 10.2478/foecol-2020-0007

Buitenwerf, R. & Higgins, S.I. 2016. Convergence among global biogeographical realms in the physiological niche of evergreen and deciduous vegetation. Global Ecol. Biogeogr. 25(6):704–715. doi: 10.1111/geb.12447

Bytyqi, V., Agaj, T. & Ramadani, I. 2024. Spatiotemporal change analysis of land cover on soil resources in Kosova Plain. Polonian Journal of Environmental Studies 33(3). doi: 10.15244/pjoes/175780

Chobanova, M., Avukatov, V., Atanasovsk,a K., Melovska, N., Brajanoska, R., Shushlevska, M., Jovanovska, D., Trpeski, V., Jordanov, S., Gicevski, B, Sterijovski, B, Nikolov, L., Velevski, M., Velkovski, N., Petrovski, S., Najdovski, B., Stamenkovikj, V.S., Stavrikj, V., Campange, S. & Hristovski, S. 2024. Mapping and national assessment of ecosystems and their condition in North Macedonia. Macedonian Journal of Ecology and Environment 26(1): 83–116. doi: 10.59194/mjee24261083ch

Cox, B. 2001. The biogeographic regions reconsidered. J. Biogeogr. 28(4): 511–523. doi: 10.1046/j.1365-2699.2001.00566.x

Cox, C.B., Moore, P.D. & Ladle, R.J. 2016. Biogeography: An ecological and evolutionary approach. Wiley-Blackwell, Oxford.

Ellenberg, H., Dull, R., Wirth, V., Werner, W. & Paulißen, D. 1991. Zeigerwerte von Pflanzen in Mitteleuropa. 2nd ed. Verlag Erich Goltze KG, Göttingen. 166 p.

Feliner, G.N. 2011. Southern European glacial refugia: A tale of tales. Taxon. 60(2): 365–372. doi: 10.1002/tax.602007

Fick, S.E. & Hijmans, R.J. 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37(12): 4302–4315. doi: 10.1002/joc.5086

Fukarek, P. & Jovanović, B. (Eds.). 1983. Natural potential vegetation of Yugoslavia. Scientific Council of Vegetation Map of Yugoslavia 1:1,000,000, Military Geographical Institute, Belgrade.

Hanz, D.M., Cutts, V., Barajas-Barbosa, M.P., Algar, A.C., Beierkuhnlein, C., Fernández-Palacios, J., Field, R., Kreft, H., Steinbauer, M.J., Weigelt, P., Irl, S.D.H. 2022. Climatic and biogeographical drivers of functional diversity in the flora of the Canary Islands. Global Ecol. Biogeogr. 31(7): 1313–1331. doi: 10.1111/geb.13507

Hazzi, N.A., Moreno, J.S., Ortiz-Movliav, C. & Palacio, R.D. 2018. Biogeographic regions and events of isolation and diversification of the endemic biota of the tropical Andes. Proc Natl Acad Sci USA. 115(31):7985–7990. doi: 10.1073/pnas.1803908115

Horvat I, Glavač V, Ellenberg H. 1974. Vegetation Südosteuropas. Stuttgart: Gustav Fischer Verlag.

Ibrahimi H, Gashi A, Rexhepaj D, Zhushi-Etemi F, Grapci Kotori L, Fehér Z, Bino T, Šerić Jelaska L, Mesaroš G, Théou P. 2019. Red Book of Fauna of the Republic of Kosovo. Kosovo Agency for Environmental Protection, MESP, Prishtina. 401 p.

James, G., Witten, D., Hastie, T. & Tibshirani, R. 2021. An introduction to statistical learning. Springer, New York 607 p.

Krasniqi, F. 2013. Flora and vegetation of Kosova. In: Ismajli, R. & Kraja, M. (Eds.). Kosova: A monographic survey. Pp. 61–71. Kosova Academy of Sciences and Arts, Prishtina.

Kreft, H. & Jetz, W. 2010. A framework for delineating biogeographical regions based on species distributions. J. Biogeogr. 37(11): 2029–2053. doi: 10.1111/j.1365-2699.2010.02375.x

Kuhlemann, J., Milivojević, M., Krumrei, I. & Kubik, P.W. 2009. Last glaciation of the Šara Range (Balkan peninsula): Increasing dryness from the LGM to the Holocene. Aust. J. Earth Sci. 102(1): 146–158.

Liu, Y., Fu, B., Wang, S. & Zhao, W. 2018. Global ecological regionalization: from biogeography to ecosystem services. Curr. Opin. Env. Sust. 33(1): 1–8. doi: 10.1016/j.cosust.2018.02.002

Loidi, J. & Vynokurov, D. 2024. The biogeographical kingdoms and regions of the world. Mediterr Bot. 45(2), e92333. doi: 10.5209/mbot.92333

Loveland, T.R. & Merchant, J.M. 2004. Ecoregions and ecoregionalization: geographical and ecological perspectives. Environ. Manage. 34(S1): S1–S13. doi: 10.1007/s00267-003-5181-x

MacQueen, J. 1967. Some methods for classification and analysis of multivariate observations. In: Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, vol. 1, n. 14, Pp. 281–297. University of California Press.

Malatesta, L., Sanctis, M.D., Ammann, E., Attorre, F., Buffi, F., Cambria, V.E., Fratarcangeli, C., Hoda, P., Mahmutaj, E., Meco, M., Mullaj, A., Shuka, L. & Fanelli, G. 2023. Bioregionalization of Albania: mismatch between the flora and the climate suggests that our models of Southern European bioregions are in need of a revision. Folia Geobot. 58(1): 71–87. doi: 10.1007/s12224-023-09432-7

Matvejev, S. & Puncer, I. 1989. Map of biomes and regions of Yugoslavia and their protection. Natural History Museum in Belgrade 36: 1–76.

Matvejev, S.D. 1961. Biogeography of Yugoslavia – basic principles. Institute of Biology of the PR of Serbia, Belgrade. 232 p.

Mazel, F., Pennell, M.W., Cadotte, M.W., Diaz, S., Dalla Riva, G.V., Grenyer, R., et al. 2018. Prioritizing phylogenetic diversity captures functional diversity unreliably. J. Biogeogr. 45(9): 2169–2181. doi: 10.1111/jbi.13616

Médail, F. & Diadema, K. 2009. Glacial refugia influence plant diversity patterns in the Mediterranean Basin. J. Biogeogr. 36(7): 1333–1345. doi: 10.1111/j.1365-2699.2008.02051.x

Millaku, F., Krasniqi, E., Berisha, N., Rexhepi, F. 2016. Conservation assessment of the endemic plants from Kosovo. Hacquetia 16(1): 35–47. doi: 10.1515/hacq-2016-0024

Millaku, F., Rexhepi, F., Krasniqi, E., Abdullahu, K. & Mala, Xh. 2012. Mediterranean floristic element and its influence in the alliance Ostryo-Carpinion orientalis HT. 1954 in Kosovo. Bocconea. 24: 295–300.

Millaku, F., Rexhepi, F., Krasniqi, E., Pajazitaj, Q., Mala, Xh. & Berisha, N. 2013. The Red Book of vascular flora of the Republic of Kosovo. MESP, Prishtina. 435 p.

Morrone, J.J. 2018. The spectre of biogeographical regionalization. J. Biogeogr. 45(2): 282–288. doi: 10.1111/jbi.13135

Mucina, L., Bültmann, H., Dierßen, K., Theurillat, J.P., Raus, T., Čarni, A., Šumberová, K., Willner, W., Dengler, J., Gavilán, R.G., Chytrý, M., Hájek, M., Di Pietro, R., Iakushenko, D., Pallas, J., Daniëls, F.J., Bergmeier, E., Guerra, A.S., Ermakov, N. & Tichý, L. 2016. Vegetation of Europe: hierarchical floristic classification system of vascular plant, bryophyte, lichen, and algal communities. Appl. Veg. Sci. 19(S1): 3–264. doi: 10.1111/avsc.12257

Myers, A.A. & Giller, P.S. 2012. Analytical biogeography: an integrated approach to the study of animal and plant distributions. Springer, Dordrecht. 578 p.

Olson, D.M. & Dinerstein, E. 1998. The Global 200: a representation approach to conserving the Earth's most biologically valuable ecoregions. Conserv. Biol. 12(3): 502–515.

Ottaviani, G., Keppel, G., Götzenberger, L., Harrison, S., Opedal, Y.H., Conti, L. & Chytrý, M. 2020. Linking plant functional ecology to island biogeography. Trends Plant Sci. 25(4): 329–339. doi: 10.1016/j.tplants.2019.12.022

Parenti, L.R. & Humphries, C.J. 2004. Historical biogeography, the natural science. Taxon. 53(4): 899–903. doi: 10.2307/4135556

Parenti, L. & Ebach, M. 2009. Comparative biogeography: discovering and classifying biogeographical patterns of a dynamic Earth. University of California Press, Berkeley.

Peneva E, Matov M, Tsekov M. 2023. Mediterranean influence on the climatic regime over the Balkan Peninsula from 1901–2021. Climate 11(3): 68. doi: 10.3390/cli11030068

Pllana, R. 2015. The climate of Kosovo. Prishtina: Kosovo Academy of Sciences and Arts. 320 p.

Pruthi, V. 2013. Morphological and pedological features of Kosova. In: Ismajli, R. & Kraja, M. (Eds.). Kosova: a monographic survey. Pp. 35–

39. Kosova Academy of Sciences and Arts, Prishtina.
Quézel, P. & Médail, F. 2003. Ecologie et biogéographie des forêts du bassin méditerranéen. Elsevier, Paris. 571 p.
Ramshaj, Q, Rusevska, K., Tofilovska, S. & Karadelev, M. 2021. Checklist of macrofungi from oak forests in the Republic of Kosovo. Czech Mycology 73(1): 21–42. doi: 10.33585/cmy.73102
Rexhepi, F. 1994. The vegetation of Kosovo, vol. 1. Faculty of Mathematics and Natural Sciences, University of Prishtina, Prishtina. 161 p.
Rueda, M., Rodríguez, M. & Hawkins, B.A. 2010. Towards a biogeographic regionalization of the European biota. J. Biogeogr. 37(11): 2067–2076. doi: 10.1111/j.1365-2699.2010.02388.x
Stevanović, V. 2022. Biogeographical characteristics of the territory of Serbia: richness and spatial distribution of biodiversity, endemism and biogeographical regionalization. In: Manić, E., Nikitović, V. & Djurović, P. (Eds.). The geography of Serbia. Springer, Cham. doi: 10.1007/978-3-030-74701-5_8
Veselaj, Z. & Mustafa, B. 2015. Overview of nature protection progress in Kosovo. Landsc Online. 45: 1–10. doi: 10.3097/lo.201545
Wang, R., Kass, J.M., Chaudhary, C., Economo, E.P. & Guénard, B. 2024. Global biogeographic regions for ants have complex relationships with those for plants and tetrapods. Nature Communications 15(1). doi: 10.1038/s41467-024-49918-2
Wehrens, R., Buydens, L.M.C. 2007. Self- and super-organizing maps INR: TheKohonenPackage. J. Stat. Softw. 21(5). doi: 10.18637/jss.v021.i05
Ye, F., Shi, G. & Bitner, M. 2021. Global biogeography of living brachiopods: bioregionalization patterns and possible controls. PLoS One. 16(11): e0259004. doi: 10.1371/journal.pone.0259004
Ye, J.F., Liu, Y. & Chen, Z.D. 2020. Dramatic impact of metric choice on biogeographical regionalization. Plant Divers. 42(2): 67–73. doi: 10.1016/j.pld.2019.12.003
Yessoufou K, Daru BH, Tafirei R, Elansary HO, Rampedi I. 2017. Integrating biogeography, threat and evolutionary data to explore extinction crisis in the taxonomic group of cycads. Ecol. Evol. 7(8): 2735–2746. doi: 10.1002/ece3.2660

Websites

EEA. 2017. Biogeographical regions in Europe [Internet]. [Accessed 2024 Sep 9]. Available from: https://www.eea.europa.eu/en/analysis/maps-and-charts/biogeographical-regions-in-europe-2
KAEP. 2016. Study report for determination of biogeographical regions in Kosovo. Prishtina: Kosovo Institute for Nature Protection, Kosovo Agency for Environmental Protection (KEPA). 21 p. https://www.ammk-rks.net/assets/cms/uploads/files/Raporti%20per%20gjendjen%20e%20natyres%202018-%202021%20_ANG.pdf

Supplementary material

Figure S1. Simplified geological map of Kosovo (after Independent Commission for Mines and Minerals (2006).
Figure S2. Relief map of Kosovo showing altitude variation in meters above sea level.
Figure S3. Slope map of Kosovo showing terrain steepness represented in degrees.
Figure S4. Map of Kosovo showing annual rainfall distribution (in millimeters).
Figure S5. Map of Kosovo showing annual average air temperature (in degrees Celsius).