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Population dynamics, threat assessment, and conservation strategies for critically endangered *Meconopsis aculeata* in alpine zone

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Abstract

Background The Himalayan alpine zone harbors a rich diversity of endemic medicinal plant species, such as *Meconopsis aculeata*, due to its habitat heterogeneity. Globally, alpine environments are most significantly affected by climate change, characterized by low temperatures and restricted growing seasons, offering essential services yet remaining most vulnerable. *M. aculeata* holds immense ecological significance in alpine ecosystems, while human disturbances and climate change pose serious threats to its long-term viability. The present study was conducted to explore population ecology, spatial distribution patterns, significant threats, diversity patterns along elevational gradients, and future conservation strategies for the dwindling populations of *M. aculeata*.

Methods Field sampling was carried out from 2022 to 2024 in various districts of Kashmir to examine the vegetation characteristics of *M. aculeata* populations, along with the geographic variables and threats impacting these populations. The quadrat method was used to investigate the vegetation characteristics across an extensive elevational gradient, ranging from 3000 m to 4600 m.

Results Healthier *M. aculeata* populations were found in the middle elevational range of 3700 m to 4100 m. The SIMPER analysis revealed an overall average dissimilarity of 80.08, indicating spatial variability in species composition across the studied sites. GIS analysis showed that *M. aculeata* was found on the north aspect, with steppe slope in rocky habitat. The average herb density was calculated to be 20.6/ha, while 60% of sampled sites experienced intense grazing. A total of 20 indicator species were identified as associated with *M. aculeata* populations. Mantel tests identified key species influencing the population structure of *M. aculeata*. *Aconitum heterophyllum* ($R = 0.7954$, $P = 0.003$) was found to be the most critical indicator species, followed by *Anaphalis nepalensis* ($R = 0.6564$, $P = 0.034$), and *Bistorta affinis* ($R = 0.522$, $P = 0.044$). CCA analysis identified NTFP extraction, grazing and fire as serious threats for the sustainability of *M. aculeata* populations. Alpha diversity results highlight significant altitudinal influences on the

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diversity metrics of *M. aculeata* populations. Beta diversity results indicate that Site 8 exhibited substantial differences in species composition compared to other sites, while Sites 1 and 9 highlighted the spatial heterogeneity within the *M. aculeata* populations. As this species is already classified as a critically endangered species, we recommend implementing effective conservation measures such as habitat restoration, sustainable harvesting practices, involving local communities, and promoting stewardship. These initiatives will encourage sustainable management of the species in the region.

Clinical trial number Not applicable.

Keywords Biodiversity hotspot, Climate change, Endemic, Diversity patterns, Kashmir, Sustainable management

Introduction

Climate change poses a significant threat to biodiversity, causing alterations in the function, structure, and composition of ecosystems worldwide [1]. Climate change is a reality, as evidenced by various phenomena, such as shifting tree lines, melting glaciers, the greening of alpine tundra, and the encroachment of shrubby vegetation into the alpine zone [2, 3]. Mountainous regions around the world vary in topography, elevation, and biodiversity because of their distinct climates and geographical locations [4, 5]. Plant biodiversity plays a significant role in climate regulation, ecosystem stability, and providing valuable services to humans [6]; however, it is severely threatened by anthropogenic activities and climate change over the past decades [7]. Climate variables with non-climate factors such as soil, land use, and topography govern the distribution patterns of plant species [8, 9]. Alpine plant geographical distributions are particularly sensitive to interactions between climate and topography [10]. Furthermore, anthropogenic activities in mountainous landscapes exacerbate the effects of climate change, leading to habitat fragmentation and an increased spread of invasive species, both of which contribute to biodiversity loss [11].

In mountainous landscapes, alpine ecosystems are particularly vulnerable to climate change because they harbor plant diversity and endemic species [12, 13]. Alpine plant species face shorter growing seasons due to low temperatures [14] and have adopted extreme environmental conditions, while their distribution patterns are primarily influenced by climatic factors [15]. Ongoing climate change has accelerated species richness on alpine mountain summits [16, 17]. Globally, plant species are expected to migrate to higher altitudes and poles [18]. However, some species exhibit multidirectional movements on a smaller scale due to environmental changes, such as habitat modifications, temperature fluctuations, and abrupt shifts in precipitation patterns. These factors prompt species to move at the local or microhabitat level [19]. Additionally, the dispersal capacity of alpine species is vital for adapting to future climate change; various species in this zone display limited seed dispersal abilities, which hinder their movement over long distances [20].

Generally, alpine plant species are characterized by a narrow geographic distribution and exhibit a high level of endemism, making them particularly sensitive to the impacts of climate change [21, 22]. Cold-adapted species at higher elevations are mainly confined to the nival and subnival zones of mountain summits, while species from lower elevations, which are better adapted to warmer climates, encroach on their habitats [23, 24]. *Meconopsis* is a crucial plant species for alpine ecosystems, with a narrow distribution range in upper temperate forests and alpine grasslands [25]. This genus is essential for regional biodiversity and significantly contributes to primary production, which is vital for the dynamics of alpine ecosystems [26]. Due to their narrow distribution range and limited pollinators at higher elevations, *Meconopsis* species are more susceptible to climate change. This makes them an ideal subject to investigation in the era of global change within the biodiversity hotspot region.

The genus *Meconopsis*, commonly known as blue poppies, belongs to the family Papaveraceae and contains more than 70 species [27]. This genus is renowned for its bright, elegant flowers, making it popular in ornamental horticulture [28]. Despite thriving in harsh environmental conditions, *Meconopsis* blooms beautifully, symbolizing resilience in the face of adversity [29] (Fig. 1). *Meconopsis aculeata* Royle, also part of the Papaveraceae family, is an endemic and endangered medicinal plant that typically grows on damp rocks in the alpine zone of the Himalayas [30, 31]. *M. aculeata* is confined to a narrow distribution range between 3000 m and 4700 m in the Tibet, Hindu Kush region, and western Himalayas [30]. This species contains a variety of bioactive compounds, including flavonoids, phenolics, tannins, and alkaloids, which are used for the treatment of various diseases [32–34]. However, ongoing climate change increases their vulnerability within various alpine ecosystems [15], threatening species that hold economic and medicinal importance [35–37]. The Himalayan alpine region exhibits a high level of plant diversity compared to the global alpine zone [38]. Additionally, this biodiversity hotspot is more vulnerable to climate change, which threatens its long-term sustainability [39]. Research on these high-altitude alpine ecosystems has been insufficient, leading

Fig. 1 Field photographs of *M. aculeata*

to a lack of comprehensive data [40]. Understanding the impacts of climate change and population pressures is essential for the conservation of alpine plant species, particularly those that are endemic and endangered. The primary objectives of this study were: (1) to examine the spatial distribution patterns of *M. aculeata* across the Kashmir region, using comprehensive field surveys and GIS analysis; (2) to identify and quantify the key anthropogenic and environmental threats affecting the viability of *M. aculeata* populations; (3) to assess how altitudinal gradients influence the associated floral diversity patterns of *M. aculeata* populations; and (4) to develop targeted conservation strategies for the sustainable management and long-term conservation of *M. aculeata* in the western Himalayan alpine ecosystems.

Materials and methods

Study area

Azad Jammu and Kashmir (AJK) is located in the mountainous region of the western Himalayas, covering an area of 13,297 km^2 between 33°-36° North latitude and 73°-75° East longitude. The landscape of AJK is primarily characterized by mountainous features, with terraces and sharp, curved valleys carved by numerous streams and rivers. The predominant alignment of the ridges and valleys runs from southeast to northwest, reflecting the geological layers beneath. AJK is recognized as a biodiversity hotspot and contains a diverse range of agro-climatic conditions and habitats, owing to its substantial elevational range, which varies from 488 m in the southern areas adjacent to the Punjab Plains to 6325 m in the north. This region exhibits a unique and diverse vegetation landscape, influenced by topographical variations and elevational differences. The alpine vegetation zone begins at elevations above 3000 m, and is predominantly characterized by herbaceous plants. Alpine regions experience extreme cold conditions, with significant snowfall during the winter season (October to March), resulting in snow-covered landscapes. The growing season in the alpine zone is brief, lasting only four months (June to September), with summer temperatures averaging between 0 and 10 °C. The region receives an annual rainfall of 1100–1300 mm, and its porous soil, with a pH value of 5.35–7.2, is vulnerable to erosion [41].

Sampling methodology

Sampling sites were identified in the alpine zone between 3000 m and 4600 m to explore the population structure of *M. aculeata* in the western Himalayan region of AJK. The sampling process began with an extensive preliminary survey in the alpine zone of AJK to locate *M. aculeata* populations. This survey led to the selection of 10 sites across 3 of 10 districts, including Muzaffarabad, Hattian, and Neelum Valley, ensuring broad geographic representation of the species (Fig. 2). Field visits were conducted between July and September 2022–2023 to assess the structural characteristics, associated flora, and vegetation features of *M. aculeata* in the region. A systematic quadrat-based approach was employed, with 30 quadrates established at each site, using a quadrat size of 25 m^2 (5 m ×5 m) for shrubs and 1 m^2 (1 m × 1 m) for herbaceous vegetation. At each site, quadrats were established to document the vegetation structure, habitat geography, and microclimates. The primary vegetation data of *M. aculeata* populations were recorded along with associated flora, following established phytosociological protocols. All the plants were identified by Dr. Mushtaq Ahmad, and specimens were submitted to the Herbarium of Pakistan (ISL) at Quaid-i-Azam University in Islamabad, Pakistan. Furthermore, geographic attributes, including elevation, aspect, latitude, and longitude, were assessed using a GPS system, and the slope gradient was measured using a clinometer.

GIS mapping

Remote sensing is essential for studying species distribution patterns. The GIS database was constructed using Russian maps at a 1/10,000 scale, while ArcGIS software was employed to map the *M. aculeata* sites in the western Himalayan region of Kashmir. Data were exported into Geo-TIFF format and tiled using Arc View GIS software. After creating the species inventory map, the boundaries of AJK districts were digitized using Arc Map software. The GIS inventory map was generated with Arc Map 10.8, which incorporated data from 300 plots in the study area. Reference points at each site were determined using the WGS 1984 coordinate system. Additionally, an elevation map of the study area, providing terrain measurements, was constructed using STRM DEM.

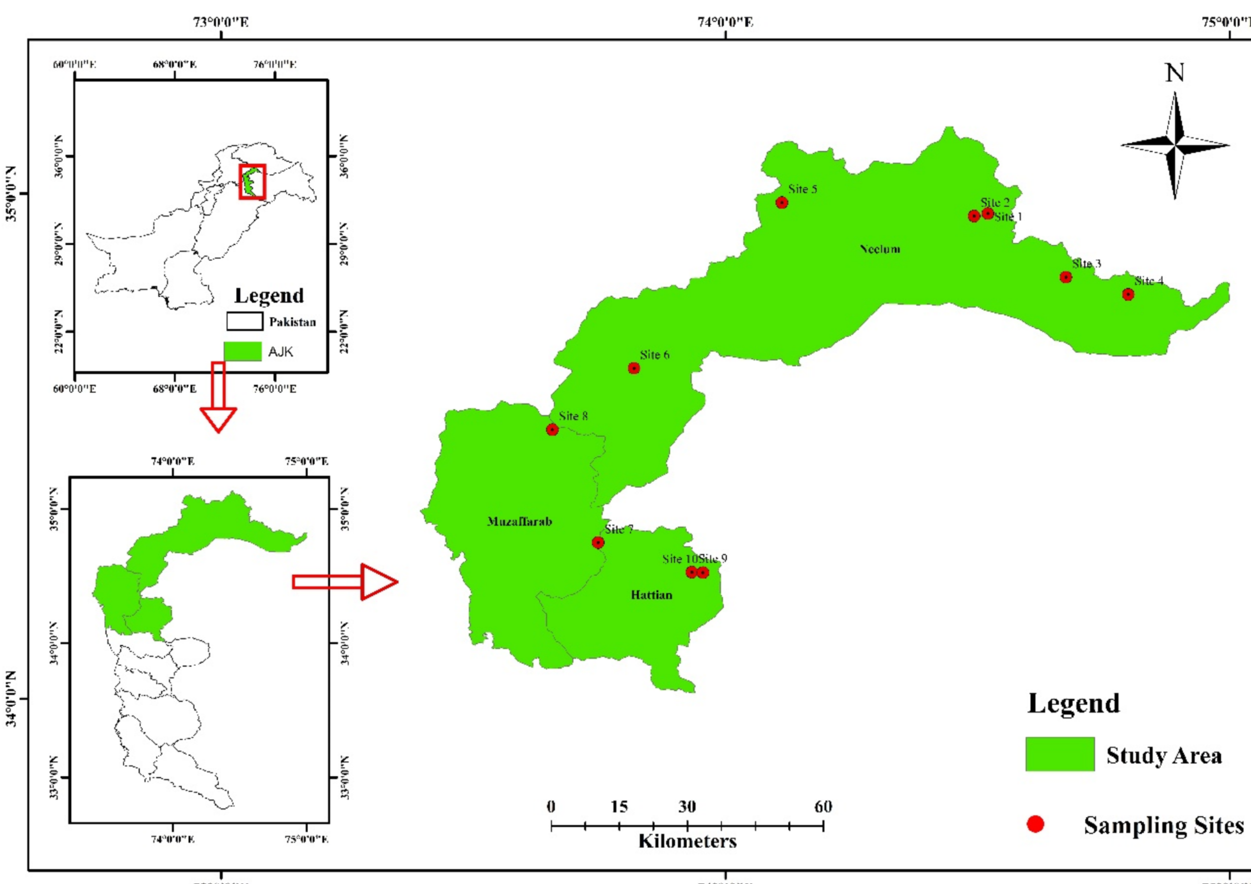

Fig. 2 Study area map showing the locations of *M. aculeata* sampling sites in the western Himalayan region of Kashmir

Disturbance Indicator

The influence of anthropogenic activities was investigated in the study area. Grazing intensity was assessed by using visual indicators, including hoof marks, trampling, browsed vegetation, bare surfaces, and animal droppings [15]. Erosion intensity was also evaluated through visual indicators by observing the soil surface, which was classified as controlled (soil surface with little to no erosion), moderate erosion (soil surface with topsoil erosion), and intense erosion (soil surface with severe erosion) [42].

Data analysis

To investigate the population dynamics and ecological associations of *M. aculeata* across the study sites, several statistical analyses were conducted using specialized software and packages. The indicator species analysis was performed using PAST software (v4.10) [43]. Indicator values were calculated to assess the strength of the association between species and specific environmental conditions across sampling sites [44]. SIMPER analysis was performed using PAST software, employing the Bray-Curtis distance matrix to quantify the contribution of individual taxa to the overall dissimilarity in species composition across the study sites, thereby identifying key species driving spatial variability. The Mantel test was conducted in R using the linkET package. This test was employed to assess the correlation between the indicator species composition and the *M. aculeata* population. Canonical Correspondence Analysis (CCA) was performed using CANOCO software (v5.12) to explore the relationships between *M. aculeata* populations and anthropogenic threats [45]. CCA is a multivariate ordination technique that allows for the simultaneous examination of species-environment interactions. The CCA biplot provided visual representation of the species-environment relationships, with arrows indicating the direction and strength of each environmental gradient. Eigenvalues and pseudo-canonical correlations were used to assess the significance of the axes, and permutation tests (999 iterations) were conducted to evaluate the statistical significance of the model. Beta diversity was assessed using the betapart package in R to understand the spatial variation in species composition across different elevational gradients [46]. Alpha diversity indices (Simpson, Shannon, and Evenness) were calculated for each site to assess within-site species diversity. These indices were visualized along the elevational gradient, revealing trends in species richness and distribution patterns. The diversity indices were analyzed using descriptive statistics and visualized using ggplot2 in R [47], providing a comprehensive understanding of the diversity patterns of *M. aculeata* across different elevations.

Results

Geographic Analysis of *M. aculeata*

A digital elevation model (DEM) was utilized to analyze the distribution patterns of *M. aculeata* populations in the western Himalayan region of Kashmir. The study found that 50% of populations occurred within the elevational range of 3000 m to 4000 m, while the remaining 50% were located above 4000 m (Fig. 3A). Aspect analysis indicated that the majority of *M. aculeata* populations were concentrated on the north aspect of the study area (Fig. 3B). Additionally, 20% of the populations were recorded on the southeast aspect and 10% on the northeast aspect, respectively. Slope analysis offered insights into the habitat preference of *M. aculeata*, revealing that 40% of the populations were situated on steep slopes, 30% on moderate slopes, 20% on plateau slopes, and 10% on flat slopes (Fig. 3C). The studied populations of *M. aculeata* at different sites showed an average herb density value of 20.6, with a maximum of 42/ha and a minimum of 7/ha (Fig. 3D). Erosion analysis indicated that 50% of sites were moderately eroded, whereas 30% had controlled erosion and 20% had as intense erosion (Fig. 3E). Grazing analysis showed that 60% of *M. aculeata* sites experienced intense grazing intensity, 30% had moderate grazing intensity, and 10% had controlled grazing intensity (Fig. 3F).

Species composition and Spatial variability

The research conducted an extensive botanical survey, documenting 161 plant species from 102 genera and 44 families. Compositae family was identified as the dominant family with 21 species, followed by Ranunculaceae (13 species), Poaceae (12 species), Rosaceae (11 species), Apiaceae (8 species), and Lamiaceae (7 species). The Leguminosae and Polygonaceae families each had 6 species recorded, while the Balsaminaceae family had 5 species. Additionally, 4 species were recorded for each of the following families; Adoxaceae, Boraginaceae, Caryophyllaceae, Dryopteridaceae, and Orobanchaceae. Furthermore, 13 families were noted for contributing single taxa. The species diversity results indicated that the studied communities were predominately composed of herbs, which included a total of 146 species, accounting for 90.68% of the diversity. This was followed by shrubs, with 8 species representing 4.97%, and ferns, with 7 species making up 4.35% of the total diversity across all studied communities (Supplementary Table 1).

The SIMPER analysis revealed an overall average dissimilarity of 80.08 among the sites. The taxa contributing most to this dissimilarity were *Rosa webbiana*,*Potentilla atrosanguinea*,*Bistorta affinis*, and *Rosa pendulina*, with contributions of 4.12%, 3.16%, 3.08%, and 3.05%, respectively, cumulatively accounting for over 13% of the dissimilarity. *Rosa webbiana*, for example, had a mean

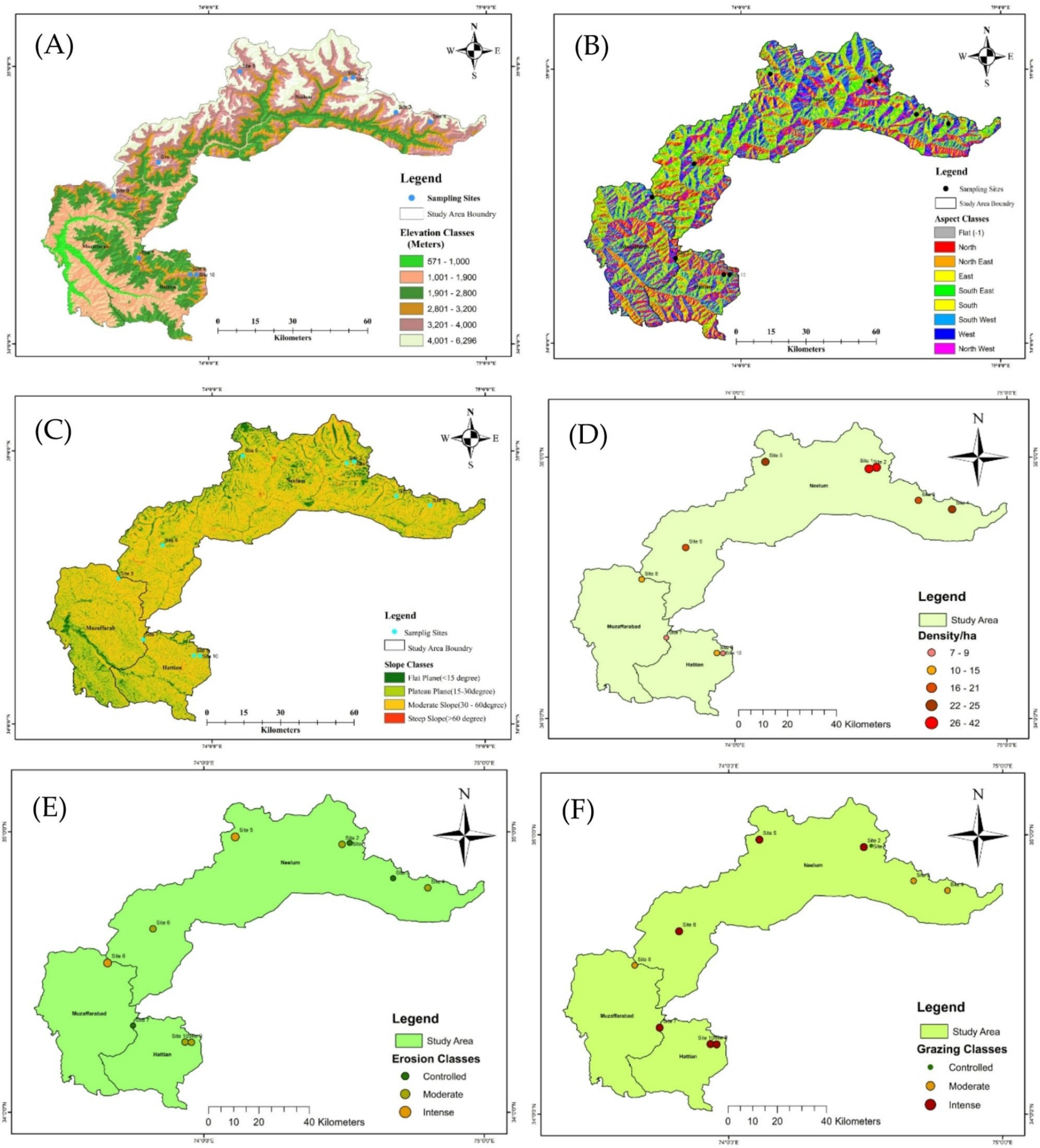

Fig. 3 GIS map representing (**a**) Digital Elevation Model (DEM), (**b**) Aspect, (**c**) Slope, (**d**) *M. aculeata* Density/ha, (**e**) Erosion intensity, and (**f**) grazing intensity

abundance of 32.2 at Site 1 and 43.9 at Site 6, while it was absent in several other sites, highlighting its uneven distribution. Similarly, *Potentilla atrosanguinea* was present in Site 1 with a mean of 27.1 and in Site 5 with a mean of 36. *Bistorta affinis* showed notable presence in Sites 7, 8, and 10, with means of 19.7, 26.6, and 38.1, respectively. Other significant contributors included *Aconitum heterophyllum,Salix flabellaris*, and *Aster alpinus*, contributing between 2.25% and 2.54% each, reflecting varied abundances across different sites. For instance, *Aconitum heterophyllum* showed a mean of 32.1 at Site 10 and was absent in several other sites (Supplementary Table 2). These findings indicate significant spatial variability in species composition across the sites, underlining the heterogeneity in the ecological characteristics of the studied areas.

Indicator species associated with *M. aculeata* population

A total of 20 significant indicator species are associated with the *Meconopsis aculeata* population. These incudes *Aconitum heterophyllum,Anaphalis nepalensis,Aster alpinus,Bergenia ciliata,Berberis pachyacantha,Bergenia stracheyi,Bistorta affinis,Bupleurum falcatum,Lilium polyphyllum,Panicum turgidum,Poa trivialis,Potentilla atrosanguinea,Primula rosea,Rosa pendulina,Rosa webbiana,Salix flabellaris,Syringa emodi,Tanacetum dolichophyllum,Viburnum grandiflorum*, and *Viola pilosa*. Several species were found to be significant indicators at multiple sites. Specifically, *Aconitum heterophyllum* was found at Sites 1 and 10, and *Salix flabellaris* at Sites 3 and 4. *Potentilla atrosanguinea* and *Rosa pendulina* were each present at Sites 1 and 2, and Sites 2 and 4, respectively. *Meconopsis aculeata* was notable for its occurrence across three sites: Sites 2, 6, and 9. Lastly, *Bistorta affinis* was identified at four sites, specifically Sites 4 and 10. This distribution of indicator species highlights the varied ecological associations of *M. aculeata* across different habitats (Fig. 4).

Association of Indicator species with *M. aculeata*

Mantel tests were employed to identify key indicator species influencing the population structure of *Meconopsis aculeata* across 10 sites. The analysis revealed that *Aconitum heterophyllum* ($R = 0.7954$, $P = 0.003$) was the most critical indicator species, individually explaining significant variation in the *Meconopsis aculeata* community composition. This was followed by *Anaphalis nepalensis* ($R = 0.6564$, $P = 0.034$), *Bistorta affinis* ($R = 0.522$, $P = 0.044$), and *Tanacetum dolichophyllum* ($R = 0.348$, $P = 0.043$) (Fig. 5). Pearson correlation analysis further identified positive correlations between *Aconitum heterophyllum* and species such as *Anaphalis nepalensis,Aster alpinus,Bistorta affinis,Panicum turgidum*, and *Primula rosea*. Similarly, Ana nep exhibited positive correlations with *Aster alpinus,Bergenia ciliata,Bergenia stracheyi,Bistorta affinis,Primula rosea*, and *Viola pilosa*. Notably, *Aster alpinus* showed positive correlations with *Bergenia ciliata,Bergenia stracheyi,Primula rosea,Rosa pendulina,Salix flabellaris,Tanacetum dolichophyllum*, and *Viburnum grandiflorum*. Conversely, *Aconitum heterophyllum* displayed negative correlations with species including *Aster alpinus,Bergenia ciliata,Berberis pachyacantha,Bergenia stracheyi,Bupleurum falcatum,Panicum turgidum,Poa trivialis,Potentilla atrosanguinea,Rosa webbiana,Salix flabellaris,Syringa emodi*, and *Viola pilosa*. These findings highlight the complex interspecies interactions that shape the *Meconopsis aculeata* population structure across the studied sites.

Threats to Meconopsis aculeata and associated indicator species

Canonical Correspondence Analysis (CCA) was employed to explore the ecological relationships between *M. aculeata* populations and indicator species under various environmental threats. The constrained analysis revealed a total variation of 3.43841, with explanatory variables accounting for 80.9% of this variation (adjusted explained variation of 13.9%). Eigenvalues for Axis 1, Axis 2, and Axis 3 indicated substantial variation explained by the model, with cumulative explained variations of 15.27%, 29.85%, and 42.59%, respectively (Fig. 6). High pseudo-canonical correlations across these axes (0.9927, 0.9996, and 0.9936 for Axis 1, Axis 2, and Axis 3) indicated strong associations between environmental variables and species composition (Tables 1 and 2). Fire, erosion, and extraction of non-timber forest products (NTFPs) emerged as significant explanatory variables, contributing 13.3%, 13%, and 11.9% to the explained variation, respectively, with varying degrees of statistical significance as shown by pseudo-F values and probabilities (P). Conversely, trampling, grazing, and nomadic settlements exhibited lower explanatory power and lesser significance in shaping species composition. Further analysis through conditional term effects reaffirmed the influence of fire, erosion, and NTFP extraction on *Meconopsis aculeata* distribution patterns, highlighting their robust associations with observed species-environment relationships. However, nomadic settlements, trampling, grazing, and slope showed reduced influence under the conditional framework, suggesting nuanced interactions with other environmental factors not fully captured in this study.

Impact of altitude on alpha diversity

The diversity indices for *Meconopsis aculeata* populations across different sites revealed specific altitudinal variations. Number of Species exhibited a decreasing trend with increasing altitude, with the highest count observed at Site 8 (3320 m) and the lowest at Site 10 (3510 m). Linear regression analysis confirmed a significant negative correlation between species count and altitude ($R^2 = 0.9593$, $p < 0.0001$). The Simpson Diversity Index was highest at Site 4 (3834 m) with a value of 0.97 and lowest at Site 9 (3489 m) and Site 10 (3510 m), both with a value of 0.92. Regression analysis revealed a significant positive correlation between altitude and the Simpson Diversity Index ($R^2 = 0.9701$, $p < 0.0001$). The Shannon Diversity Index peaked at Site 7 (3406 m) with a value of 3.42, while it was lowest at Site 3 (3981 m) with a value of 2.82. A significant positive correlation was found between

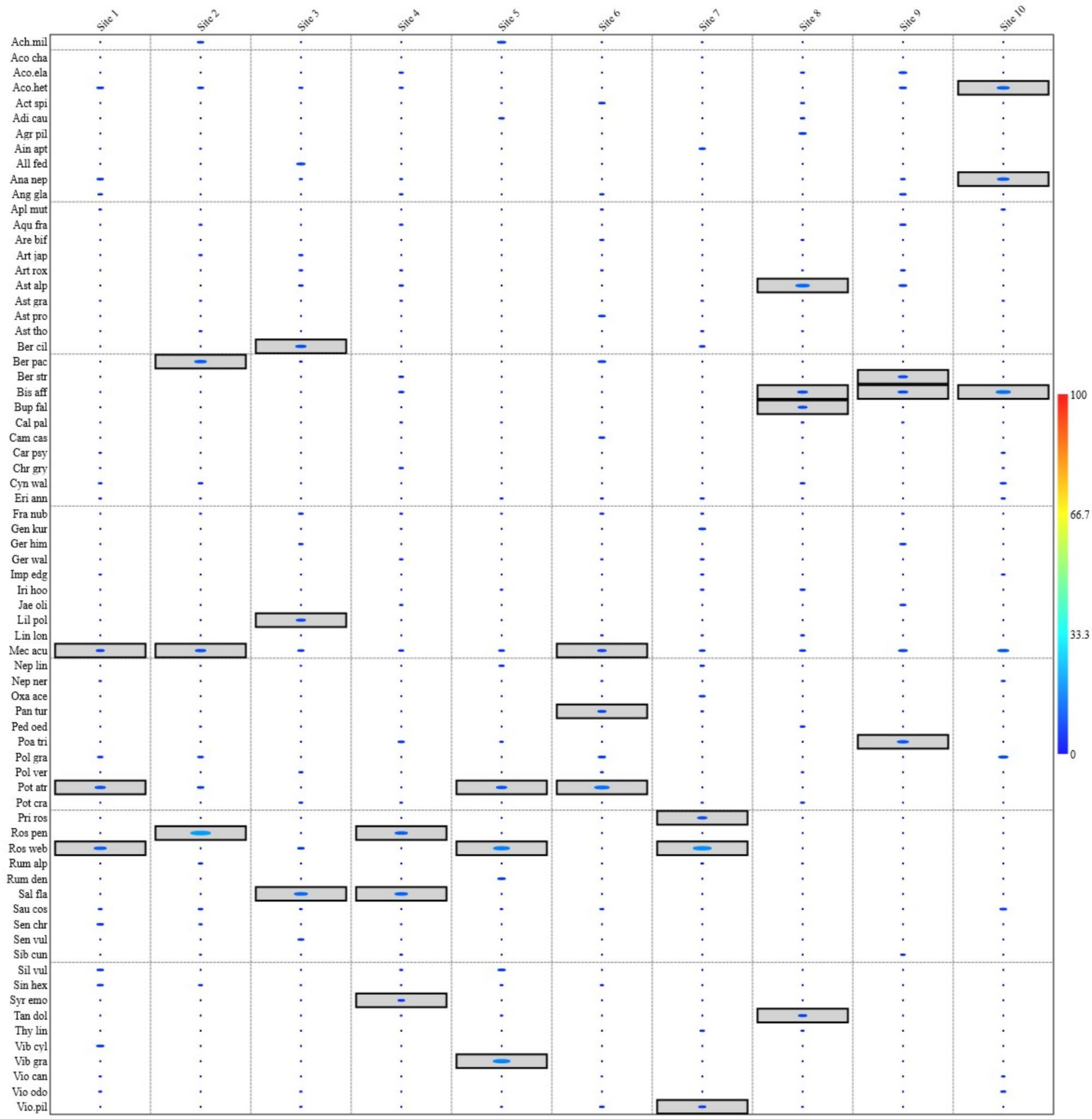

Fig. 4 Heatmap of indicator species across sampling sites (Site 1 to Site 10) for *Meconopsis aculeata* populations in the western Himalayan region. The presence and abundance of key indicator species are represented by intensity levels on a gradient scale (0 to 100). Black bars indicate the relative dominance of species across different sites, highlighting spatial variability and site-specific associations. The color gradient (blue to red) reflects the abundance range, with red indicating higher presence

Shannon Index and altitude ($R^2 = 0.9713$, $p < 0.0001$). Species Evenness was greatest at Site 4 (3834 m) with a value of 1.07 and lowest at Site 8 (3320 m) with a value of 0.74. Statistical analysis confirmed a significant increasing trend in species evenness with altitude ($R^2 = 0.9915$, $p < 0.0001$). These results highlight significant altitudinal influences on the diversity metrics of *Meconopsis aculeata* populations (Fig. 7).

Beta diversity pattern

Beta diversity analysis between various sites for *Meconopsis aculeata* populations revealed notable variations in species composition. The beta.sim index, which measures species turnover, indicated the highest dissimilarity between Site 8 and Site 1 (0.9118) and the lowest between Site 1 and Site 10 (0.0435). The beta.sne index, which quantifies nestedness, showed minimal

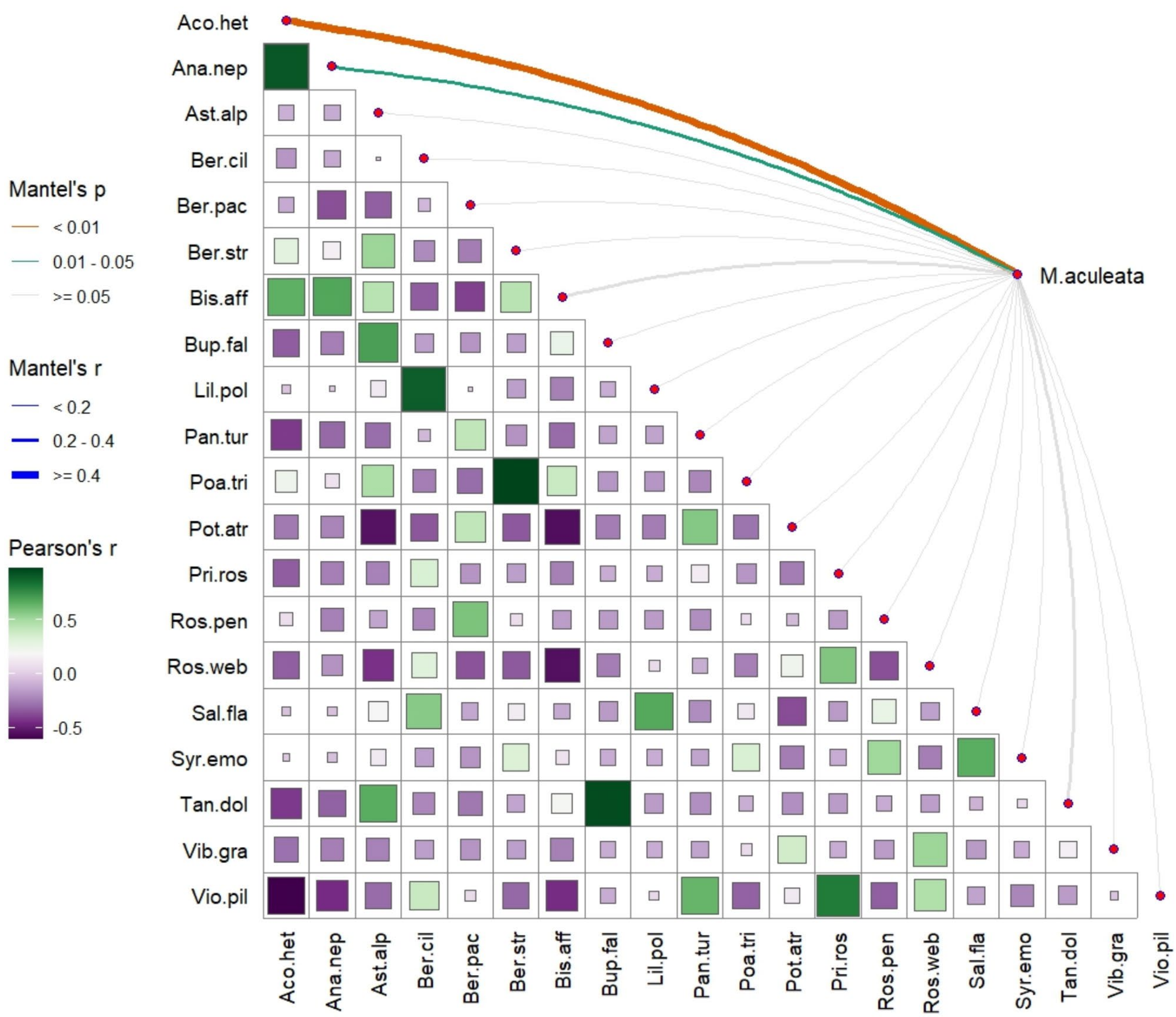

Fig. 5 Mantel test analysis illustrating the correlations between *M. aculeata* and associated indicator species. The matrix displays Pearson's r values (color gradient from green to purple) indicating positive and negative correlations. Significant Mantel's test p-values are represented by line colors: orange ($p < 0.01$), green ($0.01 < p < 0.05$), and gray ($p \geq 0.05$). The width of the lines indicates the strength of correlation (Mantel's r), with thicker lines showing stronger associations

values between most sites, with the highest dissimilarity observed between Site 9 and Site 4 (0.1349) and the lowest between Site 6 and Site 4 (0.0000). The beta.sor index, which combines turnover and nestedness, revealed that Site 8 and Site 1 exhibited the greatest dissimilarity (0.9277), while Site 1 and Site 10 had the least dissimilarity (0.2281). These results suggest that Site 8 consistently displayed the highest beta diversity, reflecting substantial differences in species composition compared to other sites, particularly Site 1 and Site 9, highlighting the spatial heterogeneity within the *Meconopsis aculeata* populations (Fig. 8).

Discussion

Meconopsis aculeata, a critically endangered species of Himalayan alpine zone ecosystems, is crucial to conservation due to its ecological importance and medicinal properties used for the cure of various ailments [30]. The current study provides valuable insights on *M. aculeata* populations in the western Himalayan region, exploring spatial distribution, population dynamics, quantifying the key anthropogenic and environmental threats, and diversity patterns along elevational gradients in Kashmir.

In the era of ongoing climate change, GIS mapping of endemic plant species can be crucial for sustainable management and habitat conservation of threatened *M. aculeata* species in future [48]. GIS analysis revealed that

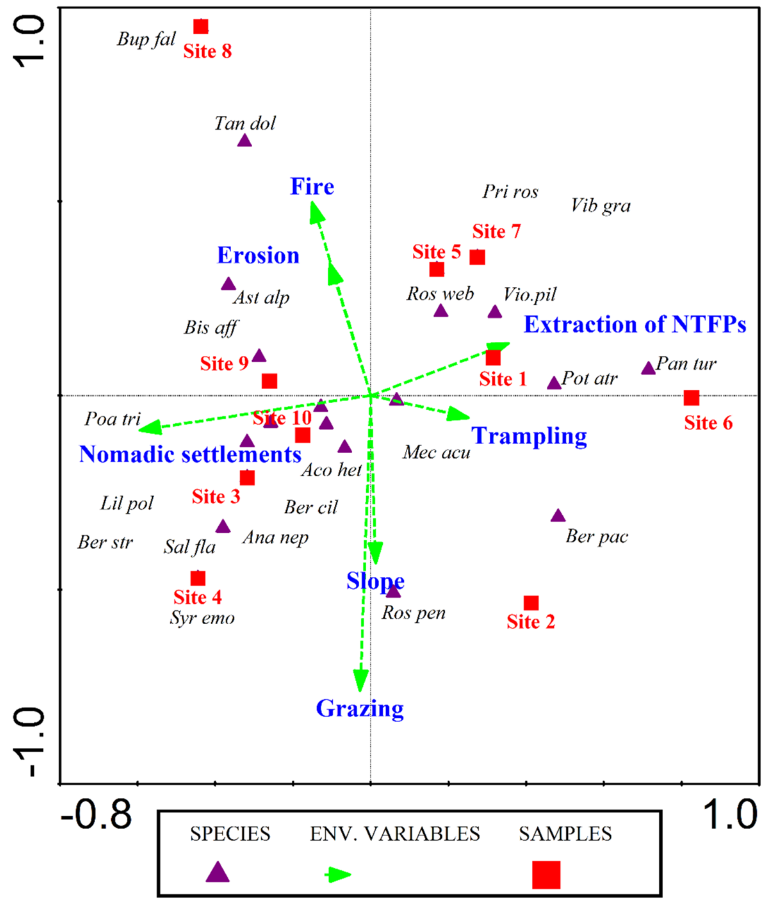

Fig. 6 Canonical Correspondence Analysis (CCA) biplot illustrating the relationships between *M. aculeata* populations, environmental variables, and associated indicator species across sampling sites. Red squares represent sampled sites, purple triangles indicate indicator species, and green arrows denote environmental variables. The direction and length of the arrows indicate the influence of environmental factors

Table 1 Summary statistics of canonical correspondence analysis (CCA) results. Eigenvalues and explained variation for each axis indicate the strength of the relationships between species composition and environmental variables

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.5252	0.5011	0.4382	0.4083
Explained variation (cumulative)	15.27	29.85	42.59	54.47
Pseudo-canonical correlation	0.9927	0.9996	0.9936	1
Explained fitted variation (cumulative)	18.89	36.91	52.68	67.36

Table 2 Effects of environmental variables on species composition based on simple and conditional terms in CCA. The table presents the percentage of explained variation, pseudo-F statistics, and p-values for each environmental variable

Simple Term Effects:			
Name	Explains %	pseudo-F	P
Fire	13.3	1.2	0.003
Erosion	13	1.2	0.034
Extraction of NTFPs	11.9	1.1	0.042
Trampling	11.2	1	0.378
Grazing	10.6	0.9	0.6
Nomadic settlements	10.2	0.9	0.692
Slope	10.2	0.9	0.744
Conditional Term Effects:			
Name	Explains %	pseudo-F	P
Fire	13.3	1.2	0.003
Erosion	12.7	1.2	0.036
Extraction of NTFPs	12	1.2	0.042
Nomadic settlements	10.6	1	0.478
Trampling	10.6	1	0.464
Grazing	9.8	0.9	0.51
Slope	11.9	1.2	0.356

M. aculeata populations were confined to the northern aspect, on rocky habitat with steep slopes. We recorded a very low herb density of *M. aculeata* species with an average value of 20.6/ha. Due to the unavailability of modern medications and the remoteness of the area, local populations utilized *M. aculeata* species for treatment of various diseases. *M. aculeata* is a highly medicinal plant that contains a variety of bioactive compounds and is a good source of natural antioxidants. It is used for the curative purposes of eye problems, pregnancy, bone fractures, chronic pain, stomachaches, backaches, narcotics, kidney problems, etc [32, 49, 50]. Overexploitation

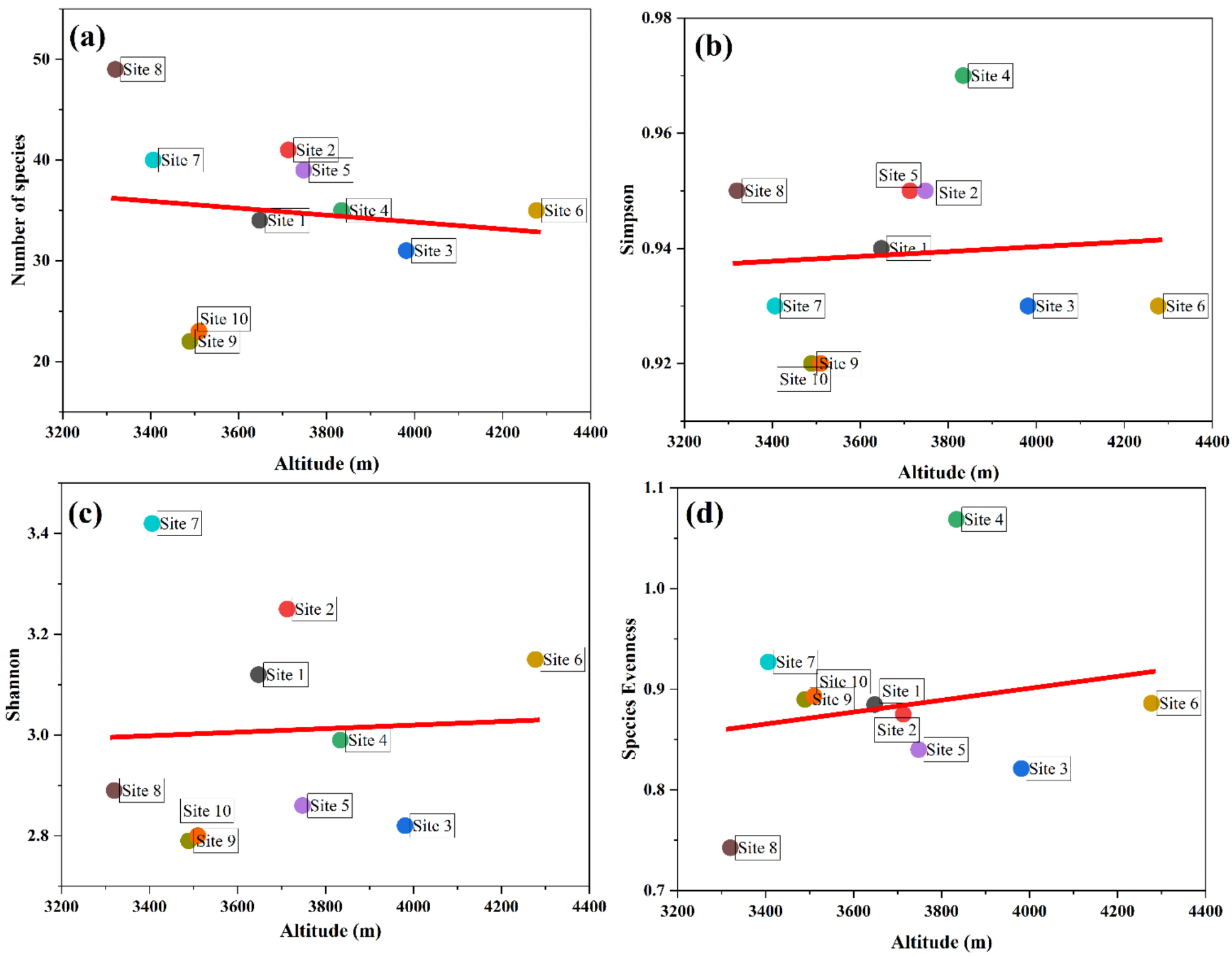

Fig. 7 Diversity patterns of *M. aculeata* populations along an elevational gradient in the western Himalayan region. (**a**) Number of species shows higher species dominance at mid-elevations, indicating optimal habitat conditions. (**b**) Simpson Diversity Index reveals increased species richness at mid-elevations, reflecting favorable ecological niches. (**c**) Shannon Diversity Index indicates greater uniformity in species distribution at higher elevations, suggesting reduced competition and niche specialization. (**d**) Species Evenness Index analysis illustrates significant variation across elevation, with peak diversity observed at mid-elevations (3700–4100 m)

of this plant for numerous healthcare purposes led to a decline in their population size in the region. Besides this, unsustainable harvesting, overgrazing, soil erosion, fires, and climate change pose serious threats towards the declining of this species population in the alpine zone, subsequently leading to the extinction of this critically endangered species [51]. DEM showed that 50% population of *M. aculeata* are present between 3000 m and 4000 m where 50% populations are present above 4000 m. DEM is very crucial for identifying the potential distribution area of *M. aculeata* populations in the region. Prior study also revealed that response curves highlight that suitable elevation for this species is above 2800 m, with maximum possibility of occurrence between 3900 m and 4200 m [30]. Similarly, another study also indicates that *M. aculeata* is more prevalent above 3200 m in western Himalayas [52]. Mountains provide opportunities for various species to migrate towards higher elevations to avoid extreme temperatures. Climate change may drive *M. aculeata* to migrate to higher elevations. Ecological modelling results showed that this species migrates towards high altitudes and cooler habitats due to rising temperatures. Our results are in line with previous studies, which also showed migration of alpine plants towards higher elevations [53, 54]. As a result of climate change, extreme weather events have become more frequent, posing some significant challenges towards plant survival and growth [55]. Climate-driven changes affect the physiology, phenology, and geographical ranges of species and influence how species individuals will adopt in the future climate scenarios [56]. We believe that these findings should serve as a valuable baseline for long-term monitoring. They might be species niches that adapt to

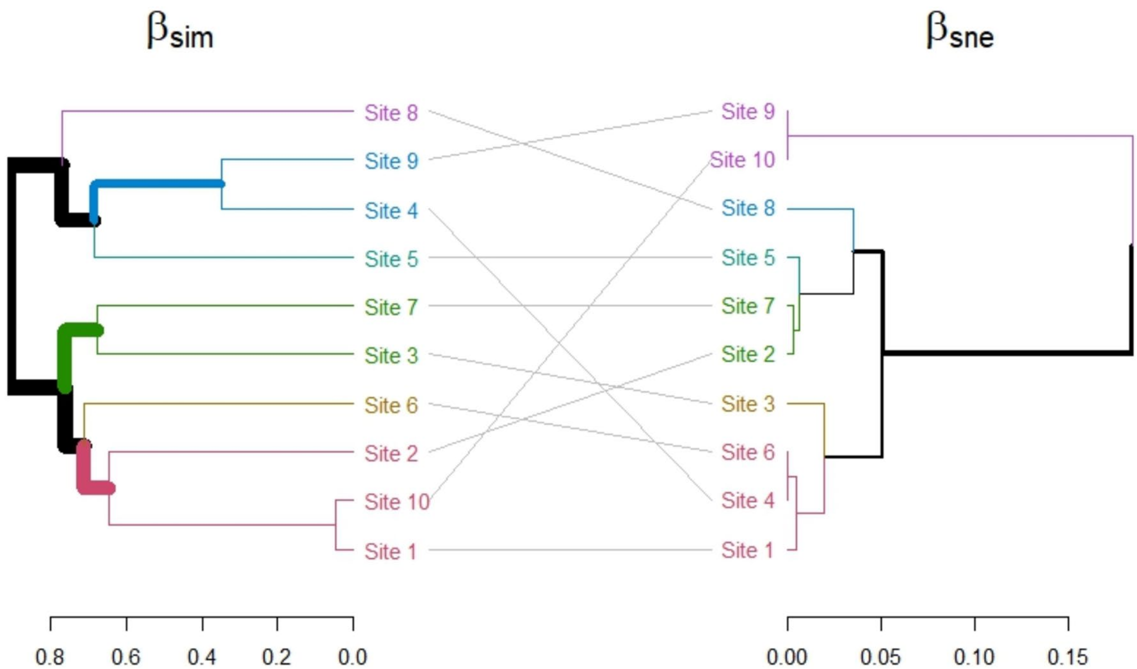

Fig. 8 Beta diversity analysis of *M. aculeata* populations across different sampling sites in the western Himalayan region. The dendrograms illustrate two distinct components of beta diversity

ongoing climate change or need active conservation efforts for their future conservation in the alpine zone.

Our results showed that species are unevenly distributed across all sites in the study area. The alpine plant composition and distribution patterns are primarily influenced by various factors, including water, soil, climate, elevation, and topography. Furthermore, topographic features with a combination of soil factors were considered as environmental gradients that affect species composition as well as species distribution patterns in the alpine zone [57]. Twenty species were found as indicator species among *M. aculeata* populations, including *Aconitum heterophyllum*, *Anaphalis nepalensis*, *Aster alpinus*, *Bergenia ciliata*, *Berberis pachyacantha*, *Bergenia stracheyi*, *Bistorta affinis*, *Bupleurum falcatum*, *Lilium polyphyllum*, *Panicum turgidum*, *Poa trivialis*, *Potentilla atrosanguinea*, *Primula rosea*, *Rosa pendulina*, *Rosa webbiana*, *Salix flabellaris*, *Syringa emodi*, *Tanacetum dolichophyllum*, *Viburnum grandiflorum*, and *Viola pilosa*. The dominance of these abovementioned species is strongly associated with exceptional adaptability and abundance in the region [15, 58]. These species serve as keystone indicator species due to their widespread ecological niche across the alpine zone [59]. Plant species that grow in the alpine zone possess some unique traits, such as seasonal resource availability, high solar energy efficiency, and limited productivity. These adaptations are crucial for alpine species to endure harsh environmental conditions such as intense UV exposure, snow, strong winds, and freezing temperatures [60]. Mantel analysis showed that *Aconitum heterophyllum* ($R = 0.7954$, $P = 0.003$) was the most critical indicator species, followed by *Anaphalis nepalensis* ($R = 0.6564$, $P = 0.034$), *Bistorta affinis* ($R = 0.522$, $P = 0.044$), and *Tanacetum dolichophyllum* ($R = 0.348$, $P = 0.043$). Vegetation composition in the mountainous ecosystems is mainly determined by elevation, impacting species diversity patterns, aligning with findings from the Himalayas. Abiotic and biotic factors also vary across the landscape, may cause shifts in species composition patterns [61, 62].

The Himalayan region is regarded as a biodiversity hotspot area, containing greater diversity of endemic species and medicinal plants [63]. CCA analysis revealed that NTFP extraction, fire, and soil erosion are the most significant threats to the long-term viability of *M. aculeata* populations in the region. Due to unsustainable extraction of *M. aculeata* for medicinal purposes, as well as extraction of associated medicinal plant species such as *Aconitum heterophyllum,Anaphalis nepalensis,Aster alpinus,Bergenia ciliata,Berberis pachyacantha,Bergenia stracheyi*, and *Bistorta affinis*, this disrupts the overall ecological functioning of the ecosystem. So, *M. aculeata* populations are declining due to unsustainable harvesting, habitat degradation, avalanches, overgrazing, and overexploitation. Various studies have also reported similar threats to *M. aculeata* populations from the Himalayas [30, 51, 64]. Furthermore, ongoing climate change coupled with anthropogenic disturbances is causing alarming conditions for the survival of *M. aculeata* populations in the region. This species is already listed as endangered species in the various parts of the Himalayas [30, 65–67] and critically endangered species in the study area [64]. Sustainable harvesting practices, sustainable land use management, and proper monitoring of *M. aculeata* populations are crucial for long-term sustainability in the region.

According to Pandit et al. [68] and Gairola et al. [69], alpine species diversity decreases with increasing altitudes in the Himalayas due to harsh environmental conditions that only allow a few well-adapted species to thrive. Our results also revealed a decreasing trend in species number was observed, whereas diversity indices showed a positive correlation along the elevational gradient in the study area (Fig. 7). The most plausible explanation is that the lower elevation in the alpine zone is mostly dominated by shrubby vegetation. The herbaceous vegetation beneath the shrubs is scarce. Additionally, these low-elevation areas are also facing high human-driven disturbances, which disturb natural vegetation, resulting in low alpha diversity. Our findings are inconsistent with several studies in the Himalayan region [70–72]. The greater alpha diversity patterns were observed at higher elevations, which are probably associated with optimum temperature, water availability, and diverse microhabitats over short distances [72–74]. Beta diversity results showed that Site 8 had the highest species variation, particularly differing from Site 1 and Site 9, highlighting the spatial heterogeneity within the *M. aculeata* populations. The greater value of beta diversity is strongly associated with unique habitat and environmental conditions as reported by various researchers [71, 75]. The higher beta diversity of herbaceous vegetation at higher elevations is attributed to distinct life-history strategies of various plant types and their environmental adaptations [76]. Our study demonstrated that alpha and beta diversity exhibit differing distribution patterns along the elevational gradient, highlighting the significance of incorporating both diversity scales in conservation plans for the western Himalayan alpine plant diversity.

Implications for future conservation

The Himalayan alpine ecosystems are increasingly susceptible to climate change. Human-driven disturbances such as unsustainable harvesting, habitat fragmentation, encroachment, and illegal trade of medicinal plants, combined with climate change factors like extreme weather patterns and rising temperatures, have devastating impacts on endemic plant species due to their restricted geographical range. *M. aculeata* is a critically endangered endemic plant species of significant ecological importance and socioeconomic value in alpine ecosystems. Recent studies have shown that climate change poses a high risk of habitat loss for *M. aculeata* [30, 35], making urgent conservation measures essential for maintaining the stability and sustainability of its habitat. In addition to climate change, anthropogenic disturbances have the potential to drastically disrupt the habitats of endemic mountain plant species [77, 78]. Thus, it is critical to maintain the habitats of this species for the benefits of local communities, whose diverse and traditional cultural knowledge are rooted in concepts of environmental protection and harmony between humans and nature. Future climate scenarios are likely to alter the potential suitable habitats for *M. aculeata*. It is possible to track and monitor these habitats to effectively reduce the impact of factors contributing to habitat loss. Future adaptation strategies should consider the effects of climate change on *M. aculeata* and associated alpine flora with an emphasis on ecosystem-based conservation. A habitat protection strategy for *M. aculeata* should have grassroots support and prioritize “prepare for the worst” concepts [79]. Rainfall strongly influences the distribution of *Meconopsis*. Integrated soil and water conservation programs could enhance its habitat suitability and support other key endemic species to sustain ecosystem functions of the area. It is imperative for landscape planners to use appropriate conservation techniques based on a socio-ecological framework [80]. It is critical to develop agro-techniques for cultivating species and to assess the availability, market trends, and wild collection methods of *M. aculeata*. Sustainable harvesting and benefit-sharing can conserve species while supporting local communities. Identifying industries that utilize these resources will aid in implementing this approach.

Conclusion

The present study revealed the geographical distribution, vegetation dynamics, threats to long-term viability, and the impact of elevation on alpha and beta diversity patterns of *M. aculeata* in the western Himalayan region of Kashmir. Significant variations were observed in the vegetation associated with *M. aculeata* along the elevational gradient. Healthier populations were found between the middle elevational range (3700 m to 4100 m), where diversity indices also showed moderate values. Elevation was identified as a significant factor influencing both the vegetation patterns and diversity trends in the region. Human-driven disturbances drastically decrease *M. aculeata* population size and disrupt their natural habitats, as this species is restricted to the Himalayan alpine zone within a specific elevational range. These disturbances, combined with ongoing climate change, pose serious threats to their suitability and sustainability in the region. Furthermore, this species has already been identified as critically endangered. Due to its high medicinal value, local communities unsustainably harvest *M. aculeata* and other associated medicinal plants for various health purposes, threatening the ecological integrity and functionality of alpine ecosystems, which require more conservation efforts. We recommend effective conservation measures for this critically endangered species, prioritizing habitat restoration, sustainable harvesting practices, collaboration between government and non-government organizations, involving local communities, and promoting stewardship to safeguard these unique *M. aculeata* populations. Local community engagement is crucial, as these efforts foster sustainable practices and raise awareness of the species importance. By implementing these conservation strategies, we can aid in the recovery of valuable *M. aculeata* populations and reduce extinction risks, preserving biodiversity for future generations.

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Data availability
Data is contained within the article.

Declarations

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References

1. Verrall B, Pickering CM. Alpine vegetation in the context of climate change: A global review of past research and future directions. Sci Total Environ. 2020;748:141344.
2. Nie Y, Pritchard HD, Liu Q, Hennig T, Wang W, Wang X, Liu S, Nepal S, Samyn D, Hewitt K. Glacial change and hydrological implications in the himalaya and Karakoram. Nat Rev Earth Environ. 2021;2(2):91–106.
3. Shi H, Zhou Q, He R, Zhang Q, Dang H. Climate warming will widen the lagging gap of global treeline shift relative to densification. Agricult Met. 2022;318:108917.
4. Rogora M, Frate L, Carranza M, Freppaz M, Stanisci A, Bertani I, Bottarin R, Brambilla A, Canullo R, Carbognani M. Assessment of climate change effects on mountain ecosystems through a cross-site analysis in the alps and apennines. Sci Total Environ. 2018;624:1429–42.
5. Bisht M, Sekar KC, Kant R, Ambrish K, Singh P, Arya D. Floristic diversity in Valley of flowers National park. Indian Himalayas. 2018.
6. Chen S, Wang W, Xu W, Wang Y, Wan H, Chen D, Tang Z, Tang X, Zhou G, Xie Z. Plant diversity enhances productivity and soil carbon storage. Proce Nat Acad Sci. 2018;115(16):4027–32.
7. Guo F, Lenoir J, Bonebrake TC. Land-use change interacts with climate to determine elevational species redistribution. Nat Commun. 2018;9(1):1315.
8. Zhang K, Yao L, Meng J, Tao J. Maxent modeling for predicting the potential geographical distribution of two peony species under climate change. Sci Total Environ. 2018;634:1326–34.
9. Lenoir J, Gégout JC, Guisan A, Vittoz P, Wohlgemuth T, Zimmermann NE, Dullinger S, Pauli H, Willner W, Svenning JC. Going against the flow: potential mechanisms for unexpected downslope range shifts in a warming climate. Ecography. 2010;33(2):295–303.
10. Alatalo JM, Jägerbrand AK, Molau U. Impacts of different climate change regimes and extreme Climatic events on an alpine meadow community. Sci Rep. 2016;6(1):21720.
11. Ceballos G, Ehrlich PR, Barnosky AD, García A, Pringle RM, Palmer TM. Accelerated modern human–induced species losses: entering the sixth mass extinction. Sci Adv. 2015;1(5):e1400253.
12. Noroozi J, Talebi A, Doostmohammadi M, Rumpf SB, Linder HP, Schneeweiss GM. Hotspots within a global biodiversity hotspot-areas of endemism are associated with high mountain ranges. Sci Rep. 2018;8(1):1–10.
13. Niskanen AKJ, Niittynen P, Aalto J, Väre H, Luoto M. Lost at high latitudes: Arctic and endemic plants under threat as climate warms. Divers Distrib. 2019;25(5):809–21.
14. Korner C, Spehn EM. Mountain biodiversity: a global assessment. Routledge; 2019.
15. Shaheen H, Aziz S, Nasar S, Waheed M, Manzoor M, Siddiqui MH, Alamri S, Haq SM, Bussmann RW. Distribution patterns of alpine flora for long-term monitoring of global change along a wide elevational gradient in the Western Himalayas. Glob Ecol Conserv. 2023;48:e02702.
16. Steinbauer MJ, Grytnes J-A, Jurasinski G, Kulonen A, Lenoir J, Pauli H, Rixen C, Winkler M, Bardy-Durchhalter M, Barni E. Accelerated increase in plant species richness on mountain summits is linked to warming. Nature. 2018;556(7700):231–4.
17. Negi VS, Giri L, Sekar KC. Floristic diversity, community composition and structure in Nanda Devi National park after prohibition of human activities, Western Himalaya, India. Curr Sci. 2018;115(6):1056–64.
18. Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature. 2003;421(6918):37–42.

19. Lenoir J, Svenning JC. Climate-related range shifts–a global multidimensional synthesis and new research directions. Ecography. 2015;38(1):15–28.
20. Morgan JW, Venn S. Alpine plant species have limited capacity for long-distance seed dispersal. Plant Ecol. 2017;218:813–9.
21. Jump AS, Huang TJ, Chou CH. Rapid altitudinal migration of mountain plants in Taiwan and its implications for high altitude biodiversity. Ecography. 2012;35(3):204–10.
22. Sekar KC, Thapliyal N, Pandey A, Joshi B, Mukherjee S, Bhojak P, Bisht M, Bhatt D, Singh S, Bahukhandi A. Plant species diversity and density patterns along altitude gradient covering high-altitude alpine regions of West Himalaya, India. Geol Ecol Landscap. 2024;8(4):559–73.
23. Rumpf SB, Hülber K, Klonner G, Moser D, Schütz M, Wessely J, Willner W, Zimmermann NE, Dullinger S. Range dynamics of mountain plants decrease with elevation. Proc Natl Aca Sci. 2018;115(8):1848–53.
24. Sekar KC, Pandey A, Giri L, Joshi BC, Bhatt D, Bhojak P, Dey D, Thapliyal N, Bisht K, Bisht M. Floristic diversity in cold desert regions of Uttarakhand Himalaya, India. Phytotaxa. 2022;537(1):1–62.
25. Xie H, Ash JE, Linde CC, Cunningham S, Nicotra A. Himalayan-Tibetan plateau uplift drives divergence of polyploid poppies: *Meconopsis Viguier* (Papaveraceae). PLoS ONE. 2014;9(6):e99177.
26. Duffy JE, Godwin CM, Cardinale BJ. Biodiversity effects in the wild are common and as strong as key drivers of productivity. Nature. 2017;549(7671):261–4.
27. Xiao W, Simpson BB. A new infrageneric classification of *Meconopsis* (Papaveraceae) based on a well-supported molecular phylogeny. Syst Bot. 2017;42(2):226–33.
28. Li X, Tan W, Sun J, Du J, Zheng C, Tian X, Zheng M, Xiang B, Wang Y. Comparison of four complete Chloroplast genomes of medicinal and ornamental Meconopsis species: genome organization and species discrimination. Sci Rep. 2019;9(1):10567.
29. Guo Q, Bai R, Zhao B, Feng X, Zhao Y, Tu P, Chai X. An ethnopharmacological, phytochemical and Pharmacological review of the genus Meconopsis. Amer J Chin Med. 2016;44(03):439–62.
30. Paul S, Samant S. Population ecology and habitat suitability modelling of an endangered and endemic medicinal Meconopsis aculeata royle under projected climate change in the himalaya. Environ Exp Bot. 2024;105837.
31. Mehta P, Sekar KC, Bhatt D, Tewari A, Bisht K, Upadhyay S, Negi VS, Soragi B. Conservation and prioritization of threatened plants in Indian Himalayan region. Biodivers Conserv. 2020;29:1723–45.
32. Manzoor M, Ahmad M, Zafar M, Gillani SW, Shaheen H, Pieroni A, Al-Ghamdi AA, Elshikh MS, Saqib S, Makhkamov T. The local medicinal plant knowledge in Kashmir Western Himalaya: a way to foster ecological transition via community-centred health seeking strategies. J Ethnobiol Ethnomed. 2023;19(1):56.
33. Gillani SW, Ahmad M, Zafar M, Manzoor M, Shah GM, Shaheen H, Zaman W, Sultana S, Sadia B, Khishlatovna KK. Ethnobotanical exploration of traditional medicinal plants among the rural inhabitants of district Muzaffarabad, Kashmir Himalayan region. Plant Sci Today. 2024;11:sp1.
34. Bahukhandi A, Sekar KC, Barola A, Bisht M, Mehta P. Total phenolic content and antioxidant activity of Meconopsis aculeata Royle: a high value medicinal herb of himalaya. Proc Nat Acad Sci Ind Sect Biol Sci. 2019;89:1327–34.
35. Shi N, Naudiyal N, Wang J, Gaire NP, Wu Y, Wei Y, He J, Wang C. Assessing the impact of climate change on potential distribution of Meconopsis punicea and its influence on ecosystem services supply in the southeastern margin of Qinghai-Tibet plateau. Front Plant Sci. 2022;12:830119.
36. Mehta P, Bisht K, Sekar KC. Diversity of threatened medicinal plants of Indian Himalayan region. Plant Biosystems-An Int J Dealing all Aspects Plant Biology. 2021;155(6):1121–32.
37. Kumar R, Arya D, Sekar KC, Bisht M. Threat assessment and prioritization of high-value medicinal plants in Pindari Valley, Nanda Devi biosphere reserve, India. Curr World Environ. 2021;16(1):236–49.
38. Salick J, Byg A. Indigenous peoples and climate change. 2007.
39. Peer T, Gruber JP, Millinger A, Hussain F. Phytosociology, structure and diversity of the steppe vegetation in the mountains of Northern Pakistan. Phytocoenologia. 2007;37(1):1–65.
40. Rawat GS, Adhikari BS. Floristics and distribution of plant communities across moisture and topographic gradients in Tso Kar basin, Changthang plateau, Eastern Ladakh. Arct Antar Alp Res. 2005;37(4):539–44.
41. Shaheen H, Attique A, Riaz MT, Manzoor M, Khan RWA, Riaz MT. From biodiversity hotspot to conservation hotspot: assessing distribution, population structure, associated flora and habitat geography of threatened Himalayan Yew in temperate forest ecosystems of Kashmir. Biodivers Conserv. 2024;1–25.
42. Manzoor M, Shaheen H, Attique A, Khan RWA, Gillani SW, Khan MS. Distribution pattern, population structure and habitat geography of Betula utilis subalpine forests of Kashmir region in the Western Himalayas: implications for conservation and sustainable management. Environ Develop Sustain. 2024;1–26.
43. Hammer Ø, Harper DA. Past: paleontological statistics software package for educaton and data Anlysis. Palaeontologia Electronica. 2001;4(1):1.
44. Dufrêne M, Legendre P. Species assemblages and indicator species: the need for a flexible asymmetrical approach. Ecol Monogr. 1997;67(3):345–66.
45. Ter Braak CJ, Smilauer P. CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5). www.canoco. com; 2002.
46. Baselga A, Orme CDL. Betapart: an R package for the study of beta diversity. Methods Ecol Evol. 2012;3(5):808–12.
47. Wickham H. ggplot2. Wiley Interdisciplinary Reviews: Comput Stat. 2011;3(2):180–5.
48. Porfirio LL, Harris RM, Lefroy EC, Hugh S, Gould SF, Lee G, Bindoff NL, Mackey B. Improving the use of species distribution models in conservation planning and management under climate change. PLoS ONE. 2014;9(11):e113749.
49. Chauhan P, Nigam A, Santvan VK. Ethnobotanical uses of medicinal plants among the rural people of Pabbar Valley in district Shimla, Himachal Pradesh, India. Plant Arch. 2020;20(2):3707–19.
50. Hadi A, Singh S. Ethno-botanical studies of some threatened medicinal plants and local perception of its population decline in Kargil, Ladakh UT. J Med Plants Stud. 2021;9:44–50.
51. Rana MS, Samant S. Diversity, Indigenous uses and conservation status of medicinal plants in Manali wildlife sanctuary. North Western Himalaya. 2011.
52. Dad JM, Rashid I. Differential responses of Kashmir Himalayan threatened medicinal plants to anticipated climate change. Environ Conserv. 2022;49(1):33–41.
53. Wolf A, Zimmerman NB, Anderegg WR, Busby PE, Christensen J. Altitudinal shifts of the native and introduced flora of C Alifornia in the context of 20th-century warming. Glob Ecol Biogeogr. 2016;25(4):418–29.
54. He X, Burgess KS, Yang XF, Ahrends A, Gao LM, Li DZ. Upward elevation and Northwest range shifts for alpine Meconopsis species in the Himalaya–Hengduan mountains region. Ecol Evol. 2019;9(7):4055–64.
55. Niu S, Luo Y, Li D, Cao S, Xia J, Li J, Smith MD. Plant growth and mortality under Climatic extremes: an overview. Environ Exp Bot. 2014;98(13– 9.
56. Hama AA, Khwarahm NR. Predictive mapping of two endemic oak tree species under climate change scenarios in a semiarid region: range overlap and implications for conservation. Ecol Inf. 2023;73:101930.
57. Zhang Q-p, Wang J, Wang Q. Effects of abiotic factors on plant diversity and species distribution of alpine meadow plants. Ecol Inf. 2021;61:101210.
58. Hamid M, Khuroo AA, Malik AH, Ahmad R, Singh CP. Assessment of alpine summit flora in Kashmir himalaya and its implications for long-term monitoring of climate change impacts. J Mt Sci. 2020;17(8):1974–88.
59. Ge X-J, Zhang L-B, Yuan Y-M, Hao G, Chiang T-Y. Strong genetic differentiation of the East-Himalayan megacodon Stylophorus (Gentianaceae) detected by inter-simple sequence repeats (ISSR). Biodivers Conserv. 2005;14(849– 61.
60. Nautiyal M, Nautiyal B, Prakash V. Effect of grazing and Climatic changes on alpine vegetation of Tungnath, Garhwal Himalaya, India. Environ Syst Dec. 2004;24(2):125.
61. Thakur M, Santvan V, Nigam A. Floristic composition and biological spectrum of Darlaghat wild life sanctuary Solan Himachal Pradesh, India. New York Sci J. 2012;5(12):1–14.
62. Jamba N, Kumar BM. Medicinal plants in the broad-leaf mixed coniferous forest of Tshothang Chiwog, Bhutan: floristic attributes, vegetation structure, ethnobotany, and socioeconomic aspects. Front Environ Sci. 2018;5:96.
63. Mehta P, Bisht K, Sekar KC, Tewari A. Mapping biodiversity conservation priorities for threatened plants of Indian Himalayan region. Biodivers Conserv. 2023;32(7):2263–99.
64. Majid A, Ahmad H, Saqib Z, Ali H, Alam J. Conservation status assessment of Meconopsis aculeata Royle: a threatened endemic of Pakistan and Kashmir. Pak J Bot. 2015;47:1–5.
65. Goraya G, Jishtu V, Rawat G, Ved D. Wild medicinal plants of Himachal Pradesh: an assessment of their conservation status and management prioritisation. Shimla: Himachal Pradesh Forest Department; 2013.
66. Ved D, Kinhal G, Ravikumar K, Prabhakaran V, Ghate U, Vijaya Shankar R, Indresha J. Conservation assessment and management prioritization for the medicinal plants of Jammu & Kashmir, Himachal Pradesh & Uttaranchal.

Foundation for Revitalisation of Local Health Traditions, Bangalore, India 2003;206.
67. Rani P, Bose SK, Sarkar S, Sharma A, Dutt A. Meconopsis aculeata: A critically endangered medicinal plant and its multifarious medicinal properties. Int J Bot Stud. 2022;7:19–26.
68. Pandit MK, Manish K, Koh LP. Dancing on the roof of the world: ecological transformation of the Himalayan landscape. Bioscience. 2014;64(11):980–92.
69. Gairola S, Rawal R, Todaria N. Forest vegetation patterns along an altitudinal gradient in sub-alpine zone of West Himalaya, India. Afr J Plant Sci. 2008;2(6):42–8.
70. Acharya BK, Chettri B, Vijayan L. Distribution pattern of trees along an elevation gradient of Eastern Himalaya, India. Acta Oecol. 2011;37(4):329–36.
71. Ahmed MJ, Murtaza G, Shaheen H, Habib T. Distribution pattern and associated flora of Jurinea dolomiaea in the Western Himalayan highlands of Kashmir: an indicator endemic plant of alpine phytodiversity. Ecol Indic. 2020;116:106461.
72. Zhang W, Huang D, Wang R, Liu J, Du N. Altitudinal patterns of species diversity and phylogenetic diversity across temperate mountain forests of Northern China. PLoS ONE. 2016;11(7):e0159995.
73. Vibhuti, Bargali K, Bargali S. Effects of homegarden size on floristic composition and diversity along an altitudinal gradient in central Himalaya, India. Curr Sci. 2018;2494– 503.
74. Manral V, Bargali K, Bargali SS, Karki H, Chaturvedi RK. Seasonal dynamics of soil microbial biomass C, N and P along an altitudinal gradient in central Himalaya, India. Sustainability. 2023;15(2):1651.
75. He X, Arif M, Zheng J, Ni X, Yuan Z, Zhu Q, Wang J, Ding D, Li C. Plant diversity patterns along an elevation gradient: the relative impact of environmental and Spatial variation on plant diversity and assembly in arid and semi-arid regions. Front Environ Sci. 2023;11:1021157.
76. Qin H, Zhang Y-B, Dong G, Zhang F. Altitudinal patterns of taxonomic, phylogenetic and functional diversity of forest communities in Mount Guandi, Shanxi, China. Chin. J. Plant Ecol. 2019;43(9):762.
77. Naudiyal N, Wang J, Ning W, Gaire NP, Peili S, Yanqiang W, Jiali H, Ning S. Potential distribution of abies, Picea, and Juniperus species in the sub-alpine forest of Minjiang headwater region under current and future climate scenarios and its implications on ecosystem services supply. Ecol Indic. 2021;121:107131.
78. Wang WT, Guo WY, Jarvie S, Svenning JC. The fate of *Meconopsis* species in the Tibeto-Himalayan region under future climate change. Ecol Evol. 2021;11(2):887–99.
79. Wright AN, Hijmans RJ, Schwartz MW, Shaffer HB. Multiple sources of uncertainty affect metrics for ranking conservation risk under climate change. Divers Distrib. 2015;21(1):111–22.
80. Virapongse A, Brooks S, Metcalf EC, Zedalis M, Gosz J, Kliskey A, Alessa L. A social-ecological systems approach for environmental management. J Environ Manage. 2016;178:83–91.

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