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Synergizing population structure, habitat preferences, and ecological drivers for conservation of *Cedrus deodara*

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Abstract

Background Climate change is impacting forest tree species adversely and making the ecological system vulnerable. The Himalayan cedar (*Cedrus deodara*), a keystone species in Western Himalayan forests, plays an important ecological role but is under increasing threats from natural and anthropogenic pressures. The current study analyses the population structure, spatial distribution, environmental factors, and future conservation strategies for Himalayan cedar populations in the Kashmir Himalayas.

Methods Field sampling was carried out between 2023 and 2024 in various districts of the Kashmir Himalayas. The quadrat method was used to record the vegetation data across an elevational gradient ranging from 1300 to 2700 m. GIS and spatial analysis were used to map population distribution while, cluster analysis was performed to identify species associations. Canonical Correspondence Analysis (CCA) was applied to identify the influence of environmental factors while, Non-Metric Multidimensional Scaling (NMDS) and SIMPER analysis were used to investigate inter-association dissimilarity.

Results The populations showed an average stem density of 110.73 trees/ha and low regeneration rates, with just 15 seedlings per ha on average. Stump density (mean: 90.62 stumps/ha) demonstrated human-induced pressures. GIS and spatial analysis revealed that Cedar populations were mostly found at altitudes ranging from 1900 to 2200 m, with a preference for north-facing slopes. Cluster analysis identified four distinct species associations in which each with a different species richness and ecological composition. Association 3 was the most diverse (Shannon index: 3.31 ± 0.05), while Association 4 showed the highest dominance (0.062 ± 0.002). Canonical Correspondence Analysis (CCA) identified altitude and timber extraction as the key drivers of variation, accounting for 16.2% and 15.2% of the distribution variance, respectively. Grazing, erosion, and fire accelerated the degradation of habitat. Cedar density was influenced by various edaphic parameters, with total nitrogen ($R^2 = 0.11$) and soil moisture ($R^2 = 0.09$) demonstrating the strongest association. Soil pH, electrical conductivity, and total phosphorus exhibited minimal or negligible effects. Associations 1 and 2 were associated with increased soil pH and electrical conductivity, but Associations 3 and 4 were influenced more by nutrient-rich and moisture-retentive soils. Non-Metric Multidimensional Scaling (NMDS) and SIMPER analysis identified a 56.99% dissimilarity between associations, mostly driven by species such as *Parrotiopsis jacquemontiana* and *Viburnum grandiflorum*.

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Conclusion The study reveals that Himalayan cedar populations in the Kashmir Himalayas face low regeneration rates and significant anthropogenic pressure. Their distribution is influenced by various factors, including altitude, timber extraction, soil nitrogen, moisture, grazing, erosion, and fire. These findings highlight the necessity for targeted conservation strategies. Future conservation strategies should encompass controlled grazing, regulated timber extraction, soil conservation measures, anti-logging policies, ecotourism initiatives, and collaboration among local communities and policymakers.

Keywords Anthropogenic pressure, Climate change, Conservation, Environmental variables, Population dynamics

Introduction

The Western Himalayas forests are critical to ecological balance because they support biodiversity, regulate climate, and provide key ecosystem services such as water filtration, carbon sequestration, and soil stability [1–4]. These forests encompass a rich flora and fauna, many of which are endemic or medicinally valuable, and they provide livelihoods through timber (TFPs), non-timber forest products (NTFPs), and ecotourism [5–8]. They also contribute significantly to local cultural and spiritual traditions. As a result, forests play an important role in meeting global conservation goals such as the Aichi Biodiversity Targets and the Sustainable Development Goals (SDGs).

Cedrus deodara (Roxb. ex D. Don) G. Don, commonly known as the"Himalayan cedar,"typically grows in pure forest stands at elevations ranging from 1200 to 3050 m asl [9, 10]. This monotypic genus in the Pinaceae family is native to the Western Himalayas [10, 11] and spreads from the Karakoram region to Nepal, Bhutan, and the northeastern Indian Himalayas [11, 12]. Himalayan cedar is a keystone species, known for its sacred groves throughout the region [12]. It has substantial economic [13], medical [14], and cultural value [15], as well as providing important ecosystem services to the region [16]. Furthermore, it contributes significantly to ecosystem functioning, carbon sequestration, and the development of low-carbon settlements [17]. The research on Himalayan cedar highlights its different characteristics, including medicinal properties [18], ethnobotanical relevance [19], phytochemistry [20], and taxonomy [21]. In addition, in the twenty-first century, there has been an increasing interest in the role of Himalayan cedar in climate change research, notably its ecological and environmental importance [11]. Himalayan cedar is known for having the highest biomass and carbon sequestration capacity among Himalayan conifers [17, 22]. However, climate change [23] and other human-induced variables have limited its expansion. Himalayan cedar populations are declining as the climate warms, increasing the species'vulnerability [10, 24]. Under present and future temperature scenarios, climate change-induced shifts are projected to drive this species to potentially interact with subalpine and timberline species [25].

Plant species'structure and diversity are influenced by a variety of biotic and abiotic variables that operate on distinct geographical and temporal scales [26, 27]. Abiotic factors such as topography and soil composition are important in influencing the physical properties of plants throughout a wide range of habitats [28–30]. Furthermore, there is an increasing awareness of the importance of soil in explaining biological patterns within forests. This has important consequences for biogeography, biome classification [31], and the abundance and growth dynamics of plant communities on a regional and local scale. Plant-soil interactions link plant populations to biogeochemical and hydrological cycles that are influenced by components such as water availability, soil pH, and the necessary nutrients for growth [32]. These edaphic factors have an impact on ecosystems'functional and phylogenetic diversity as well as their successional processes. They have an important role in species selection from the regional species pool, as well as influencing plant species establishment and growth patterns [32, 33]. One of the primary factors affecting the distribution, composition, and structure of forest vegetation in mountainous regions is generally recognized as altitude [34]. This is due to the fact that altitude involves a complex interaction of elements that influence climate, soil parameters, and disturbance regimes, including solar radiation, water availability, and nutrient distribution. In temperate mountain ecosystems these differences significantly influence the composition and structure of plant communities [35–37]. Furthermore, these ecosystems'wide altitudinal gradients provide distinctive vegetation patterns, which makes altitude a useful and simple metric for describing vegetation [38, 39]. Moreover, anthropogenic pressures such as overexploitation, deforestation, and overgrazing have a substantial impact on species regeneration, as can natural disturbances such as erosion, snow drifts, forest fires, and landslides [40, 41].

The ecology of the western Himalayan region of Azad Jammu and Kashmir (AJK) is highly adaptive, characterized by a diverse range of vegetation types and distinct species compositions influenced by seasonality, topography, soil, and climate [42, 43]. This emphasizes the importance of vegetation studies on these rich plant species in documenting biodiversity, understanding its fundamental drivers, and guiding conservation and management initiatives in the region. Despite its importance, much of the area remains ecologically unexplored due to its remoteness, challenging geography, and severe climate [44–46]. These Himalayan forests are impacted by serious challenges, such as climate change is changing precipitation patterns and promoting glacial retreat, threatening forest ecosystems [41, 47–50]. In addition to the effects of climate change, the Himalayan flora and fauna are facing significant anthropogenic challenges, posing a major risk of severe biodiversity loss and reduced ecosystem services in the future [51, 52]. Deforestation for household or agricultural expansion, habitat fragmentation and degradation, species invasion, and unsustainable overexploitation of medicinal plants have all contributed to the loss of many natural ecosystem services [41, 47, 53–58]. However, there is insufficient data on existing biodiversity at the species level with habitat geography, threat assessment, the impact of biotic and abiotic variables on diversity and distribution, and implications for future conservation and management in AJK (Western Himalaya). These concerns highlight the critical need to study these forests at species level for conservation programs and sustainable management to ensure the long-term survival of these valuable ecosystems. The research questions of this study were: 1) How do habitat variability and altitudinal gradients affect the spatial distribution, population structure, and community composition of Himalayan cedar in the AJK region of the western Himalayas? and 2) What impacts do edaphic factors and human activities have on the distribution, species richness, and population dynamics of Himalayan cedar, and what conservation strategies could be implemented to mitigate these threats? Furthermore, edaphic variables and anthropogenic threats substantially impact biodiversity richness and distribution, seeking targeted conservation and effective management strategies for preserving this ecologically and economically important species. The specific objectives of this study are as follows: (1) To investigate the spatial distribution patterns of Himalayan cedar in AJK, Pakistan. (2) To study the population structure and the community patterns across elevational gradients. (3) To assess the effect of edaphic factors on population structure, distribution patterns, and richness of Himalayan cedar. (4) To identify the key anthropogenic threats and propose implications for their conservation and sustainable management. Achieving these study objectives can provide valuable data to develop conservation and sustainable forest management strategies in the Himalaya.

Materials and methods

Study area

AJK (western Himalayas) has a total land area of about 13,297 km^2. The study area lies between latitudes 33°E and 36°E and longitudes 73°N and 75°N (Fig. 1). It has a hilly landscape with deep ravines with steep slopes, undulating the ground and dense vegetation. The total annual precipitation ranges from 800 to 1600 mm in different areas, and the snowline remains at around 1200 m a.s.l. in the winter and rises to around 3300 m a.s.l. in the summer [59, 60]. Similarly, the average monthly minimum and maximum temperatures range from 2 °C to 40 °C [61]. AJK is a biodiversity hotspot with a wide range of agroclimatic zones and ecosystems due to its substantial altitudinal range, which ranges from 360 m in the southern Punjab Plains to 6,325 m in the northern area [44, 62]. In temperate forest ecosystems, soils are typically loamy to sandy loam, moderately deep, and well-drained, which facilitates the accumulation of rich organic matter. The pH levels range from slightly acidic to neutral, supporting the growth of temperate flora. Key nutrients, particularly nitrogen, phosphorus, and potassium, are essential for forest productivity. Additionally, soil moisture and texture influence species composition along elevational gradients [63, 64]. The state encompasses various breathtaking landscapes, including tumbling rivers, meandering streams, and lush forests wrapped with sparkling flowers. A field survey was conducted in three districts of Kashmir: Muzaffarabad, Neelum Valley, and Jhelum Valley.

Sampling methodology

The Himalayan cedar populations in AJK were studied by selecting sampling sites in temperate woods at elevations between 1300 and 2700 m. These populations were identified by a comprehensive preliminary survey in the temperate forests of the state. Then, 23 forest points were selected from AJK's three districts: Hattian, Muzaffarabad, and Neelum Valley. The objective of this selection was to ensure that all Himalayan cedar populations in the state were adequately represented by including the species'broad geographic range (Fig. 1). The field expeditions were carried out between June and September 2023–2024 to record the structural attributes, associated flora, and vegetation attributes of Himalayan cedar populations in the region. Forest sampling was conducted in three districts, with multiple sites in each district, using the transect approach. We established larger quadrats at regular intervals of 20 m at each site along the elevational gradients. We conducted systematic quadrat-based sampling at 23 locations, allocating 5 quadrats for tree sampling, 10 for shrubs, and 15 for grasses and herbaceous vegetation. The quadrat sizes were 400 m^2 for trees, 25 m^2 for shrubs, and 1 m^2 for grasses and herbs. Within the

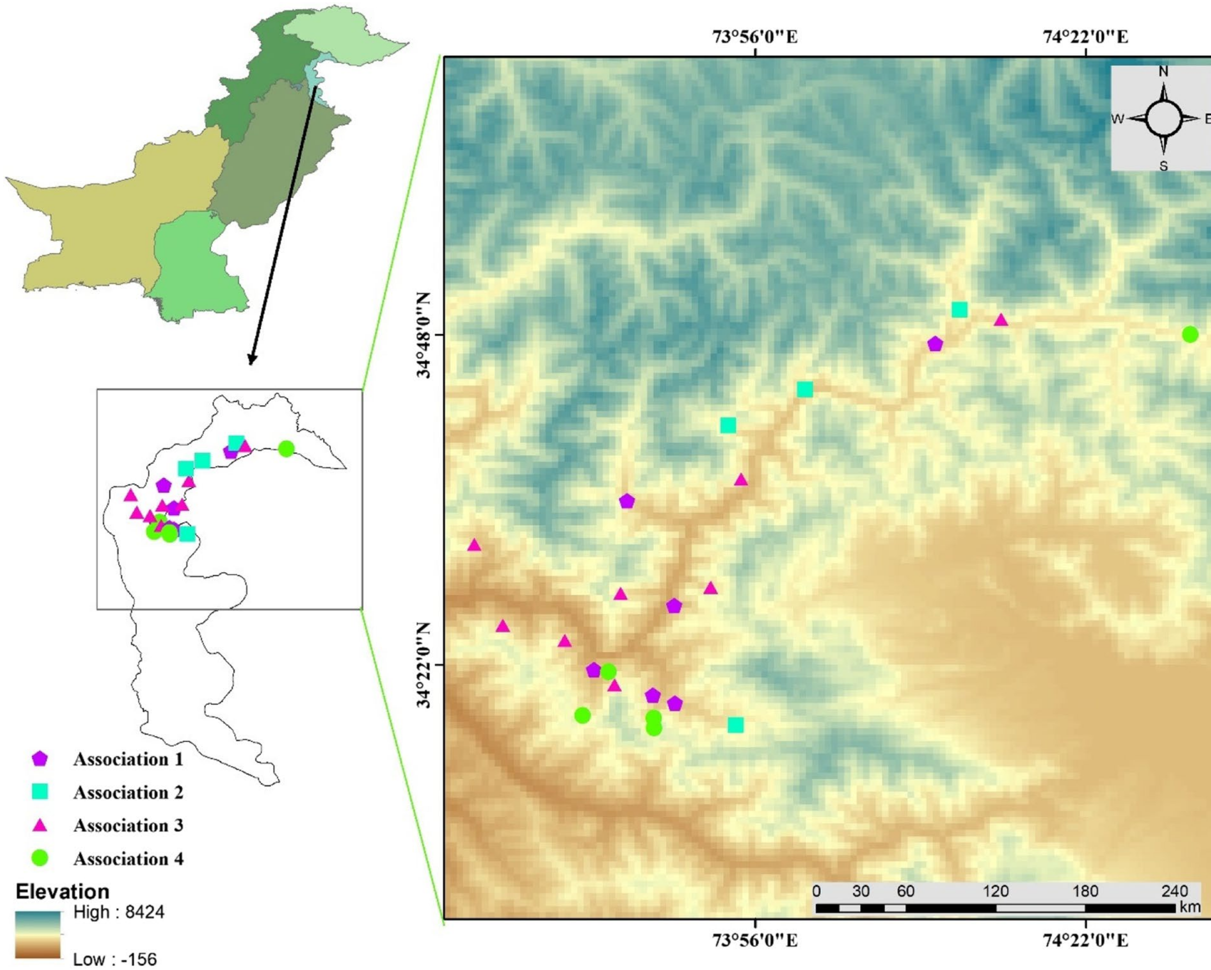

Fig. 1 Study area map representing the Himalayan Cedar sampling sites in western Himalaya

larger 20 m × 20 m quadrats designated for tree sampling, we used nested sub-quadrats to assess shrubs, herbs, and grasses. This nested design facilitated a comprehensive examination of vegetation distribution, habitat characteristics, and microclimatic conditions at each site [42]. The primary vegetation data for Himalayan cedar populations, including cover, frequency, density, and importance values, were collected at the study sites, along with all associated plant species, using standard phytosociological protocols. The IVI for each species was calculated using the formula:

$$\text{IVI} = \text{Relative Frequency} + \text{Relative Density} + \text{Relative Dominance},$$

following Curtis and McIntosh (1950). This approach helps assess species dominance and ecological role within communities. IVI was calculated separately for each species at every site, and full results are provided in Supplementary Table 1 [42, 43, 64]. All plant specimens associated with Himalayan cedar have been preserved and transferred to Quaid-i-Azam University's herbarium for identification using online floras and literature [65]. All the specimens were identified by Prof. Dr. Mushtaq Ahmad and deposited in the Herbarium of Pakistan (ISL) at Quaid-Azam University, Pakistan. Geographic factors such as altitude, aspect, latitude, and longitude were recorded at every site using a GPS device, and slope gradient was evaluated using a clinometer to collect exhaustive data on the geography of the Himalayan cedar habitat.

Geographic information system (GIS)

ArcGIS software (version 10.8.02) was used for the spatial study of Himalayan cedar populations in the state of AJK. The GIS data was exported to GeoTIFF format, tiled into accessible data sheets, and utilized to create a digital boundary for the study area. GPS data from all sample plots were used to generate an inventory map of Himalayan cedar sampling sites. The georeferencing and location of the study sites were based on the World Geodetic System 1984 (WGS 84) coordinate system. A Digital Elevation Model (DEM) with a 12.5 m resolution was also developed using PALSAR/ALOS data (ASF DAAC, 2020). We used ArcGIS version 10.8.02's geospatial toolbox features to analyze the slope, aspect, curvature, and hill shade of Himalayan cedar populations in the region. Structural variables of Himalayan Cedar, including tree density, height, regeneration status, and deforestation indicators, were analyzed. Tree density and height were recorded by counting mature individuals within each quadrat and measuring their height with a clinometer. Regeneration status was assessed by counting the number of seedlings. Signs of deforestation, such as stumps, were also recorded. The data were compiled and organized in Microsoft Excel and integrated into ArcGIS software for mapping these structural attributes. This enabled the detection of both vulnerable and healthy populations of the species in AJK [66].

Soil analysis

Soil samples were collected from each transect, with a focus on the distribution of Himalayan cedar at the specified study site. Random samples weighing 250 g were obtained from a depth of 0–20 cm using a post hole digger and screw auger. Individual samples have been mixed to form composite soil samples for each site. The collected samples were placed in airtight polythene bags, air-dried, crushed, and sieved with a 2 mm sieve. They were subsequently kept for physicochemical investigation, as described by Allen (Allen et al., 1974). The soil samples were analyzed for pH, organic matter content (%), soil electrical conductivity (EC), total available nitrogen (%), available phosphorus (ppm), and available potassium. All soil sample tests were carried out using standard methods [64, 67].

Anthropogenic indicators

The effects of anthropogenic disturbances on forest structure and Himalayan cedar populations were investigated. Deforestation intensity was determined by counting the number of stumps in each sampling plot. We measured the severity of grazing using observable indicators such as hoof prints, trampling signs, soil compaction, animal feces, and short livestock trails. Grazing pressure was classified as low, moderate, or high based on the frequency and extent of these indicators across the plots. To assess erosion, we also observed exposed roots, soil displacement, and loss of vegetation cover, especially on slopes. Furthermore, we evaluated fire intensity by examining burnt tree bark, ash layers, scorched vegetation, and fire scars on tree trunks, within each sampling quadrant [45, 60, 66]. The regeneration status of tree species was determined by counting the seedlings in each 20 m^2 quadrat and then converting the value to a per-hectare basis, following the method of Shaheen et al. [43]. The level of anthropogenic disturbance was visually recorded at each site. These visual indicators were classified based on field observation data into three distinct categories according to the severity of disturbances: 1 for low, 2 for moderate, and 3 for high [64].

Data analysis

The data analysis of the study was conducted using a combination of multivariate and statistical approaches to understand the ecological dynamics of Himalayan cedar populations. Ward's cluster analysis was performed to classify the 23 sampling sites into four distinct associations based on species composition [67, 68] SIMPER (Similarity Percentage) and Non-Metric Multidimensional Scaling (NMDS) were carried out using the Bray–Curtis dissimilarity method in the vegan package of R [69]. Diversity indices, including Shannon, Simpson, Dominance, and Evenness, were calculated for each association and visualized through box plots created using the ggplot2 package in R [70]. Tukey's post hoc test was employed to assess significant differences in diversity indices between associations. Canonical Correspondence Analysis (CCA) was conducted in CANOCO version 5 to examine the influence of anthropogenic pressures and soil variables on the Himalayan cedar associations [71]. Chi-square goodness-of-fit tests were applied to determine whether the distributions of grazing and erosion intensity levels significantly deviated from uniform expectations across the sampling sites. Linear regression analysis was applied to evaluate the relationships between Himalayan cedar density and various soil parameters.

Results

Population structure of Himalayan cedar

A total of 120 species were recorded from the study area, belonging to 102 genera and 51 plant families, respectively. The Asteraceae family was observed as the dominant family, exhibiting 11 species, followed by the Rosaceae, Lamiaceae, Fabaceae, and Pinaceae families. The studied Himalayan cedar populations at 23 different sites represent an average stem density of 110.73 trees/ha with a minimum value of 23 trees/ha and a maximum value of 269 trees/ha (Fig. 2a). The Himalayan cedar populations showed an average tree height of 22.91 m with a minimum value of 17.3 m and a maximum value of 27.3 m (Fig. 2b). The studied Himalayan cedar populations showed an average tree diameter of 262.36 cm with

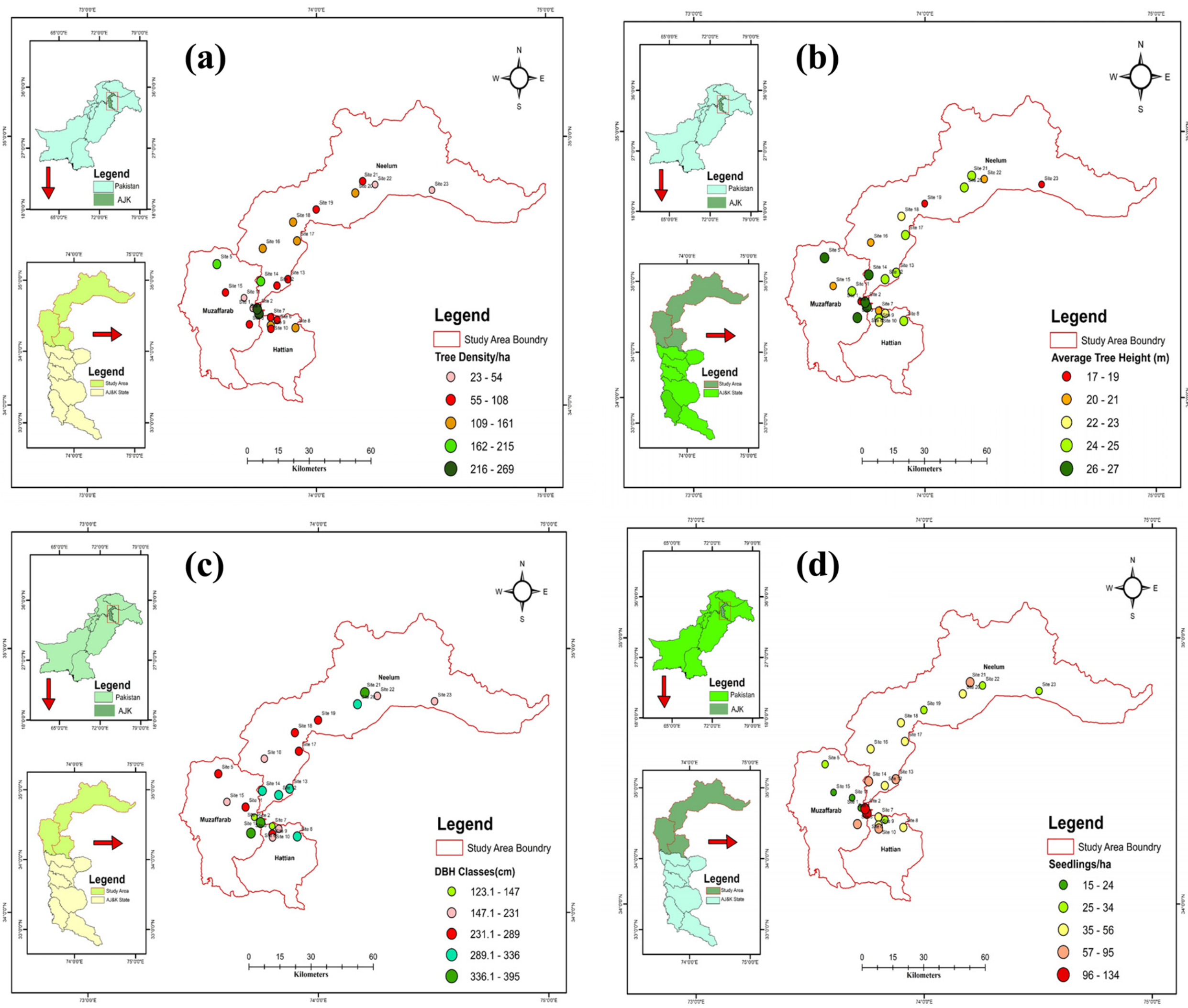

Fig. 2 GIS analysis of Himalayan Cedar populations: **a** Tree density/ha, **b** Average tree height (m), **c** DBH (Diameter at breast height) (cm), **d** Seedlings/ha

a minimum value of 123.1 cm and a maximum value of 395.6 cm (Fig. 2c). We observed poor regeneration patterns for Himalayan cedar with an average seedling of 15 seedlings/ha and a maximum value of 134 seedlings/ha (Fig. 2d). Stumps density represents the population pressure on Himalayan cedar forests, with the mean stump value recorded as 90.62 stumps/ha, the minimum value as 6 stumps/ha, and the maximum value of 179 stumps/ha, respectively (Fig. 4a).

Spatial distribution patterns of Himalayan cedar

The digital elevation model (DEM) is used to analyze and provide valuable insights into the distribution patterns of Himalayan cedar in the western Himalayan region of Kashmir. The DEM results revealed that the majority of Himalayan cedar sites are located between the 1900–2200 m elevational range, comprising 13 sites. In contrast, 6 sites were found between 1300–1800 m and 4 sites between 2300–2700 m (Fig. 3a). Aspect analysis showed that Himalayan cedar is predominantly found on the north aspect (60.68%), while some sites were also recorded on the north-southern (21.73%) and north-eastern aspects (17.39%) of the study area (Fig. 3b). Slope analysis indicated habitat preferences for Himalayan cedar, with the majority of sites recorded on moderate slopes (73.91%), while 8.69% were on plateau plane slopes and 17.39% on steep slopes (Fig. 3c).

Grazing analysis revealed that the majority of Himalayan cedar sites (14 sites, 60.86%) were classified as moderately grazed. In comparison, 6 sites (26.08%)

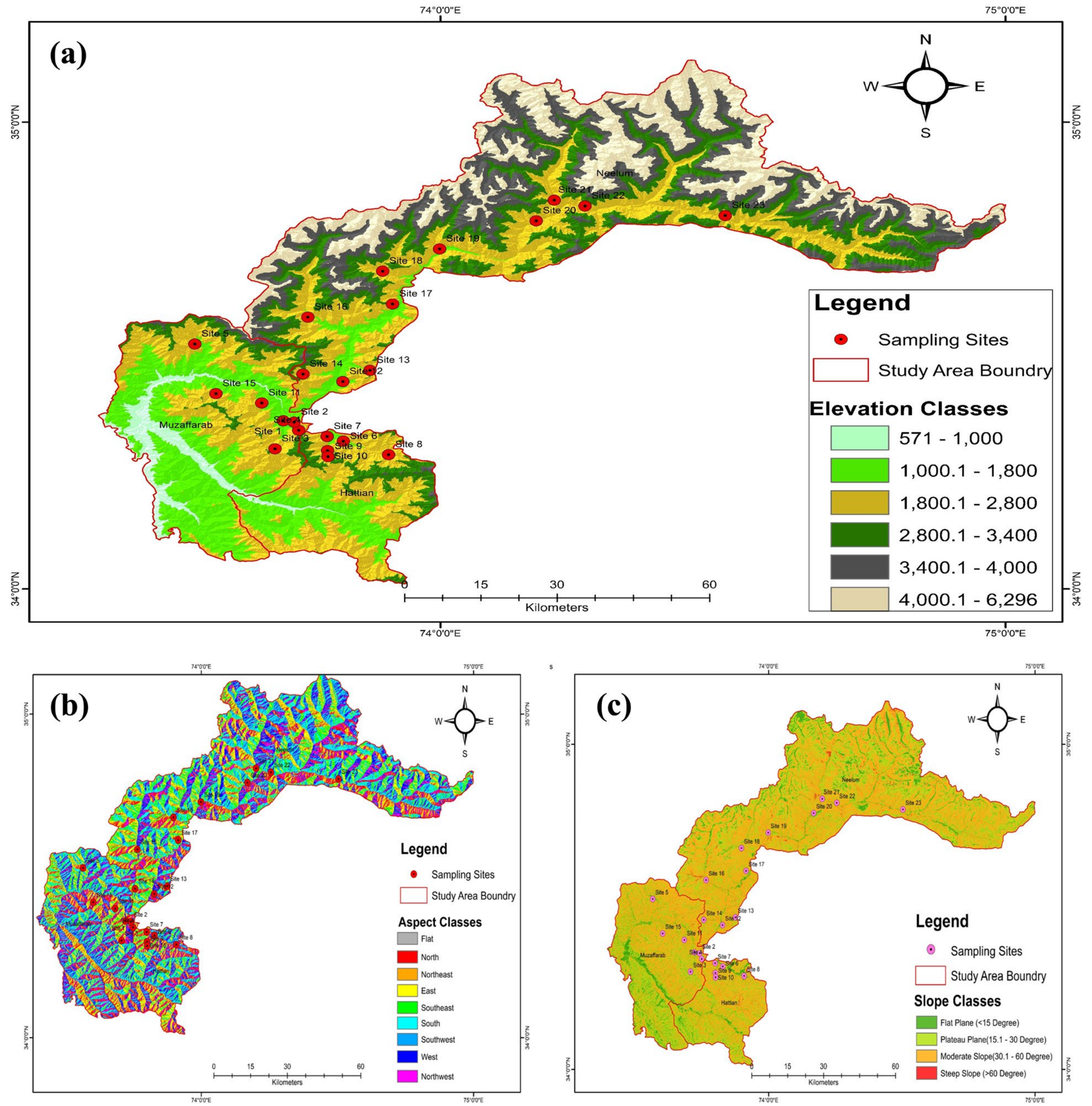

Fig. 3 GIS analysis of Himalayan Cedar populations: **a** Digital Elevation Model (DEM), **b** Aspect, **c** Slope

experienced intense grazing, and 3 sites (13.04%) had low grazing intensity (Fig. 4b). Erosion analysis of Himalayan cedar sites showed that 12 sites (52.17%) exhibited moderate erosion, 9 sites (39.13%) experienced intense erosion, and 2 sites (8.69%) showed controlled erosion (Fig. 4c).

Himalayan cedar association pattern

The Ward Cluster Analysis, conducted across 23 surveyed sites of Himalayan cedar populations, classified the sites into four major associations based on species presence and absence (Fig. 5). Association 1 comprises six sites with 75 species, dominated by *Himalayan*

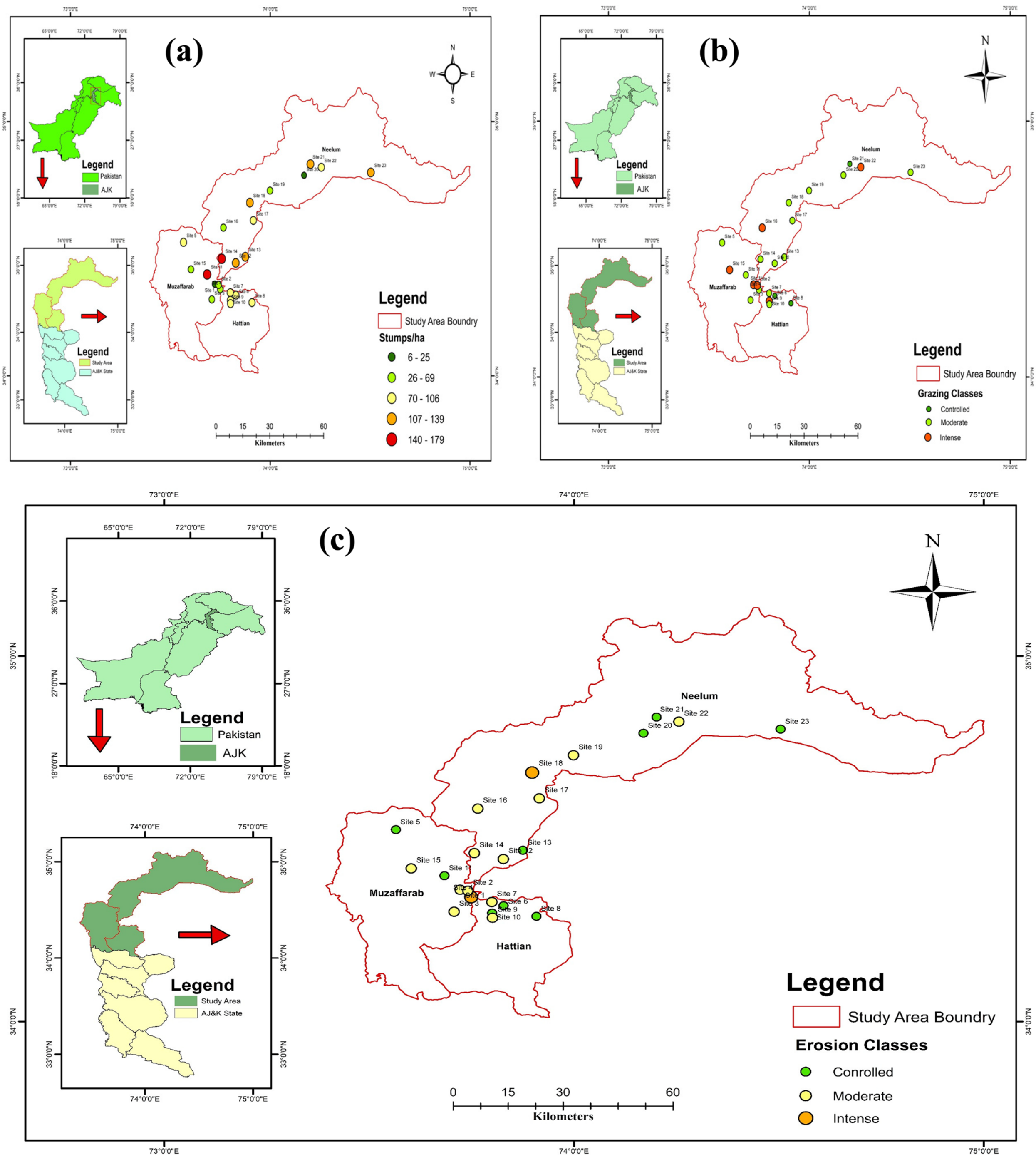

Fig. 4 GIS analysis of Himalayan Cedar populations: **a** Stumps/ha, **b** Grazing, **c** Erosion

cedar (IVI = 4.53 ± 0.43), followed by *Rubus fruticosus* (IVI = 2.95 ± 0.19), *Pinus wallichiana* (IVI = 2.90 ± 0.63), *Fragaria nubicola* (IVI = 2.30 ± 0.52), *Parrotiopsis jacquemontiana* (IVI = 2.23 ± 0.97), *Cymbopogon citratus* (IVI = 2.10 ± 0.65), *Viburnum grandiflorum* (IVI = 1.88 ± 0.51), *Indigofera heterantha* (IVI = 1.58 ± 0.43), *Sarcococca saligna* (IVI = 1.55 ± 0.54), and *Teucrium royleanum* (IVI = 1.52 ± 0.72) (Supplementary Table 1). Association 2 consists of four sites with 66 species, where *Pinus wallichiana* is

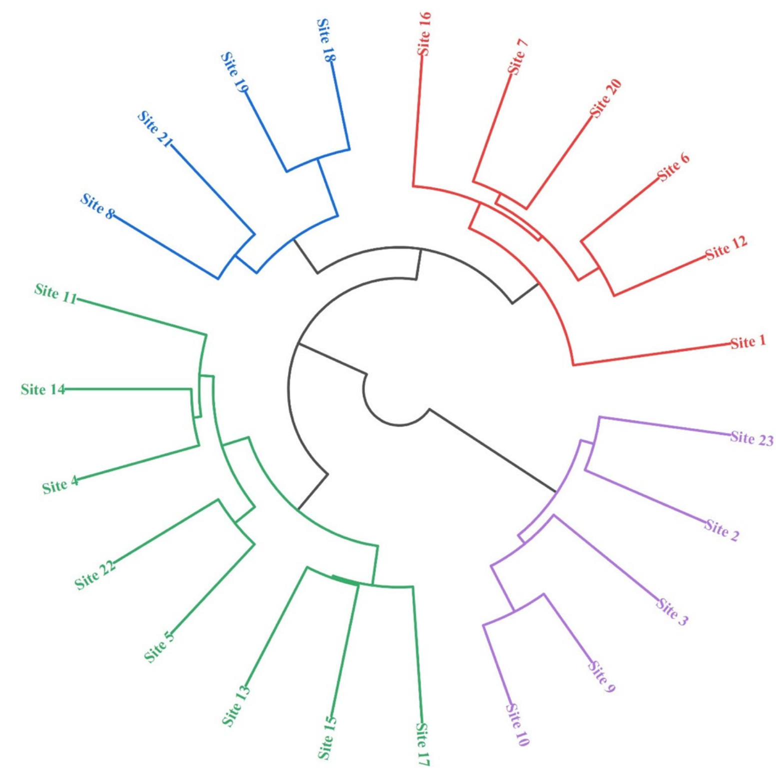

Fig. 5 Ward's Cluster Analysis of Himalayan cedar populations based on species presence and absence across 23 surveyed sites. The dendrogram identifies four distinct associations, represented by different clusters

predominant (IVI = 3.95 ± 0.50), accompanied by *Viburnum grandiflorum* (IVI = 3.20 ± 0.60), *Fragaria nubicola* (IVI = 3.05 ± 0.22), *Sarcococca saligna* (IVI = 2.10 ± 0.71), *Aesculus indica* (IVI = 1.90 ± 0.52), *Jasminum grandiflorum* (IVI = 1.73 ± 0.51), *Berberis lycium* (IVI = 1.55 ± 0.34), *Oxalis corniculata* (IVI = 1.28 ± 0.18), *and Sorbaria tomentosa* (IVI = 1.08 ± 0.37) (Supplementary Table 1). Association 3 includes eight sites with 82 species, predominantly featuring *Fragaria nubicola* (IVI = 2.66 ± 0.17), and *Viburnum grandiflorum* (IVI = 2.46 ± 0.47), alongside *Sarcococca saligna* (IVI = 2.43 ± 0.61), *Parrotiopsis jacquemontiana* (IVI = 2.34 ± 0.49), *Quercus incana* (IVI = 1.48 ± 0.39), *Teucrium royleanum* (IVI = 1.43 ± 0.50), *Berberis lycium* (IVI = 1.00 ± 0.26), and *Indigofera heterantha* (IVI = 1.26 ± 0.36) (Supplementary Table 1). Association 4 consists of five sites with 88 species, characterized by *Viburnum grandiflorum* (IVI = 3.78 ± 0.63), as the dominant species, followed by *Fragaria nubicola* (IVI = 2.92 ± 0.08), *Abies pindrow* (IVI = 1.78 ± 0.58), *Parrotiopsis jacquemontiana* (IVI = 1.54 ± 0.53), *Viburnum cotinifolium* (IVI = 1.44 ± 0.42), *Aesculus indica* (IVI = 1.33 ± 0.40), *Jasminum grandiflorum* (IVI = 0.99 ± 0.45), and *Taxus wallichiana* (IVI = 0.98 ± 0.32) (Supplementary Table 1). Associations 1 and 3 exhibited wider spatial spread in the ordination, reflecting higher ecological variability within these groups. This may be attributed to a mix of moderate disturbance levels, diverse microhabitats, and higher species richness. In contrast, Associations 2 and 4 implying more homogeneous site conditions, possibly due to dominant environmental pressures such as consistent timber extraction (Association 2) or severe erosion (Association 4).

Variation between the associations

The analysis of the Himalayan cedar populations through SIMPER (Similarity Percentage) revealed an overall dissimilarity of 56.99% across the four identified plant associations. The species *Parrotiopsis jacquemontiana* emerged as the top contributor to this dissimilarity, accounting for 3.77% with an average dissimilarity of 2.15, predominantly found in Associations 1 and 3 (Fig. 6 & Supplementary Table 2). *Viburnum grandiflorum* closely followed, contributing 3.65% and demonstrating higher mean abundance in Associations 2 and 4, thereby playing a significant role in differentiating these groups. Other notable contributors included *Sarcococca saligna* (3.52%) and *Pinus wallichiana* (3.47%), which was consistently present across all associations, particularly in Association 4. Despite Himalayan cedar being the focal species, its contribution to overall dissimilarity was

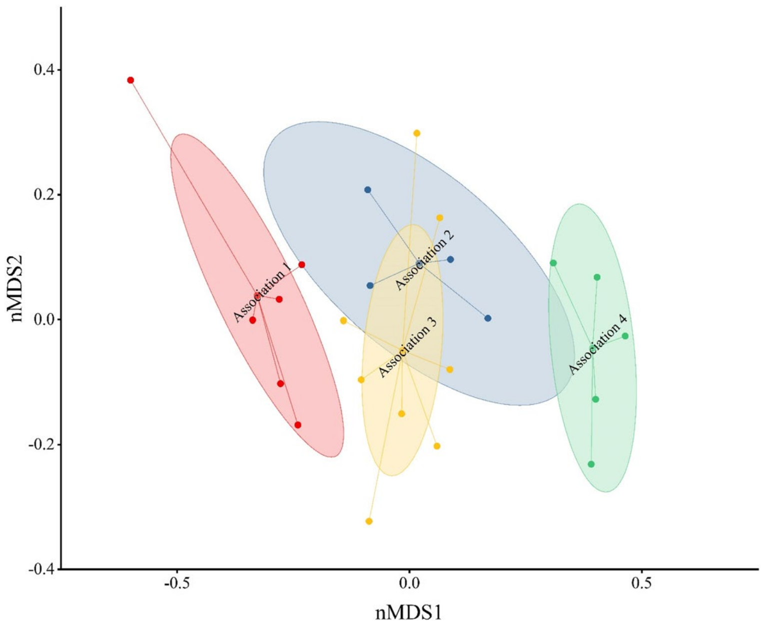

Fig. 6 Non-Metric Multidimensional Scaling (NMDS) plot illustrating the differentiation of plant associations in Himalayan cedar populations based on species composition

2.34%, indicating that while it remains dominant, other taxa are more variable and influential in distinguishing the associations. Species like *Teucrium royleanum* (2.62%) and *Cymbopogon citratus* (2.61%) were also significant, exhibiting differential distributions that marked their roles in shaping specific associations. As cumulative contributions approached 50%, lesser abundant species such as *Oxalis corniculata* and *Quercus floribunda* (both at 1.69%) were noted for their impact on dissimilarity, particularly in understory and ground vegetation. Furthermore, shrubs like *Berberis lycium* (2.01%) and *Rubus fruticosus* (3.24%) added to the structural complexity and species diversity among the associations (Supplementary Table 2). The prominence of *Parrotiopsis jacquemontiana* in SIMPER analysis (3.77% contribution to dissimilarity) suggests its selective association with certain microhabitats. It was particularly abundant in Associations 1 and 3, which were characterized by moderate grazing and higher soil nitrogen levels, while nearly absent in other associations. This uneven distribution implies that *P. jacquemontiana* may be sensitive to disturbance gradients or specific soil and canopy conditions, making it a potential indicator species for moderately disturbed temperate cedar habitats.

NMDS ordination

The results of the Non-Metric Multidimensional Scaling (NMDS) analysis complemented these findings, showcasing distinct differences among the four associations through two-dimensional coordinates (nMDS1 and nMDS2) and a stress value of 0.16762, indicating a good fit. Association 1 displayed variation with coordinates ranging from (−0.60, 0.38) to (−0.23, 0.08), while Association 2 exhibited a more compact clustering with points like (−0.08, 0.05) and (0.16, 0.002). Association 3 revealed a broader distribution (0.08, −0.07) to (−0.01, −0.15), indicating considerable variability, whereas Association 4 was characterized by coordinates ranging from (0.3, 0.09) to (0.46, −0.02), demonstrating a clear clustering distinct from other groups.

Diversity pattern

The analysis of diversity indices across different associations revealed significant variations among the studied groups. The Shannon diversity index showed the highest mean value in Association 3 (3.31 ± 0.05), indicating the highest species richness and diversity, with a significant difference compared to Association 4 (3.07 ± 0.04), which had the lowest mean value. Associations 1 and 2 exhibited intermediate values (3.15 ± 0.06 and 3.23 ± 0.04, respectively), suggesting no significant difference from each other but showing variability relative to Associations 3 and 4. For the Simpson diversity index, the highest mean was observed in Association 3 (0.95 ± 0.002), followed closely by Association 2 (0.95 ± 0.003), indicating higher diversity and lower dominance of any single species. Association 4 had the lowest Simpson index (0.93 ± 0.005), highlighting reduced species diversity.

Association 1 presented an intermediate value (0.95 ± 0.004), signifying a moderate level of diversity. The Dominance index was significantly higher in Association 4 (0.062 ± 0.002), suggesting greater dominance of specific species within this group. In contrast, Association 3 had the lowest dominance index (0.045 ± 0.001), indicating a more even distribution of species. Associations 1 and 2 showed similar values (0.056 ± 0.003 and 0.053 ± 0.003, respectively). Regarding Evenness, Association 1 exhibited the highest value (0.67 ± 0.017), reflecting a more balanced distribution of species abundances. Association 2 had the lowest evenness (0.60 ± 0.016), indicating less uniformity. Associations 3 and 4 showed intermediate values (0.64 ± 0.009 and 0.67 ± 0.023, respectively), indicating moderate evenness (Fig. 7).

Threats to the Himalayan cedar population

The Canonical Correspondence Analysis (CCA) results reveal the primary environmental threats affecting the distribution of Himalayan cedar populations across surveyed sites. The CCA identified four significant axes, with eigenvalues of 0.179, 0.1151, 0.0958, and 0.0885, cumulatively explaining 22.94% of the dataset's variance (Supplementary able 3). Pseudo-canonical correlations, increasing across the axes (Axis 1: 0.7696 to Axis 4: 0.8661), suggest a strong correlation between environmental variables and species distribution patterns. Among these variables, altitude emerged as the most influential, accounting for 16.2% of the variation ($p = 0.026$), highlighting its essential role in defining the cedar populations'ecological niche. The extraction of Timber Forest Products (TFPs) also significantly impacted species distribution, explaining 15.2% of the variation ($p = 0.024$), underscoring the role of anthropogenic activities in shaping these populations. Additionally, fire accounted for 11.3% of the variation ($p = 0.042$), while other variables, such as erosion, grazing, settlements, and slope, contributed less significantly, each explaining approximately 4% and showing limited statistical significance (Supplementary Table 3). A Chi-square test showed that grazing intensity differed significantly across sites ($\chi^2 = 8.43$, $p = 0.0147$). Similarly,

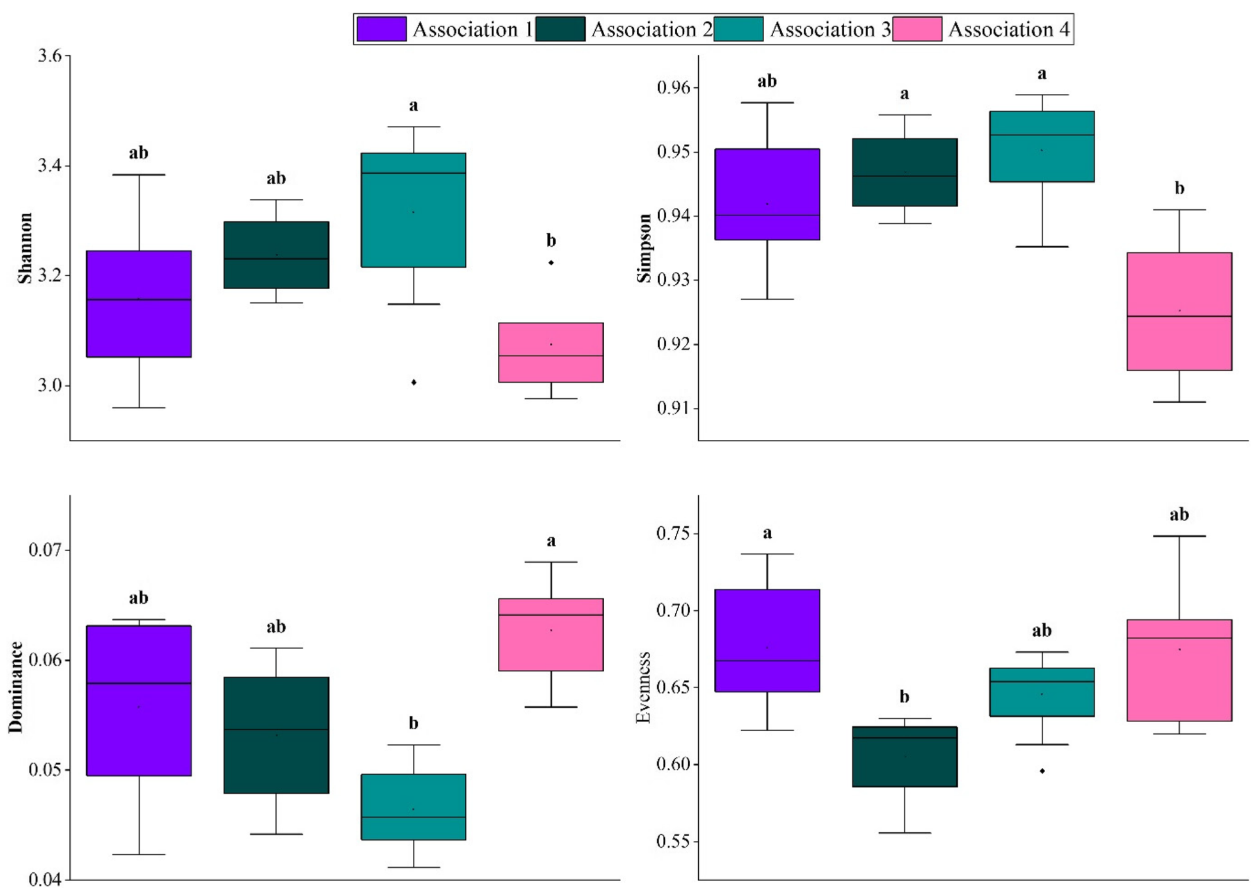

Fig. 7 Boxplot showing the diversity indices for Himalayan cedar populations across four associations. **a** Shannon Index: **b** Simpson Index: **c** Dominance Index: **d** Evenness Index. Different letters (a, b, ab) denote significant differences based on the Tukey post hoc test

erosion intensity also showed a significant non-uniform distribution ($\chi^2 = 6.87$, $p = 0.0322$), indicating that both pressures vary meaningfully across the landscape.

The CCA biplot further illustrates these relationships, with Association 1 closely linked to altitude and slope, indicating these natural factors'influence on its composition. Association 2 aligns with extraction of TFPs and fire, suggesting greater susceptibility to human pressures and fire-related disturbance. Association 3 is influenced by grazing and settlements, highlighting the impact of livestock activity and human habitation, while Association 4 is associated with erosion, indicating that soil degradation may be a key threat to this group. The directional vectors in the biplot, particularly the prominent arrows for altitude and extraction of TFPs, indicate these factors'strong contribution to variation among associations. The clear separation of associations along environmental gradients reinforces the importance of both natural (altitude, slope) and anthropogenic (extraction, fire, grazing) pressures in shaping the ecological structure of Himalayan cedar populations (Fig. 8). These findings suggest that conservation efforts should prioritize mitigating the impacts of altitude-related challenges and regulating resource extraction to support the sustainability of cedar populations.

Impact of edaphic variables on Himalayan cedar association

The total variation in the dataset was 2.08546, with the explanatory variables accounting for 35.0% of the total variance (adjusted explained variation: 4.7%). The eigenvalues for the first four axes were 0.2814, 0.1245, 0.1092, and 0.0703, respectively, with a cumulative explained variation of 28.07% by Axis 4 (Supplementary Table 3). The analysis of simple term effects showed that Total Potassium (TK) and Total Nitrogen (TN) were the most influential factors, explaining 9.3% and 9.2% of the variation, respectively. Total Phosphorus (TP) and pH were also significant, accounting for 7.5% and 7.2% of the variation. Although Soil Moisture accounted for 6.9% of the variation, its effect was not statistically significant ($p = 0.06$). In contrast, Soil Organic Matter (SOM) and Electrical Conductivity (EC) contributed less, with 4.6% and 3.6% explained variation, respectively, and were not significant ($p > 0.05$). Soil Moisture and SOM have strong influences along the left axis, suggesting a distinct ecological gradient affecting Associations 3 and 4. Associations 1 and 2 are more aligned with the vectors for TP, pH, and EC (Supplementary Table 3). The separation of associations along the axes suggests distinct environmental niches, with Association 1 and Association 2 being influenced by higher soil pH and electrical conductivity. Association 3 shows a closer relationship with nutrient variables like

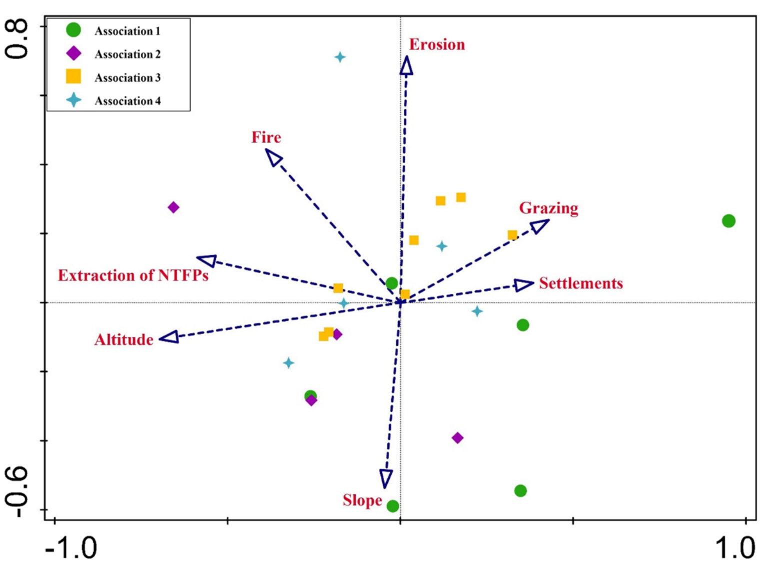

Fig. 8 CCA biplot depicting the relationships between Himalayan cedar associations (colored symbols) and key environmental threats (arrows). Each association is represented by a different symbol: green circles (Association 1), purple diamonds (Association 2), yellow squares (Association 3), and blue stars (Association 4). Arrows indicate the direction and strength of influence of environmental variables, with longer arrows (e.g., altitude, extraction of TFPs) representing stronger impacts on species distribution. The positioning of associations relative to the arrows suggests that altitude and slope strongly influence Association 1, extraction of TFPs and fire affect Association 2, grazing and settlements impact Association 3, and erosion plays a significant role in Association 4. The clear clustering of associations along environmental gradients illustrates the combined effect of natural and anthropogenic factors on cedar populations; NTFPs (Non-timber Forest Products)

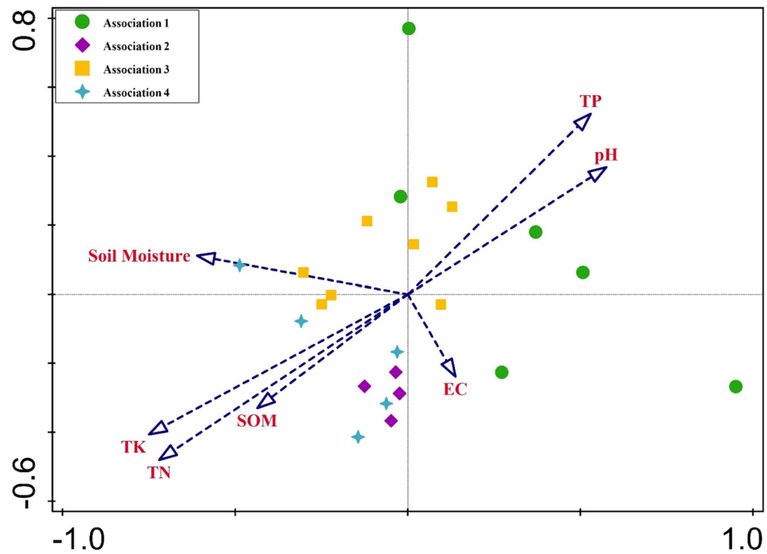

Fig. 9 Canonical Correspondence Analysis (CCA) biplot depicting the relationships between Himalayan cedar associations (colored symbols) and key environmental variables (arrows). Associations are represented by distinct symbols: green circles (Association 1), purple diamonds (Association 2), yellow squares (Association 3), and blue stars (Association 4). The length and direction of the arrows indicate the strength and influence of environmental factors such as Total Potassium (TK), Total Nitrogen (TN), Total Phosphorus (TP), pH, Soil Moisture, Soil Organic Matter (SOM), and Electrical Conductivity (EC)

TK and TN, while Association 4 is associated with higher soil moisture (Fig. 9).

Influence of altitude and edaphic factors on Himalayan cedar

The regression analysis of Himalayan cedar density against altitude and various edaphic parameters revealed differing levels of association. The relationship between density and altitude showed a moderate positive trend ($R^2 = 0.09$), suggesting that cedar density tends to increase slightly with higher altitudes. For soil moisture, a positive association was also observed ($R^2 = 0.09$), indicating that higher soil moisture content is linked to increased cedar density. In contrast, the relationship between density and pH was weaker ($R^2 = 0.05$), suggesting a limited impact of soil pH on cedar density. Although the trend was slightly negative, it indicates that minor variations in pH do not strongly influence the distribution of Himalayan cedar within the studied range. Electrical conductivity (EC) showed no significant association with cedar density. Similarly, total phosphorus (TP) had a very weak association ($R^2 = 0.03$), suggesting minimal influence of available phosphorus on cedar density, which could indicate a lower dependence of cedar on phosphorus availability in these habitats. Soil organic matter (SOM) and total potassium (TK) both exhibited weak positive relationships with cedar density ($R^2 = 0.05$), while total nitrogen (TN) showed the strongest positive association ($R^2 = 0.11$), among the edaphic parameters analyzed. The positive trend with TN suggests that higher nitrogen levels, which are critical for plant growth, may support greater cedar density. The analysis indicates that altitude, soil moisture, and nitrogen availability are more influential in determining the density of Himalayan Cedar, while factors like soil pH, EC, TP, SOM, and TK show limited or weak associations. These results emphasize the importance of specific environmental gradients in shaping the population dynamics of Himalayan cedar across its natural range (Fig. 10).

Discussion

The Himalayan temperate forest ecosystem is crucial for regulating ecological dynamics, providing valuable ecosystem services, maintaining environmental conditions, and offering habitat for numerous species [17, 44, 66, 72, 73]. To understand the forest dynamics of the Himalayan cedar Forest, it is essential to explore the spatial distribution, vegetation structure, species associations, and impact of edaphic factors, threats, and diversity patterns. Research has shown that topographic and edaphic factors contribute to significant variations in vegetation community structures along elevational gradients [74].

Four significant species connections were identified using the Ward Cluster Analysis of 23 *Himalayan cedar* population survey sites. *Himalayan cedar* dominates Association 1, which includes 75 species spread across six sites (IVI = 4.53 ± 0.43). In Association 2, *Pinus wallichiana* (IVI = 3.95 ± 0.50) is the dominant species

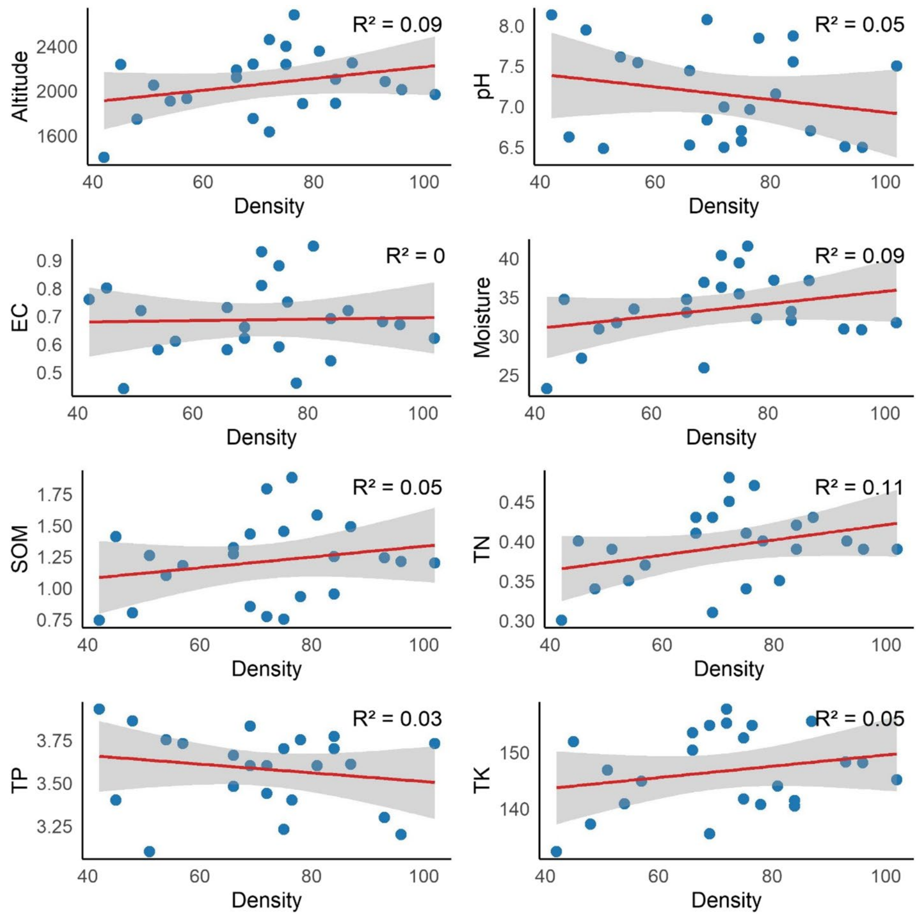

Fig. 10 Relationship between Himalayan cedar density and environmental variables, including altitude and various edaphic factors (pH, electrical conductivity (EC), soil moisture, soil organic matter (SOM), total nitrogen (TN), total phosphorus (TP), and total potassium (TK)). Each plot displays the linear regression line with a 95% confidence interval (shaded area), along with the R^2 values indicating the strength of the association

among 66 species found at four sites. Association 4 consists of five sites with 88 species, predominantly featuring *Viburnum grandiflorum* (IVI =3.78 ±0.63). Association 3 encompasses eight sites with 82 species, primarily *Fragaria nubicola* (IVI =2.66 ±0.17). Our results are in consistent with previous studies which also reported dominance of similar species from the temperate forests of Himalayan region [10, 72, 75]. The species *Pinus wallichiana, Viburnum grandiflorum*, and *Fragaria nubicola* were recorded as indicator species in these associations due to their broad elevation range across the temperate forests of the western Himalayan region. Altitude significantly influences tree distribution as it directly affects the microclimate of the environment [23, 43, 76]. Forest community composition is influenced by regional climate, topography, biotic interactions, disturbances, and microhabitats [53, 77]. However, human activities such as construction, illicit plant extraction, and grazing disrupt ecological processes, altering habitat characteristics and species composition at all scales [78]. Due to the aforementioned reasons, the current study results showed significant variations among the four associations in the region, resulting in a heterogeneous species distribution, except for a few predominant species across the study area.

The predominance of plant families in the study area, such as Rosaceae, Asteraceae, Poaceae, and Lamiaceae, aligns with findings from temperate forests of the Himalayas [38, 77, 79, 80]. Asteraceae broad ecological flexibility makes it the leading plant family in several Himalayan studies [60, 64, 81]. The Rosaceae family ranks as the second most common in the region due to its adaptability, diverse growth forms, effective reproduction, and ability to thrive in various environmental conditions along elevational gradients [82, 83]. The varied distribution of plant families across forest types is driven by dynamic ecological niches and differences in microhabitats, with herbaceous species accounting for the majority of diversity among the four species associations in the research area.

Altitude influences species distribution by altering climatic variables such as temperature, humidity, and precipitation. Himalayan cedar populations in Kashmir are found at altitudes between 1400 and 2700 m, according to a digital elevation model. This highlights the significance of specific altitudinal gradients in their distribution, likely as an adaptive response to environmental factors such as temperature and soil properties [10, 84, 85]. Notably, only 17.39% of populations inhabit higher elevations (2300–2700 m), suggesting that these altitudes are more susceptible to harsher conditions or less favorable environments [86]. Himalayan cedar populations exhibit a low stem density of 110.73 trees per hectare, significantly lower at some sites than the reported by [87]. Additionally, a stump count of 90.62 per hectare indicates extensive deforestation. The decline of these trees is further exacerbated by the high demand for their sturdy wood and high calorific value for fuel, furniture, and timber [88]. The primary factor contributing to this sharp worldwide loss is anthropogenic disturbances, underscoring the vital role human activity plays in the survival of this species [10, 84, 89, 90]. Himalayan cedar populations regenerate extremely poorly, with only 15 seedlings per hectare, raising concerns about the species long-term viability. More than 60.86% of these populations experience moderate to heavy grazing pressure, which significantly impairs seedling regeneration. These seedlings are particularly susceptible to specific microclimatic factors such as shade, moisture, and canopy cover [91].

The diversity indices results showed considerable heterogeneity between relationships. Association 3 had the greatest Shannon (3.31) and Simpson (0.95) indices, suggesting richness and evenness, whereas Association 4 had the least variety and most dominance. Himalayan cedar populations exhibit moderately low diversity and richness, with significant heterogeneity between sites. Geographical variables, species count, and community structure are the primary factors contributing to variations in Shannon's diversity and species richness [13, 92]. Generally, north-facing slopes are more diverse than drier, warmer south-facing slopes due to higher moisture content and lower temperatures [93]. Our study results indicated that populations on north and northeast-facing slopes exhibit reduced diversity at certain locations due to human pressures. In the AJK region, most human settlements are situated on these slopes, where local communities heavily rely on forest resources to sustain their livelihoods in harsh environmental conditions. Consequently, the observed patterns of diminished diversity in various forest ecosystems can be attributed to several factors, including interspecies competition, excessive grazing, anthropogenic disturbances, and uneven resource distribution [42, 66, 94]. The formation of climax communities is hindered by ecological succession, which is further disrupted by intense human pressure and challenging mountain conditions [95]. In Himalayan cedar populations, ongoing disturbance regimes impede successional processes, postponing the climax and maturity of the vegetation [96]. In temperate forests, the altitudinal range of 2000–3000 m contains good soil quality and more precipitation than the lower subtropical zones, which leads to more biodiversity [97]. Plant communities with fewer species typically have distributions that are evenly spaced, which encourages effective use of resources and reduces competition [98, 99]. On the other hand, because of their high species richness and heightened competition, more diversified ecosystems have low evenness and maturity.

The directional vectors in the biplot, especially the prominent arrows for NTFP extraction and altitude, demonstrate their significance in causing variance among relationships. The clear division of relationships along environmental gradients highlights how human factors (extraction, fire, grazing) and natural factors (altitude, slope) affect the biological structure of Himalayan cedar communities. The GIS vegetation analysis of Himalayan cedar forests revealed low stem density, moderate regeneration capacity, and high deforestation pressures. The study findings were less than those of Ahmed et al. [86], Sheikh et al. [17], and Rahman et al. [72]. Deforestation, overgrazing, erosion, fire, settlements, and NTFPs extraction are major threats to Himalayan cedar populations in Kashmir, as reported by various researchers [17, 72, 86]. These forests are at risk due to rising temperatures and decreased soil moisture brought on by climate change and global warming [84]. According to ecological models, global warming may cause Himalayan cedar to migrate to higher elevations [10, 85, 90]. Grazing intensity showed a statistically significant variation across sites, with more than 60% of populations experiencing moderate to heavy grazing. High grazing pressure reduces regeneration by damaging seedlings, compacting soil, and disrupting microhabitat conditions. Erosion intensity also varied significantly, with over one-third of the sites facing severe erosion. These conditions contribute to the degradation of habitat quality by removing topsoil, reducing moisture retention, and increasing susceptibility to landslides—factors that ultimately affect the vitality and distribution of Himalayan cedar populations.

Edaphic variable results showed that the dataset has a total variation of 2.085, with explanatory variables accounting for 35.0% (adjusted 4.7%). Total nitrogen (9.2%) and total potassium (9.3%) were important components that significantly impact the Himalayan cedar populations in the Kashmir region. Associations were shaped by specific environmental niches that were impacted by ecological gradients and soil characteristics. Soil nutrients play a pivotal role in maintaining the community population structure and distribution of plant species and also influence the growth and development of plants [67, 100]. The balance of carbon, nitrogen, potassium, and phosphorus in plants, soils, and microorganisms is critical to forest ecosystem functions [101]. Forest transitions affect soil carbon and nutrient levels by altering root and litter nutrient inputs due to shifts in plant communities [102]. The regression analysis identifies altitude, soil moisture, and total nitrogen (R^2 = 0.09–0.11) as significant drivers of Himalayan cedar density, with moderate to strong positive relationships. However, for soil pH, electrical conductivity, total phosphorus, organic matter, and potassium, the impacts were modest or insignificant (R^2 = 0.03–0.05). The significance of particular environmental conditions in cedar dispersal is highlighted by these studies. Current soil nutrients and environmental variables are in consistent with various studies [64, 67, 103]. The results of the current study on soil properties emphasize that altitude, soil moisture, and total nitrogen have the greatest effects on Himalayan cedar populations in Kashmir, exhibiting substantial positive associations. In contrast, factors such as potassium, electrical conductivity, and soil pH had minimal impact on these populations. This highlights the significance of certain environmental and edaphic elements in influencing population dynamics.

Future conservation implications

Sustainable forest management is a preferred strategy that may achieve various goals, including ecosystem services, resilience to climate change, recreation, timber production, and conservation of biodiversity [104]. Managed forests represent a significant level of diversity due to positive responses to forest management [105]. Recent studies indicate that managed forests have greater species richness compared to unmanaged forests because forest management can create diverse microhabitats [106–108]. Anthropogenic activities have substantially restricted the distribution regions of Himalayan cedar, with limited populations in mountainous areas being vulnerable to disturbances. To preserve Himalayan cedar forests and their habitat, we urge a complete ban on activities like deforestation, branch picking, and habitat trampling where this species is found. Specifically, more rigorous management practices should be implemented in these hotspot areas. Our goal is to reduce human disturbance and safeguard suitable habitats to foster population growth and expand distribution ranges. Forest fragmentation could threaten biodiversity and conservation efforts for plants [109, 110]. The government and Forest Department must regulate tourism and road construction in Himalayan cedar habitats in order to mitigate negative impacts such as habitat fragmentation, illegal timber smuggling, soil erosion, and tree removal for the sustainability of Himalayan cedar forests. The government, stakeholders, and forest department should develop public awareness and outreach programs in areas where Himalayan cedar forests are present. In-situ conservation, plant micro-reserves, dynamic monitoring, and conservation consciousness are among the efforts required to prioritize conservation to prevent habitat degradation. Climate change poses a significant threat to current conservation networks [111], especially in the most sensitive regions like the mountainous temperate forests of the Himalayas [112]. Involving organizations and local communities is crucial for the long-term conservation of this species and should be encouraged from the outset. Hence, it is critically important that decision-makers give thoughtful consideration and then implement measures that prioritize the conservation and sustainable utilization of these valuable resources, ensuring their availability for future generations.

Conclusion

This study indicates the Himalayan cedar's vital ecological role in Western Himalayan forests, as well as the increasing challenges it confronts from both natural and human-induced resources. The findings indicated an average stem density of 110.73 trees per hectare and poor regeneration, with only 15 seedlings per hectare. Human pressures were evident, reflected in a mean stump density of 90.62 stumps per hectare. GIS analysis revealed that cedar populations preferentially inhabit elevations between 1900 and 2200 m on north-facing slopes. CCA identified altitude (16.2%) and timber extraction (15.2%) as key drivers of cedar distribution. Additionally, soil nitrogen (R^2 = 0.11) and moisture (R^2 = 0.09) were found to influence cedar density, while NMDS indicated a 56.99% inter-association dissimilarity. The study establishes a baseline for the population dynamics of Himalayan cedar, emphasizing the effects of edaphic and anthropogenic factors along an elevation gradient. It employs GIS, spatial analysis, and multivariate statistical methods to evaluate distribution patterns. However, limitations include the need for a larger sample size and the consideration of additional ecological variables. Future research should incorporate GIS-based forest cover estimation and habitat suitability modelling. To sustainably manage Himalayan cedar, site-specific conservation strategies should encompass controlled grazing, regulated timber extraction, community-based afforestation programs, soil conservation measures, anti-logging policies, ecotourism initiatives, and collaboration among local communities, researchers, and policymakers. Protecting the Himalayan cedar is critical for preserving the biodiversity and ecological health of the Kashmir Himalayas, ultimately contributing to the overall resilience of the forest ecosystem.

Supplementary Information

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Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

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Clinical trial number

Not applicable.

Informed consent statement

Not applicable.

Ethical guidelines statement

This study is a part of the research work of Ph.D. scholar Mr. Syed Waseem Gillani (first author), which was approved by the Advanced Studies & Research Board (ASRB) at the Quaid-i-Azam University Islamabad, Pakistan. All sampling was conducted on public land with the appropriate permissions granted by the local government body.

Authors' contributions

Conceptualization, S.W.G. and M.A.; Methodology, S.W.G; software, M.W. and M.M.; validation, F.A. and S.I.; formal analysis, M.W.,; investigation, M.W.; resources, H.S. and M.A.; Data curation, A.A., B.F.A.,; writing—original draft preparation, S.W.G., M.W., M.M; writing—review and editing, M.W., M.M., A.T., A.B.M., M.A., A.A., H.S., S.W.G, and B.F.A.,; visualization, M.W.; supervision, M.A. and M.W.; project administration, H.S.; funding acquisition A.A.. All authors having substantial contributions in research, read and agreed to the published version of the manuscript.

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Data availability

Data is contained within the article.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable—this manuscript has no personal data from the authors.

Competing interests

The authors declare no competing interests.

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