ECOLOGICAL PATTERNS OF *QUERCUS* SPECIES ALONG ENVIRONMENTAL GRADIENTS IN THE WESTERN HIMALAYA, PAKISTAN

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ABSTRACT

Himalaya is one of the global biodiversity hotspots and hosts a complex mountain ecosystem due to high topographic and climatic heterogeneity, yet its forests are under constant pressure from climate change and human-driven disturbances. In this study, we examined the distribution, community structure, and ecological factors affecting *Quercus*-dominating forests in the Hazara Division, Pakistan. A total of 98 sites were sampled using the quadrat method to assess plant associations and species composition. Quadrat sizes were 10 × 10 m^2 for trees, 5 × 5 m^2 for shrubs, and 1 × 1 m^2 for herbs. A total of 180 plant species belonging to 142 genera and 65 families were recorded. *Quercus* species showed clear elevational stratification with *Q. glauca* dominant at low elevation of 942 meters above sea level (MASL), *Q. baloot* and *Q. dilatata* at mid elevation (1123-2423 MASL), while *Q. semecarpifolia* at high altitude (2687-3306 MASL). Cluster analysis revealed 6 assemblages of communities: *Quercus incana-Asparagus officinalis-Avena fatua* community (QAA), *Quercus incana-Aesculus indica-Phragmites communis* community (QAP), *Quercus semecarpifolia-Bergenia stracheyi- Indigofera heterantha* community (QBI), *Quercus dilatata-Cannabis sativa-Quercus glauca* community (QCQ), *Quercus incana-Prunus vulgaris-Quercus dilatata* community (QPQ), and *Quercus baloot-Quercus dilatata-Cynodon dactylon* community (QQC). Highest diversity (richness=22.3) was recorded in the QQC community at mid elevation with Shannon index (2,78), and the lowest diversity (13.8) was found in the QBI community at high elevation (H=2.37). Multivariate analyses showed that temperature (r^2=0.25), relative humidity (r^2=0.14), and altitude (r^2=0.5) were the most important climatic and geographic factors determining species distribution. *Q. semecarpifolia* and *Q. glauca* showed a poison model with the environmental variable, while other species exhibited a negative binomial model in response to environmental gradients. This study provides baseline strategies for the preservation and conservation of *Quercus* species under climatic and anthropogenic pressures and supports the development of effective management strategies in the western Himalayan forests in the Hazara division of Pakistan.

Keywords: *Quercus*, Distribution, Community structure**,** Multivariate analyses, Species richness, Environmental variables

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INTRODUCTION

The Himalaya is globally recognized as a biodiversity hotspot, supporting exceptional species richness and endemism driven by complex topography and diverse microclimatic conditions (Tali *et al.*, 2019). However, due to anthropogenic stress, rapid land-use change, and climate impact, the Himalayan biodiversity is being lost at a faster rate (Yadav *et al.*, 2021; Premlata *et al.*, 2024). Excessive use of medicinal plants further contributes to this crisis, threating several endemic species, leading to their extinction (Shivali and Namrata, 2022; Shinwari *et al.*, 2024). These impacts are particularly severe in mountainous regions, where species adapted to narrow ecological niches exhibit limited resilience to environmental change (Agnihotri *et al.*, 2017).

The genus *Quercus* (oak), comprising approximately 600 species, is ecologically and economically important across the Northern Hemisphere (Aldrich and Cavender-Bares, 2011). Oaks take up various habitats, maintain biodiversity and soil stability, and provide food and shelter for wildlife. Their durable timber, acorns, and tannins have long been valued, and their longevity and versatility make them essential components of forest ecosystems. The current phenomenon in molecular genetics and breeding provides the chance of improving their management and conservation in the context of evolving environmental conditions (Tantray *et al.*, 2017).

In Pakistan, *Quercus*-dominated forests are primarily distributed in dry and moist temperate zones along elevational gradients ranging from approximately 1200 to 3500 meters above sea level (MASL), forming pure and mixed stands with other forest types (Khan *et al*., 2010; Rahman *et al*., 2022). Species such as *Q. baloot* and *Q. oblongata* dominate dry temperate regions, whereas *Q. semecarpifolia* and *Q. dilatata* are more prevalent in moist temperate zones, reflecting their ecological adaptations to varying climatic conditions (Khan *et al*., 2010; Rahman *et al*., 2022).

Vegetation distribution in mountainous ecosystems is strongly regulated by environmental gradients, particularly climate, topography, and soil properties. The Hazara Division of the western Himalaya represents a critical region for studying these dynamics due to its steep elevational gradients and heterogeneous edaphic conditions (Haq *et al.*, 2024, 2025). However, increasing anthropogenic pressures, including deforestation, overgrazing, and land-use conversion, are significantly altering forest structure and ecological processes in this region (Singh *et al.*, 2019; Kumar *et al*., 2022).

Despite the ecological importance of *Quercus* forests, previous studies in the region have largely focused on understory vegetation, with limited emphasis on woody species and the integrated role of environmental drivers in shaping community structure (Farooq, 2019; Ahmed *et al.*, 2021; Faisal *et al.*, 2022). This lack of comprehensive, gradient-based analysis limits our understanding of species distribution patterns, regeneration dynamics, and ecosystem functioning in these forests. Therefore, the current study was designed to quantify the distribution and community structure of *Quercus* species along environmental gradients in the Hazara Division of the Western Himalaya, and identify key environmental drivers (climatic, edaphic, and topographic) influencing species composition, population structure, and regeneration potential. By integrating vegetation and environmental data, this study provides a robust ecological framework to support conservation planning and sustainable management of oak forests under increasing climatic and anthropogenic pressures.

MATERIALS AND METHODS

Study area: Hazara Division is an ecologically diverse landscape located between the 33º-44′ to 35º-35′ North latitude and from 72º-33′ to 74º-05′ East longitude and spans over Abbottabad, Haripur, Tor Ghar, Mansehra, Battagram, and Kohistan districts as detailed in Figure 1. The study was carried out in 98 different localities, comprised of 294 quadrats and 98 stands. The area is typified by high altitude meadows, fertile cultivated land, mountainous mountain ranges, snowy glaciers, picturesque tributary systems, such as rivers, streams, lakes, and ponds. Due to diverse topography, geological and habitat heterogeneity, Hazara sustains a high number of flora throughout the seasons (Rahman *et al*., 2023).

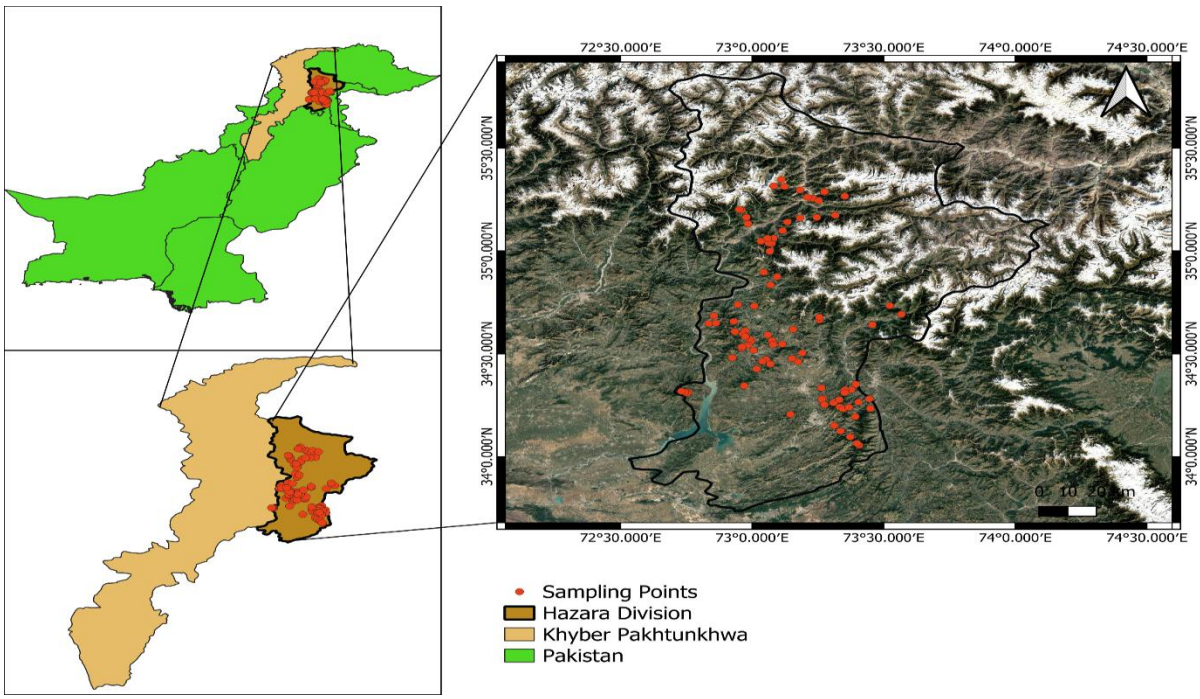

Figure 1: The spatial distribution of sampling sites of Himalaya of Hazara Division, KP, Pakistan.

The climate of the area is characterized by high seasonality, hot and humid summer, cold and snowy winter. This environmental variability combined with diverse habitats, supports vegetation cover and a high diversity of medicinal and aromatic plants of significant economic and ecological importance (Shekhar *et al.*, 2010).

Plant Collection: A total of 98 sampling sites were selected using a stratified sampling design to spatial heterogeneity along environmental gradients (temperature, elevation, slope angle, slope aspect), ensuring proportional representation of major habitat types and adequate spatial replication with sufficient inter-site distance to minimize spatial autocorrelation. At each site, three stratified quadrats were established to assess species composition and plant associations, with quadrat sizes based on plant habit: 10 m × 10 m for trees, 5 m × 5 m for shrubs, and 1 m × 1 m for herbaceous species, following standard phytosociological attributes. Field surveys were conducted over three consecutive growing seasons (2022–2024), with each site sampled during the same season (Matiullah *et al.*, 2022; Lata *et al.*, 2024).

Density, relative density, cover, relative cover, frequency, and relative frequency of plant species were computed at each quadrat (Curtis, 1956). These parameters calculated the Importance Value Index (IVI) with the help of conventional formulas (Curtis and McIntosh, 1950). The computation of biodiversity indices, i.e., Species richness, the Shannon index, Simpson index, and the Evenness of Pilou was done using the standard formulas (Shannon, 1948; Simpson, 1949; Pielou, 1966).

The collected plant specimens were dried, mounted, and labelled on herbarium sheets, and deposited in Herbarium of Hazara University, Mansehra. The geographic coordinates, including altitude, latitude, and longitude of each site were measured with the help of a Garmin eTrex 20x GPS device.

$$\text{Frequency} = \frac{\text{No.of times in which a Species occurs}}{\text{Total no.of quadrates}} \times 100$$

$$\text{RF} = \frac{\text{Frequency of a spcies}}{\text{Total frequency of all species}} \times 100$$

$$\text{Density} = \frac{\text{Total no.of individuals of a species}}{\text{Total no.of quadrates}}$$

$$\text{RD} = \frac{\text{density of a species}}{\text{density for all species}} \times 100$$

$$\text{RC} = \frac{\text{Cover of a species}}{\text{Total covers of all species in quadrate}} \times 100$$

$$\text{Canopy cover} = \frac{\text{Total cover of a species}}{\text{Total number of quadrate}}$$

$$\text{IVI} = \text{RD} + \text{RF} + \text{RC}$$

$$\text{Simpson's Diversity Index } D = \frac{\Sigma ni(ni-1)}{N(N-1)}$$

$$\text{Shannon–Wiener Diversity Index } H' = \sum(Pi\ In\ pi)$$

$$\text{Species Evenness } J' = \frac{H'}{In\ S}$$

$$\text{Species Richness } D = \frac{S}{\sqrt{N}}$$

Soil Sampling and Field Observations: Soil samples were collected in triplicates at depths of 0–15 cm from all 98 sampling sites to ensure the representative data. Collected samples were cleaned to remove debris (stones, roots, and extraneous materials) and stored in labeled polythene bags according to sampling location before laboratory analysis at the Agricultural Research Institute, Tarnab, Peshawar, Pakistan. At each site, environmental variables were measured, including microclimatic parameters (air temperature and relative humidity using a portable hygrometer/thermometer), soil characteristics (pH, electrical conductivity, moisture contents, organic matter, nitrogen, phosphorus, potassium, calcium carbonate, and texture), and topographic factors (elevation, slope, and aspect using GPS (Garmin eTrex 20x), clinometer (MD900-T Digital Clinometer), and compass. Soil organic matter was determined using the dichromate oxidation method, available Nitrogen (N), Phosphorous (P), and Potassium (K) were estimated using the AB-DTPA extraction method (Soltanpour and Schwab, 1977), and soil texture (sand, silt, and clay fractions) was analyzed using the sieve method, following standard protocols (Bouyoucos, 1962).

Statistical Analyses: The data on 180 plant species of 98 sampling stands were entered into MS Excel to be statistically evaluated. Species-environment relationships and community gradients were analyzed using R software (version 4.5.2) through multivariate ordination techniques, including Detrended Correspondence Analysis (DCA), Canonical Correspondence Analysis (CCA), Principal Component Analysis (PCA), and Non-Metric Multidimensional Scaling (NMDS). While Cluster Analysis (CA), Hierarchical Cluster Analysis (HCA), Two-Way Cluster Analysis (TWCA), and Indicator Species Analysis (ISA) were conducted in PC-ORD 5.0 (McCune and Mefford, 2006). Plant communities were classified using the Sørensen distance and the Ward method of linkage to measure floristic similarity among sampling sites (Sorenson, 1948; Ward, 1963). Both presence-absence and abundance data were applied to determine associations, with ISA identifying significant indicator species ($P \leq 0.05$). Additionally, the Generalized Linear Model (GLM) was used to analyze

the effects of abiotic factors on species abundance. The QGIS software (Version. 3.40) was used to create distribution maps of the plant communities (QGISorg 2022).

RESULTS

***Quercus* species distribution in the study area:** A total of five *Quercus* species were recorded across the study area with elevational stratification. *Quercus baloot*, *Q. dilatata*, *Q. glauca*, *Q. incana*, and *Q. semecarpifolia*. *Q. glauca* was found in low altitude (884–1077 MASL), while *Q. baloot* was abundant at lower- to mid-elevation (1123–2423 MASL). *Q. dilatata* and *Q. incana* showed broad ecological amplitude, extended from lowlands (942 MASL) to high montane sites (>2500 MASL), often co-occurring in mid-elevation forests (Table 01). In contrast, *Q. semecarpifolia* was restricted to high elevations (2687–3306 MASL), reflecting its adaptation to subalpine habitats (Figure 2).

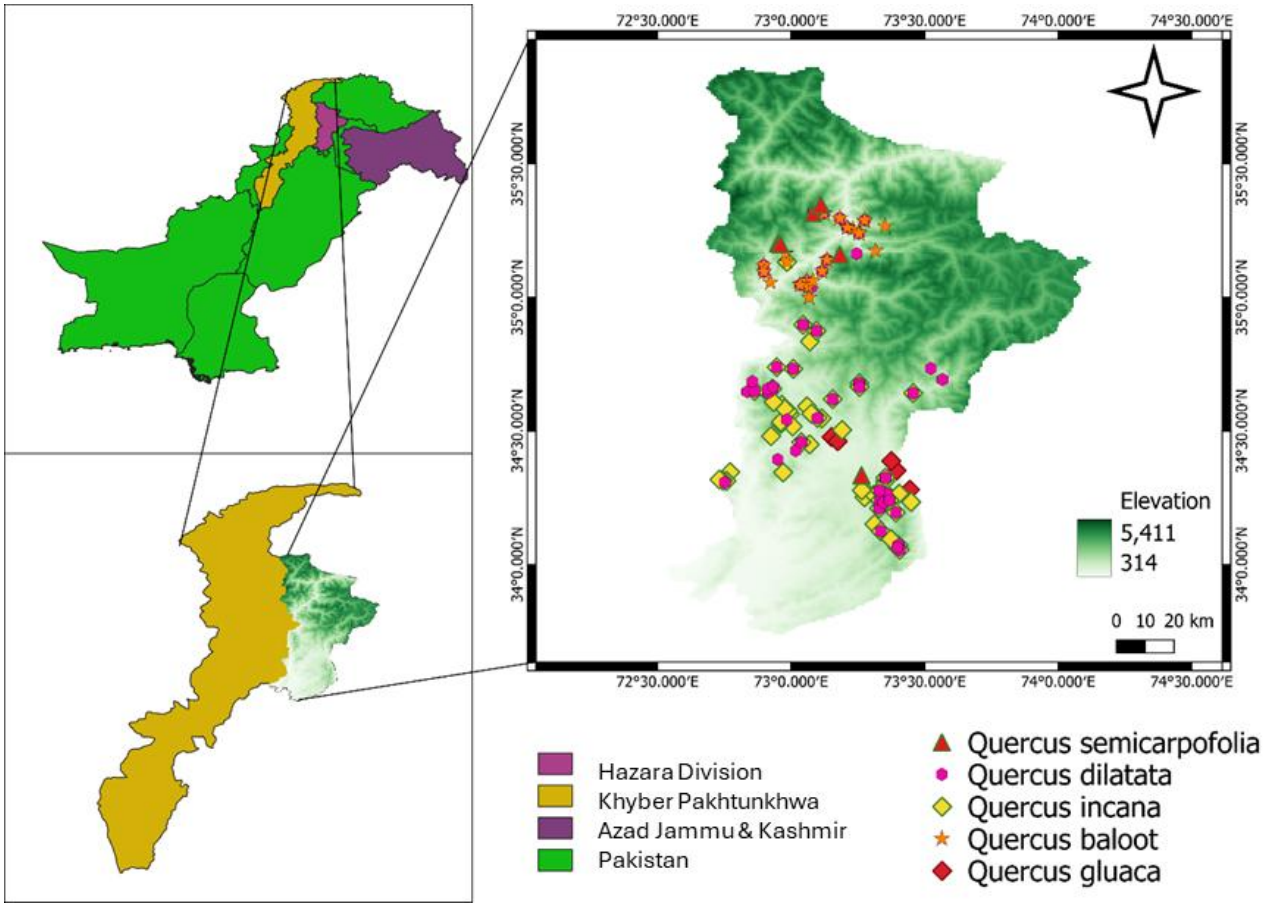

Figure 2: Elevational distribution of *Quercus* species, ranging from lowland (*Q. glauca*) to subalpine (*Q. semecarpifolia*) zones of Himalaya of Hazara Division, Pakistan.

Plants growth form in study area: The chord diagram shows the structural composition and relationships of plant growth forms observed in the study area. Plants were classified into five forms: trees, shrubs, herbs, ferns, and climbers. Herbs were most common, followed by shrubs and trees; ferns and climbers were least represented. Connecting arcs indicate correlations and distribution patterns, revealing the floristic diversity and dominance of herbaceous vegetation. This highlights herbs' ecological role in community stability, while the abundance of woody and climbing species reflects the complexity and heterogeneity of habitats within the sites (Figure 3).

Table 1. Elevational stratification of recorded *Quercus* species across the study area.

S.NO	Stand	Latitude (DMS)	Longitude (DMS)	Altitude (MASL)	Species
1	Bala	35°17′09.18″ N	73°16′26.88″ E	1947	*Quercus baloot*
2	Banil Banda	35°07′58.21″ N	72°59′04.62″ E	1218	*Quercus baloot*
3	Chartoo	35°15′21.62″ N	73°13′53.30″ E	1123	*Quercus baloot*
4	Datal Banda	35°09′50.61″ N	72°58′42.90″ E	1722	*Quercus baloot*
5	Gabar	35°03′22.96″ N	72°55′20.94″ E	1709	*Quercus baloot*
6	Gaheen	35°16′00.48″ N	73°21′06.98″ E	2387	*Quercus baloot*
7	Gulli Bagh	35°02′51.40″ N	73°02′00.13″ E	1808	*Quercus baloot*
8	Jailbek	35°14′23.48″ N	73°15′13.75″ E	2386	*Quercus baloot*
9	Katto	35°03′41.94″ N	73°03′30.71″ E	2423	*Quercus baloot*
10	Khargai	35°02′18.96″ N	73°03′48.35″ E	2325	*Quercus baloot*
11	Komila	35°15′42.83″ N	73°12′36.70″ E	1220	*Quercus baloot*
12	Kor	35°03′41.62″ N	73°04′53.90″ E	2020	*Quercus baloot*
13	Razica	35°18′52.70″ N	73°07′23.69″ E	2167	*Quercus baloot*
14	Sanagai	35°07′13.40″ N	72°53′50.28″ E	2089	*Quercus baloot*
15	Sasak	35°17′21.27″ N	73°16′31.56″ E	2050	*Quercus baloot*
16	Seo	35°17′48.26″ N	73°10′56.93″ E	1387	*Quercus baloot*
17	Shahal	35°10′26.90″ N	73°18′59.26″ E	1696	*Quercus baloot*
18	Sharakot	35°08′26.80″ N	73°08′03.14″ E	2029	*Quercus baloot*
19	Sheriyal	34°59′58.27″ N	73°04′02.03″ E	2391	*Quercus baloot*
20	Shitgal	35°05′43.05″ N	72°53′52.22″ E	1999	*Quercus baloot*
21	Arbora	34°27′28.56″ N	73°02′18.16″ E	1475	*Quercus dilatata*
22	Ayubia	34°04′23.58″ N	73°24′07.17″ E	2056	*Quercus dilatata*
23	Banbaik	34°15′47.41″ N	73°21′33.01″ E	2329	*Quercus dilatata*
24	Barin Galli	34°11′40.06″ N	73°23′31.65″ E	1832	*Quercus dilatata*
25	Batila Allai	34°52′29.70″ N	73°05′42.20″ E	2048	*Quercus dilatata*
26	Changel Shareef	34°44′20.17″ N	72°56′45.11″ E	942	*Quercus dilatata*
27	Chatter Plain	34°37′08.90″ N	73°09′20.63″ E	1775	*Quercus dilatata*
28	Dabben	34°19′30.14″ N	73°21′10.14″ E	1776	*Quercus dilatata*
29	Dana	35°05′56.62″ N	73°06′57.28″ E	2392	*Quercus dilatata*
30	Danat	35°14′43.98″ N	73°15′11.83″ E	1977	*Quercus dilatata*
31	Donga Galli	34°03′20.07″ N	73°24′24.63″ E	2295	*Quercus dilatata*
32	Galli Badral	34°25′35.36″ N	73°01′02.07″ E	1343	*Quercus dilatata*
33	Gharri Shah Muhammed	34°18′28.66″ N	72°45′05.37″ E	1582	*Quercus dilatata*
34	Giganey Samsargay	34°38′48.63″ N	72°50′09.40″ E	1421	*Quercus dilatata*
35	Jaraid	34°41′32.53″ N	73°34′02.78″ E	1994	*Quercus dilatata*
36	Jatka Syedan	34°38′58.03″ N	72°51′46.52″ E	2077	*Quercus dilatata*
37	Jiskot Oghi	34°32′32.62″ N	72°59′02.66″ E	1364	*Quercus dilatata*
38	Kala Bagh	34°03′52.38″ N	73°23′55.06″ E	2326	*Quercus dilatata*
39	Kala Pani	34°12′37.28″ N	73°19′47.17″ E	1842	*Quercus dilatata*
40	Kamaiser	34°39′29.49″ N	72°55′49.13″ E	2216	*Quercus dilatata*
41	Kandrey	34°41′06.33″ N	72°51′18.65″ E	1543	*Quercus dilatata*
42	Kansian	34°44′03.70″ N	73°31′23.70″ E	2593	*Quercus dilatata*
43	Karoori	34°23′36.73″ N	72°56′59.70″ E	1543	*Quercus dilatata*
44	Khabal	34°32′54.95″ N	73°05′54.53″ E	1973	*Quercus dilatata*
45	Kuz Shiryal	35°02′12.09″ N	73°04′27.33″ E	2159	*Quercus dilatata*
46	Loi	35°09′49.72″ N	73°14′44.61″ E	2178	*Quercus dilatata*
47	Manda Gucha	34°40′43.53″ N	73°15′19.21″ E	2249	*Quercus dilatata*
48	Mangri Village	34°38′36.28″ N	72°54′52.93″ E	2392	*Quercus dilatata*
49	Mara Rehmat Khan	34°14′28.37″ N	73°20′00.68″ E	2230	*Quercus dilatata*
50	Paimal Shareef	34°43′57.83″ N	73°00′30.64″ E	2124	*Quercus dilatata*
51	Panjool	34°39′54.94″ N	73°15′22.54″ E	1799	*Quercus dilatata*

52	Pashto Alli	34°53′51.55″ N	73°02′40.91″ E	1671	*Quercus dilatata*
53	Sanger Galli	34°13′54.37″ N	73°20′46.43″ E	2440	*Quercus dilatata*
54	Satto Bangla	34°16′37.62″ N	73°19′52.05″ E	2229	*Quercus dilatata*
55	Shogran	34°38′30.26″ N	73°27′24.96″ E	2249	*Quercus dilatata*
56	Thandiani	34°14′24.49″ N	73°22′05.58″ E	2519	*Quercus dilatata*
57	Chirya	34°28′37.75″ N	73°09′06.09″ E	981	*Quercus glauca*
58	Dalola	34°21′07.19″ N	73°23′40.86″ E	939	*Quercus glauca*
59	Gharri Habibulla	34°23′15.25″ N	73°22′29.65″ E	1077	*Quercus glauca*
60	Gulli Bagh Mansehra	34°27′40.97″ N	73°10′27.90″ E	928	*Quercus glauca*
61	Pattan Khurd	34°16′49.17″ N	73°26′42.35″ E	884	*Quercus glauca*
62	Boi	34°19′18.80″ N	73°25′51.73″ E	859	*Quercus glauca*
63	Akhora	34°16′59.12″ N	73°16′11.32″ E	1430	Quercus incana
64	Aziz Abad	34°09′04.38″ N	73°18′42.56″ E	1197	*Quercus incana*
65	Baland Kot	34°35′49.51″ N	72°57′54.96″ E	1698	*Quercus incana*
66	Banda Peer Khan	34°15′07.34″ N	73°16′29.83″ E	1572	*Quercus incana*
67	Bandi Go	34°35′32.04″ N	73°03′33.83″ E	1302	*Quercus incana*
68	Banna Alai	34°50′06.03″ N	73°04′11.83″ E	1598	*Quercus incana*
69	Besala	34°15′42.35″ N	73°18′33.94″ E	1939	*Quercus incana*
70	Chaiiwaii	34°18′47.12″ N	72°45′29.07″ E	1503	*Quercus incana*
71	Chirri Bala	34°32′01.27″ N	72°57′41.33″ E	1663	*Quercus incana*
72	Choora Galli	34°18′38.82″ N	73°21′07.14″ E	1865	*Quercus incana*
73	Chorkalan	34°34′24.03″ N	72°59′22.05″ E	1729	*Quercus incana*
74	Dilbori	34°33′45.05″ N	72°59′44.64″ E	1387	*Quercus incana*
75	Gharri	34°18′51.54″ N	72°44′39.19″ E	1703	*Quercus incana*
76	Haripur Kuppri	34°20′45.65″ N	72°46′17.04″ E	1402	*Quercus incana*
77	Kapla	34°19′05.68″ N	72°43′53.19″ E	1779	*Quercus incana*
78	Kotli Bala	34°30′13.31″ N	73°11′26.86″ E	1359	*Quercus incana*
79	Kukmong	34°15′54.00″ N	73°24′16.49″ E	1801	*Quercus incana*
80	Kuza Banda	34°33′53.15″ N	73°04′33.03″ E	1744	*Quercus incana*
81	Manchora	34°31′00.81″ N	73°00′20.35″ E	1210	*Quercus incana*
82	Maseens Putten	34°14′02.22″ N	73°26′58.16″ E	1697	*Quercus incana*
83	Meeran	34°35′01.65″ N	72°58′31.28″ E	1988	*Quercus incana*
84	Nalla Oghi	34°32′49.57″ N	73°06′52.98″ E	1581	*Quercus incana*
85	Namli Maira	34°05′44.42″ N	73°22′24.18″ E	1992	*Quercus incana*
86	Nimal	34°31′36.24″ N	72°57′39.97″ E	1541	*Quercus incana*
87	Peer Harri	34°36′30.36″ N	72°56′04.57″ E	1846	*Quercus incana*
88	Shungli Bandi	34°28′50.04″ N	72°55′29.15″ E	1376	*Quercus incana*
89	Siri Ziarat	34°20′41.52″ N	72°58′12.59″ E	2579	*Quercus incana*
90	Susal Galli Top	34°26′59.39″ N	73°04′10.16″ E	1438	*Quercus incana*
91	Tarnawai	34°16′40.72″ N	73°15′53.27″ E	1568	*Quercus incana*
92	Thandiani	34°14′24.49″ N	73°22′05.58″ E	2519	*Quercus incana*
93	Kando Bala	35°12′10.28″ N	72°57′04.26″ E	3208	*Quercus semecarpifolia*
94	Loi Top	35°09′38.80″ N	73°10′57.23″ E	3306	*Quercus semecarpifolia*
95	Makhair	34°20′03.84″ N	73°15′48.60″ E	3157	*Quercus semecarpifolia*
96	Surbanda	35°20′52.33″ N	73°06′38.63″ E	2687	*Quercus semecarpifolia*
97	Yazai	35°11′56.40″ N	72°57′36.00″ E	2794	*Quercus semecarpifolia*
98	Seo top	35°18′59.99″ N	73°04′57.20″ E	3140	*Quercus semecarpifolia*

Note: DMS = degree, minutes and second, MASL = meters above sea level.

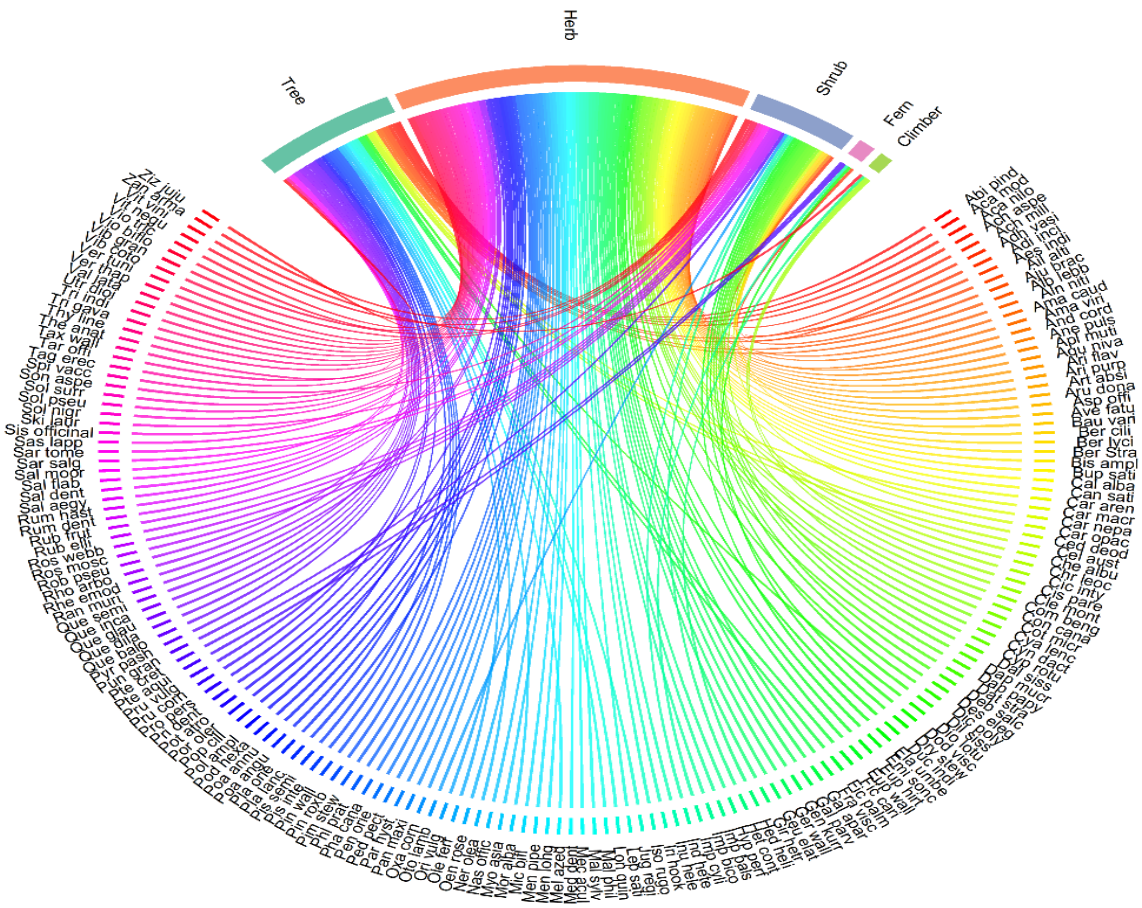

Figure 3: Chord diagram representing structural composition of plant growth forms, with herbs being the most common, followed by the shrubs and trees, and then the ferns and climbers were less represented, which represents the total floristic diversity and the heterogeneity of the habitat.

Hierarchical Cluster Analysis: Hierarchical Cluster Analysis (HCA) was conducted using Ward's minimum variance method with Bray-Curtis distance to measure floristic similarity among sampling sites. The analysis revealed clear groupings, indicating high spatial heterogeneity in species composition. The squared distance matrix showed lower dissimilarity in sites like Akhora, Arbora, and Ayubia, suggesting high ecological affinity, while more distant sites like Banda and Bala exhibited significant compositional divergence. The dendrogram illustrated hierarchical patterns of vegetation assemblages, with both small-scale clusters of high internal similarity and larger clusters representing major vegetation types. These findings underscore the role of environmental gradients in community composition and the utility of HCA for ecological interpretation and conservation planning (Figure 4).

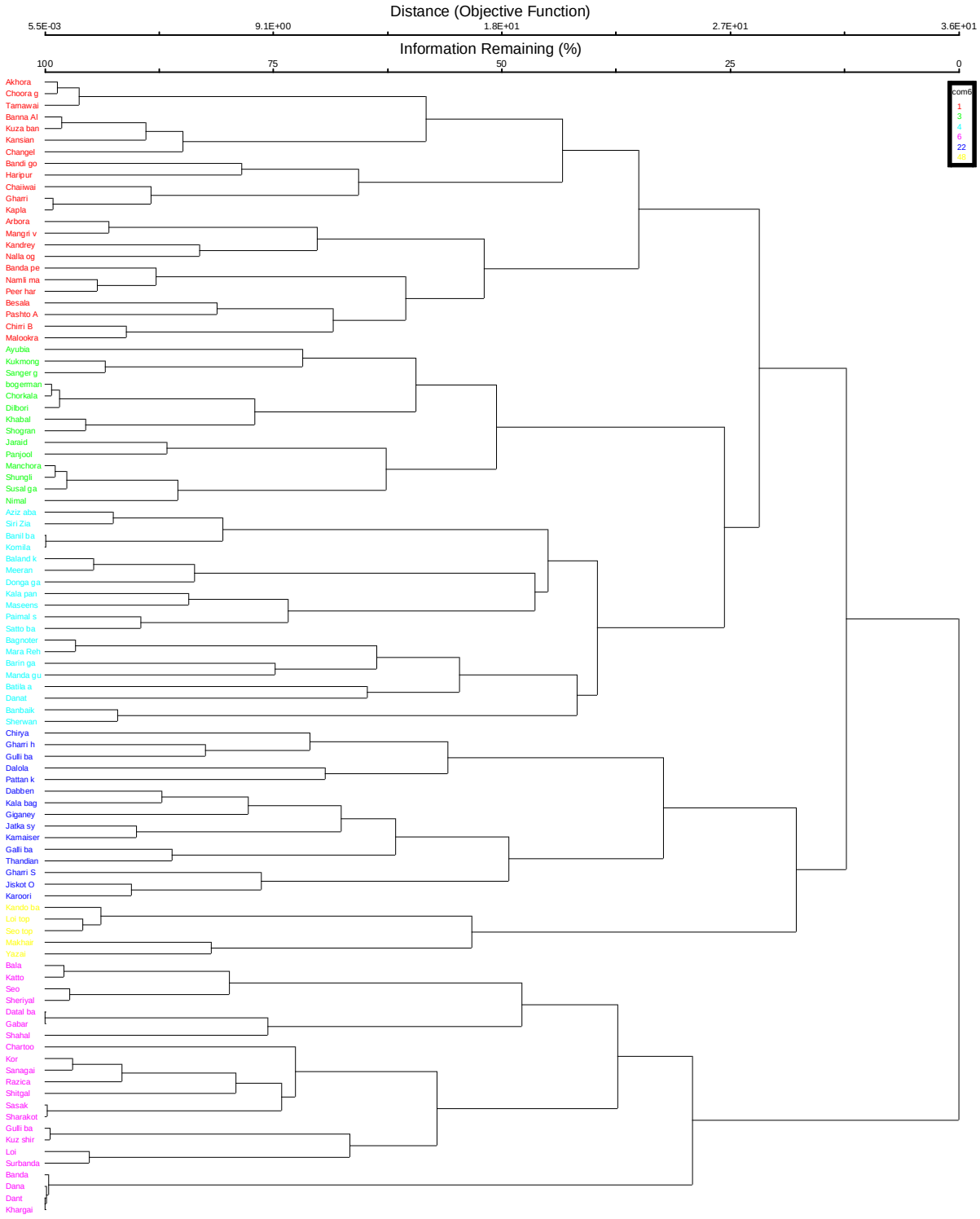

Figure 4: Bray-Curtis hierarchical clustering of 98 sampling sites based on the composition of 180 plant species, each colour represents a distinct cluster, indicating groups of sites with similar species and plant communities.

Two-Way Cluster Analysis: To classify the plant species and sampling sites at once, Two-Way Cluster Analysis (TCA) was used to find out the coherent vegetation groups in the study area. The analysis revealed separate clusters that display good ecological patterns in species distributions. A few sites, such as Akhora, Arbora, and Ayubia, were closely clustered, indicating high floristic similarity and indicative of similar environmental conditions. On the other hand, other locations like

Banda and Chaiiwai were more dissimilar and divided into discrete clusters, which suggested unique species assemblages, which might have been due to local environmental gradients or anthropogenic disturbance. The species clustering also brought out diagnostic taxa that defined each cluster, with some being dominated by shade-tolerant, moisture-loving species and others are predominantly drought-tolerant taxa due to the ecological heterogeneity of the landscape (Figure 5).

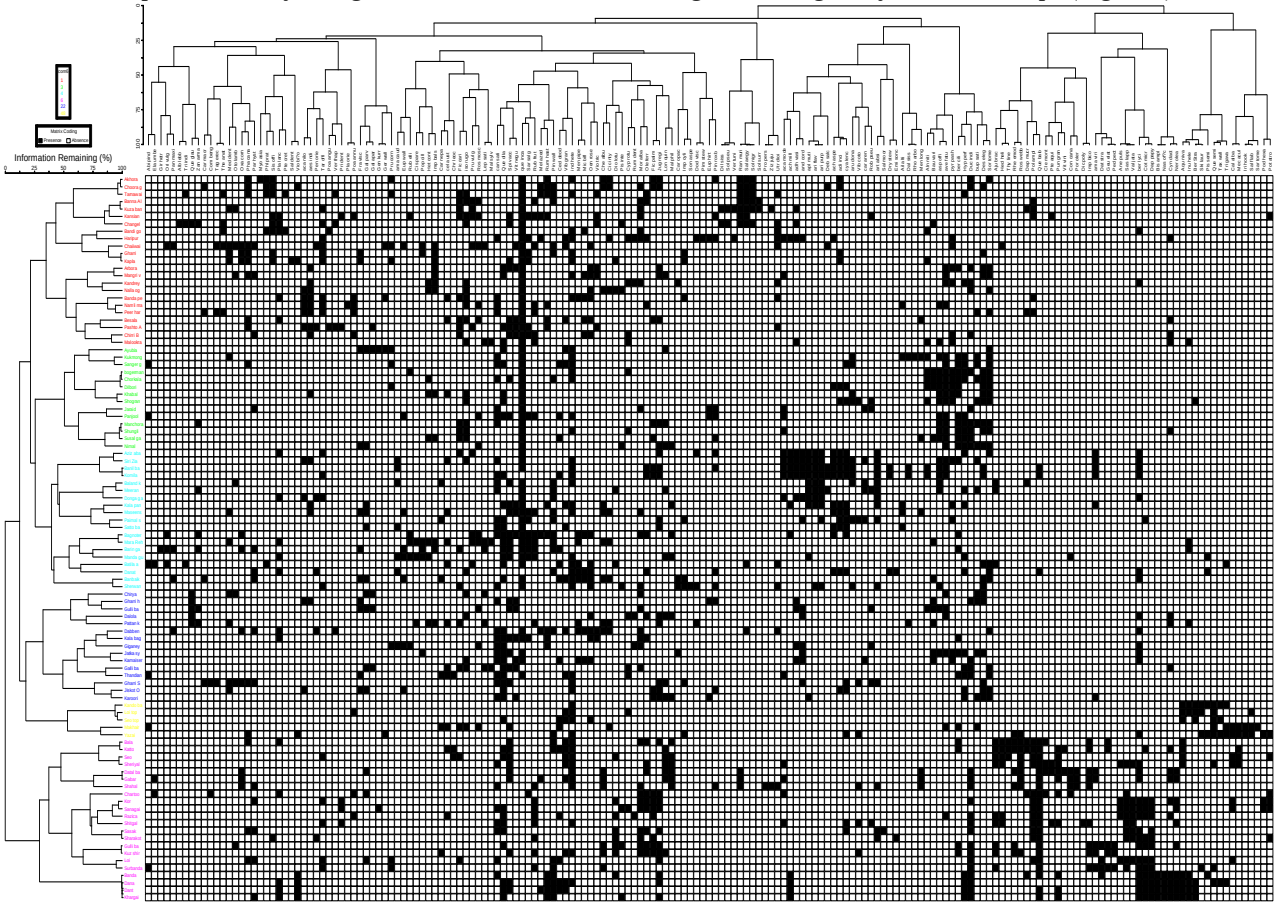

Figure 5: Two-way cluster analysis of species and sampling, black dots indicate species presence, and white dots for absence across sites in the study area.

The species-area curve: The species-area curve, based on 98 stands, indicated that 180 species had been observed. The value of richness peaked toward infinity as plots were increased (Table 01). At low sample sizes, species richness increased rapidly, averaging 18.53 species per plot. With more plots added, the rate of species accumulation decreased, reaching 103.19 species at 10 plots and 173.29 species at 60 plots. Around 80 plots, the curve leveled off. A total of 180 species were collected, indicating that most species in the study area were well represented. Jackknife estimates predicted slightly higher richness (first order: 192.9; second order: 193.0). This suggests that a small number of rare species may have been missed during sampling. The average Sørensen (Bray-Curtis) distance decreased with increasing number of plots (from 0.7970 at 1 plot to 0.0000 at 98 plots). This shows that floristic similarity among samples increased with sampling effort. This pattern confirms that the survey effort was sufficient to capture the study area's floristic diversity. The derived species pool provides a robust foundation for subsequent community analyses (Figure 6).

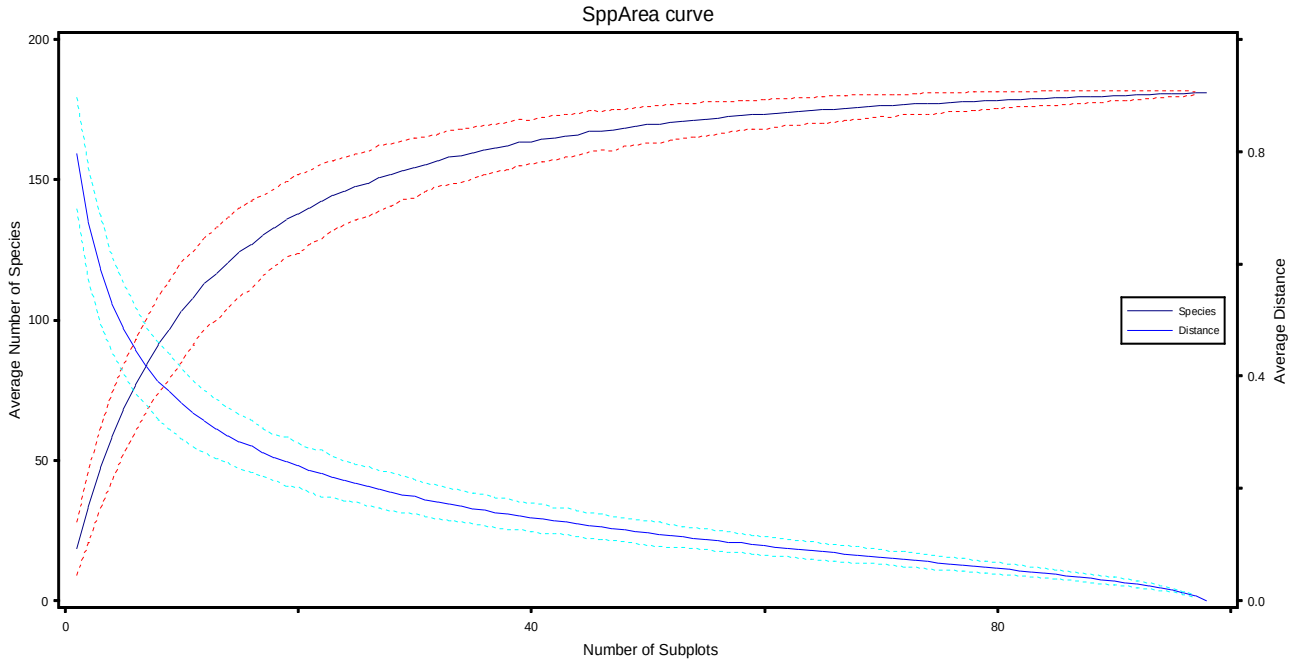

Figure 6: Species-area curve for the study area, showing the increase in cumulative species richness with sampling sites, the solid line represents the mean species accumulation, while the dashed lines indicate the confidence intervals, demonstrating sampling completeness across sites.

Species Environment Relationships: Generalized linear models (GLMs) revealed distinct species-specific responses of *Quercus* taxa to environmental and edaphic factors. *Q. baloot* showed significant negative associations with altitude, slope, and temperature, while being positively influenced by relative humidity, organic matter, nitrogen, $CaCO_3$, and silt content ($p \leq 0.05$). *Q. dilatata* was positively correlated with altitude, slope, temperature, and $CaCO_3$, but negatively with soil pH, nitrogen, potassium, phosphorus, and sand content ($p \leq 0.05$). For *Q. semecarpifolia*, altitude, relative humidity, and organic matter had strong positive effects, whereas slope, temperature, potassium, silt, and calcium exerted significant negative effects ($p \leq 0.05$). *Q. incana* responded positively to altitude, soil pH, nitrogen, sand, and calcium, but negatively to relative humidity, organic matter, $CaCO_3$, phosphorus, and silt ($p \leq 0.05$). In contrast, *Q. glauca* showed no significant relationships with the tested variables, as all predictors were statistically non-significant ($p > 0.9$). These results highlight species-specific ecological preferences and environmental filtering mechanisms shaping oak distribution across the Himalayan landscape (Figure 7).

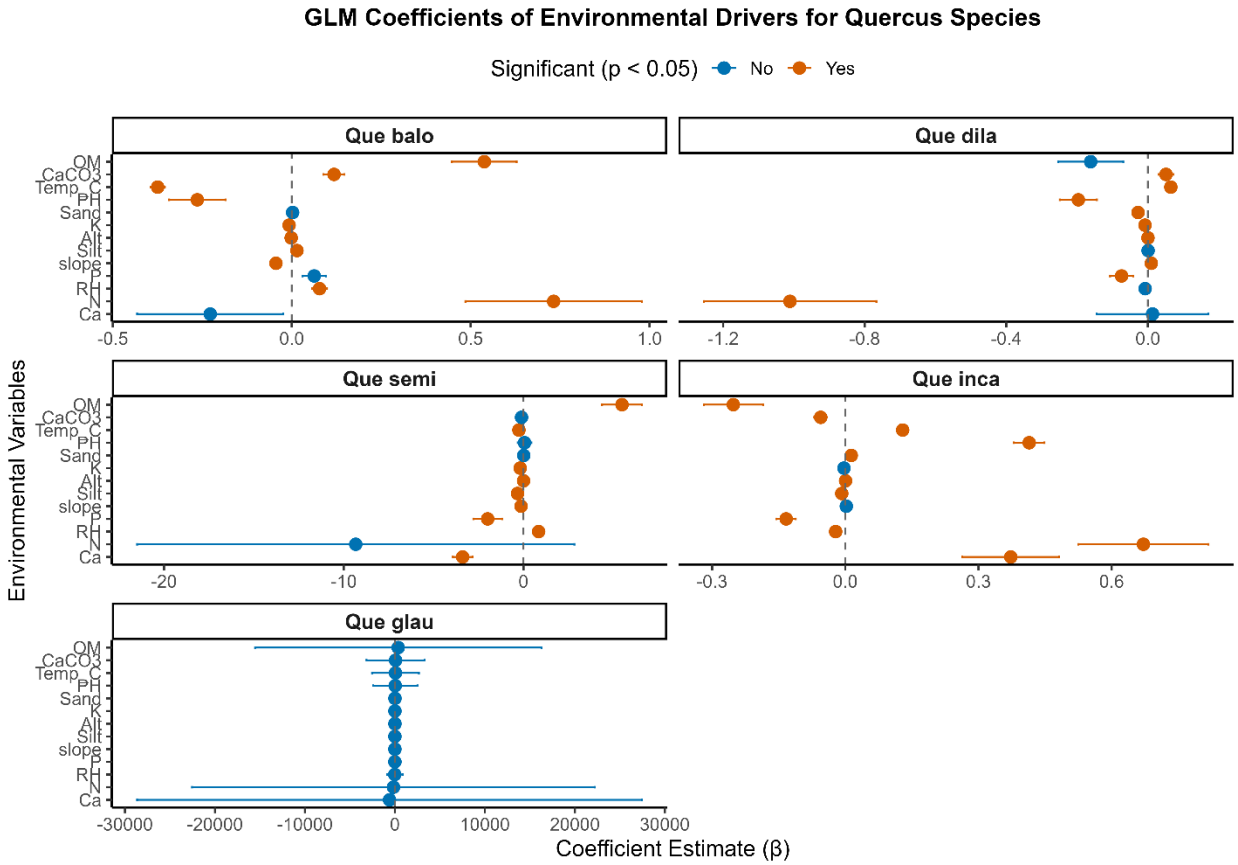

Figure 7: Generalized Linear Model (GLM) of environmental variables on *Quercus* species distribution in the study area. Coefficient estimates are presented for variables with statistically significant effects (P ≤ 0.05).

Plants association

***Quercus incana- Asparagus officinalis- Avena fatua* Community (QAA):** The *Quercus incana- Asparagus officinalis- Avena fatua* community (QAA) was composed of 58 species. The community was dominated by *Quercus incana* (38.00), *Asparagus officinalis* (14.98), *Avena fatua* (12.79), *Bergenia ciliata* (12.20), *Alnus nitida* (9.49), and *Sorghum tomentosum* (8.91). Co-dominant species included *Hypericum perforatum*, *Desmodium elegans*, *Duchesnea indica*, *Cannabis sativa*, *Quercus dilatata*, and *Arundinaria donax*. The associated species included *Pyrus pashia*, *Cynodon dactylon*, *Cedrus deodara*, *Ficus carica*, *Prunus cornuta*, *Galium aparine*, and *Medicago denticulata*. The least important species included *Zanthoxylum armatum*, *Rubus fruticosus*, *Morus alba*, *Phragmites communis*, *Bergenia stracheyi*, and *Malotus philippensis*. The QAA community was found at a mean altitude of 1739 MASL with moderately steep slopes (26.6°) and a mean temperature of 23.1 °C. Relative humidity averaged 54.4%, while soils showed near-neutral pH (6.32) and moderate organic matter content (0.95%) (Figure 9: b). This community had moderate species richness (14.6 species) and a Shannon diversity index of 2.57, with high evenness (Pielou's index = 0.96) (Figure 9: a). The combination of mid-altitude, warm climate, and well-balanced soil properties suggests that QAA supports a relatively stable assemblage with high species evenness but lower richness than higher-elevation communities.

***Quercus incana- Aesculus indica- Phragmites communis* Community (QAP):** The *Quercus incana- Aesculus indica- Phragmites communis* community (QAP) supported 94 species. The community was dominated by *Quercus incana* (52.23), *Aesculus indica* (7.63), *Phragmites communis* (7.09), *Taraxacum officinale* (5.47), *Pyrus pashia* (5.06), and *Ficus carica* (4.74). Co-dominant species included *Urtica dioica*, *Impatiens balsamina*, *Cynodon dactylon*, *Ranunculus muricatus*, *and Poa annua*. The associated species included *Pinus wallichiana*, *Phleum pratense*, *Rubus fruticosus*, *Solanum nigrum*, and *Medicago denticulata*. The least represented species were *Debregeasia salicifolia*, *Hypericum perforatum*, *Hedera helix*, *Ziziphus jujuba*, *Robinia pseudoacacia*, and *Rubus ellipticus*. The QAP community occurred at slightly lower elevations (1690 MASL) with steeper slopes (29.7°). The environment was characterized by warmer mean temperatures (24.3 °C), moderate relative humidity (55.0%), and slightly acidic soils (pH 6.62) with lower electrical conductivity (Figure 9: b).

Richness was higher than QAA (17.8 species), accompanied by Shannon diversity of 2.65 (Figure 9: a). Its evenness (0.93) was slightly lower than QAA, but it was a richer community with more species supported. QAP appears to be a higher nitrogen, mid-elevation assemblage with robust species representativeness under relatively warmer, mesic conditions and fertile soils.

***Quercus semecarpifolia- Bergenia stracheyi- Indigofera heterantha* Community (QBI):** The *Quercus semecarpifolia-Bergenia stracheyi- Indigofera heterantha* community (QBI) consisted of 46 species. The community was strongly dominated by *Quercus semecarpifolia* (68.96), accompanied by *Bergenia stracheyi* (27.48), *Indigofera heterantha* (25.35), *Skimmia laureola* (18.40), *Picea smithiana* (13.97), and *Cedrus deodara* (13.46). Co-dominant species included *Oenothera rosea*, *Viburnum grandiflorum*, *Inula helenium*, *Taxus wallichiana*, *Aquilegia nivalis*, and *Trillium govanianum*. Associated species were represented by *Salix flabellaris*, *Iris hookeriana*, *Quercus dilatata*, *Poa annua*, *Phragmites communis*, and *Celtis australis*. The least contributing species were *Rosa moschata*, *Cichorium intybus*, *Bergenia ciliata*, *Impatiens cylindrica*, and *Viburnum cotonefolium*. The QBI community was distinctly montane, located at the highest mean altitude (3104 MASL) and on the steepest slopes (36.6°). It experienced the lowest mean temperatures (16.6 °C) and relatively high humidity (60.6%). Soils were more acidic (pH 5.12) with the highest organic matter content (1.92%) (Figure 9: b). Species richness was the lowest (13.8 species) with reduced Shannon diversity (2.37) and evenness (0.93) (Figure 9: a). This indicates that QBI is a stress-prone, high-altitude community in which few specialized taxa dominate, resulting in low richness but a relatively balanced representation. The adaptation of *Quercus semecarpifolia* and its associates to cold, moist conditions reflects the specialized nature of this community.

***Quercus dilatata- Cannabis sativa-Quercus glauca* Community (QCQ):** The *Quercus dilatata- Cannabis sativa-Quercus glauca* community (QCQ) comprised 92 species. The dominant species were *Quercus dilatata* (29.29), *Cannabis sativa* (9.74), *Quercus glauca* (9.50), *Morus alba* (8.85), *Fragaria vesca* (6.63), and *Avena fatua* (6.08). Codominant included *Juglans regia*, *Cynodon dactylon*, *Bauhinia variegata*, *Quercus incana*, *Desmodium elegans*, and *Duchesnea indica*. Associated species included *Olea ferruginea*, *Bupleurum sativus*, *Spiraea vaccinifolia*, *Andrachne cordifolia*, *Vitex negundo*, *Sorbaria tomentosa*, and *Hypericum perforatum*. The least represented species were *Impatiens balsamina*, *Heteropogon contortus*, *Inula helenium*, *Dalbergia sissoo*, *Rubus fruticosus*, and *Viburnum cotonefolium*. The QCQ community occurred at lower altitudes (1590 MASL) with gentle to moderate slopes (29.3°). The mean temperature was the highest among all communities (25.7 °C), with relative humidity averaging 54.4%. Soils were slightly acidic (pH 6.65) and had moderate organic matter (0.68%) (Figure 9: b). Species richness was moderate (15.9 species) with Shannon diversity of 2.60 and high evenness (0.95) (Figure 9: a). This community reflects a transition zone where warm conditions and fertile soils support a balanced set of species, with diverse values suggesting relatively stable coexistence and reduced dominance effects.

***Quercus incana-Prunus vulgaris- Quercus dilatata* Community (QPQ):** The *Quercus incana-Prunus vulgaris-Quercus dilatata* community (QPQ) concealed 89 species. Dominant species included *Quercus incana* (28.67), *Prunus vulgaris* (12.83), *Quercus dilatata* (9.85), *Impatiens cylindrica* (9.26), *Pinus wallichiana* (7.24), and *Cynodon dactylon* (6.23). Co-dominant species were *Cannabis sativa*, *Chenopodium album*, *Pyrus pashia*, and *Artemisia absinthium*. The associated group included *Arisaema flavum*, *Achyranthes aspera*, *Pinus roxburghii*, *Adiantum incisum*, *Abies pindrow*, *Berberis lycium*, and *Morus alba*. Species with the least contribution were *Sonchus asper*, *Mentha longifolia*, *Malva sylvestris*, *Urtica dioica*, *Rubus ellipticus*, and *Dryopteris stewartii*. The QPQ community was distributed at mid- to high elevations (1863 MASL), with slopes averaging 28°. The mean temperature was 22.4 °C, the relative humidity was moderately high (57.6%), and the soil pH averaged 6.54 with organic matter 0.82% (Figure 9: b). Species richness (21.3 species) and Shannon diversity (2.76) were high, although evenness (0.91) was slightly lower, indicating dominance by a few species within a diverse assemblage (Figure 9: a). The combination of intermediate climate and fertile soils contributed to high diversity, making QPQ one of the most species-rich *Quercus* communities.

***Quercus baloot-Quercus dilatata- Cynodon dactylon* Community (QQC):** The *Quercus baloot-Quercus dilatata- Cynodon dactylon* community (QQC) was represented by 104 species. The community was dominated by *Quercus baloot* (IVI = 30.91) and *Cynodon dactylon* (24.81), followed by *Quercus dilatata* (9.97), *Pinus wallichiana* (7.88), *Berberis lycium* (7.51), and *Impatiens bicolor* (6.62). Co-dominant species included *Artemisia absinthium*, *Olea ferruginea*, *Punica granatum*, *Sassurea lappa*, *Cannabis sativa*, and *Juglans regia*. A wide range of associated species were present, such as *Polygonum amplexicaulis*, *Morus alba*, *Ficus palmata*, *Duchesnea indica*, *Ajuga bracteosa*, *Aquilegia nivalis*, and *Malotus philippensis*. Species with the lowest contribution to the community included *Sisymbrium officinale*, *Trilium gavanianum*, *Sarcococca saligna*, *Emilia sonchifolia*, and *Salvia moorcroftiana*. The QQC community occurred at elevations around 2009 MASL with steep slopes (33.8°). This community experienced the lowest mean temperatures (15.9 °C) after QBI and the highest relative humidity (60.0%). Soils were moderately acidic (pH 5.79), with organic matter averaging 0.93% (Figure 8b). It had the highest species richness (22.3 species) and Shannon diversity (2.78), although evenness was lower (0.90) than in QAA and QCQ

(Figure 8a). The colder, moister conditions, combined with fertile soils, create favorable niches for diverse taxa, explaining the high richness observed. This community represents a biodiversity hotspot within the *Quercus*-dominated vegetation.

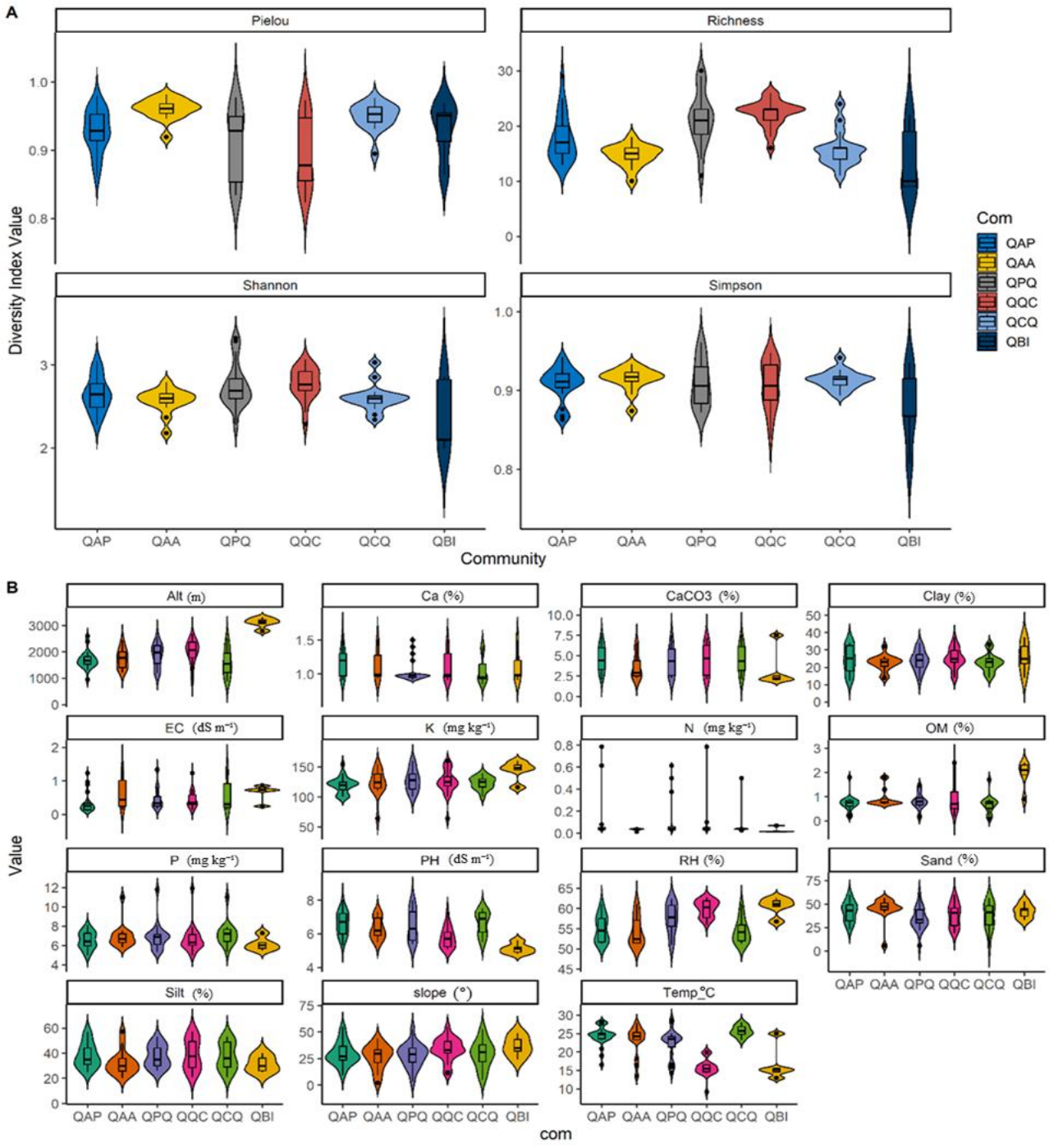

Figure 8: (a) Biodiversity indices (e.g., species richness, Shannon diversity, and evenness) and (b) environmental variables across six plant communities in the study area. *Quercus incana-Asparagus officinalis-Avena fatua* (QAA), *Quercus incana-Aesculus indica-Phragmites communis* (QAP), *Quercus semecarpifolia-Bergenia stracheyi-Indigofera heterantha* (QBI), *Quercus dilatata-Cannabis sativa-Quercus glauca* (QCQ), *Quercus incana-Prunus vulgaris-Quercus dilatata* (QPQ), and *Quercus baloot-Quercus dilatata-Cynodon dactylon* (QQC).

NMDS and PCA of communities: The NMDS analysis shows that vegetation distribution is mainly influenced by climatic and geographic factors. Temperature ($r = 0.505$, $R^2 = 0.255$) and relative humidity ($r = 0.376$, $R^2 = 0.141$) were the strongest climatic drivers, while latitude ($r = 0.438$, $R^2 = 0.192$) and altitude ($r = 0.236$, $R^2 = 0.056$) also had significant effects. Among edaphic variables, soil pH, organic matter, and clay showed weaker but significant relationships, whereas most other soil parameters were non-significant (Figure 9).

The principal component analysis (PCA) summarized the variation in the dataset, with the first three axes explaining 13.6%, 9.6%, and 7.6% of the total variance, respectively, accounting for nearly one-third (30.2%) of the cumulative variation. PC1 (9.9 eigenvalue) represented the strongest gradient, followed by PC2 (7.5) and PC3 (7.2), each contributing meaningful ecological separation among sites. The gradual decline in explained variance across subsequent components indicates that the major patterns of species distribution and environmental variation are well captured by the first few axes, while higher-order axes contributed only marginally (Figure 10).

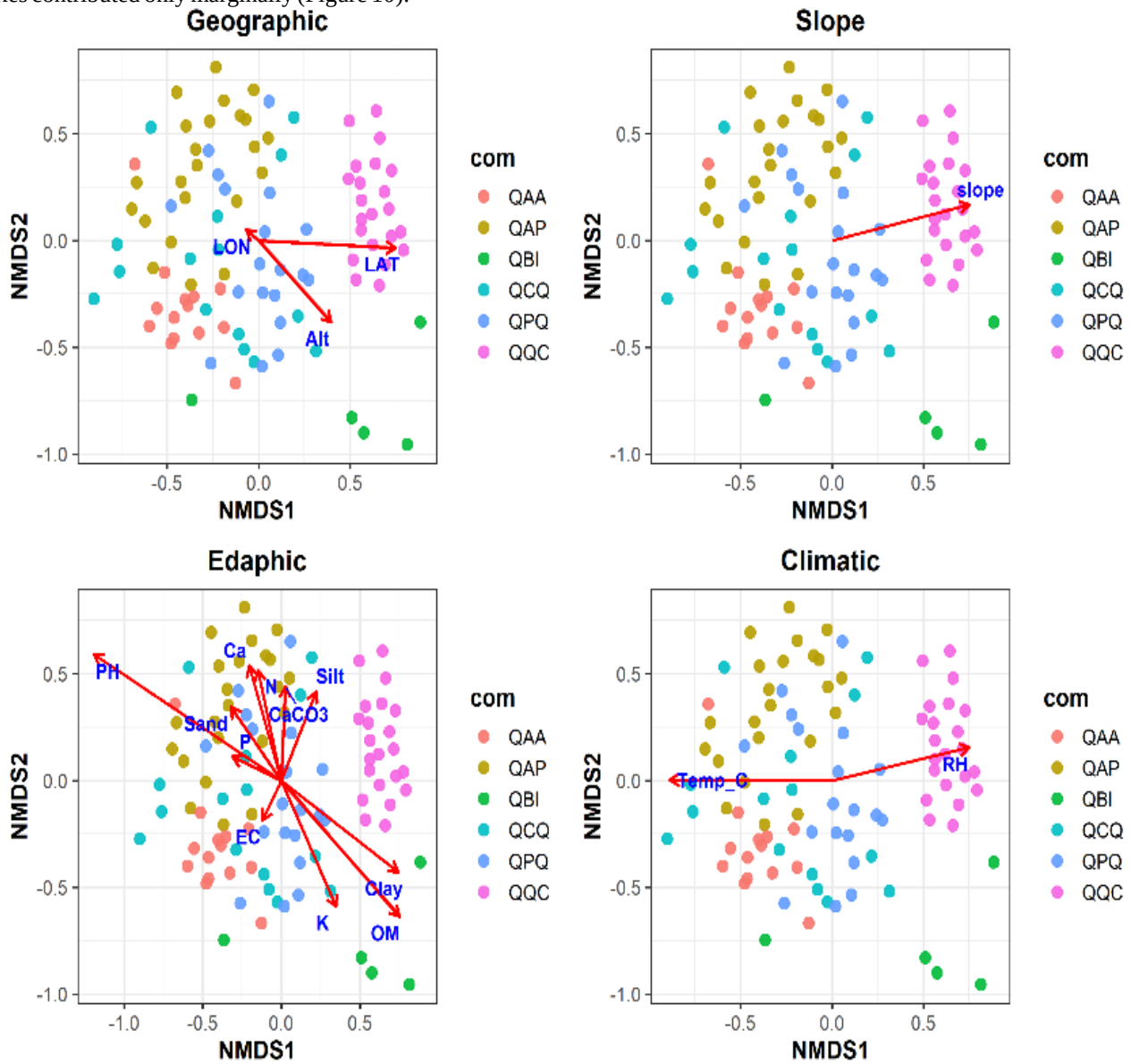

Figure 9: Non-metric multidimensional scaling (NMDS) ordination showing the influence of Environmental variables on distribution and classification of plant communities in the study area. *Quercus incana-Asparagus officinalis-Avena fatua* (QAA), *Quercus incana-Aesculus indica-Phragmites communis* (QAP), *Quercus semecarpifolia-Bergenia stracheyi-Indigofera heterantha* (QBI), *Quercus dilatata-Cannabis sativa-Quercus glauca* (QCQ), *Quercus incana-Prunus vulgaris-Quercus dilatata* (QPQ), and *Quercus baloot-Quercus dilatata-Cynodon dactylon* (QQC). Distinct colour indicates the different communities

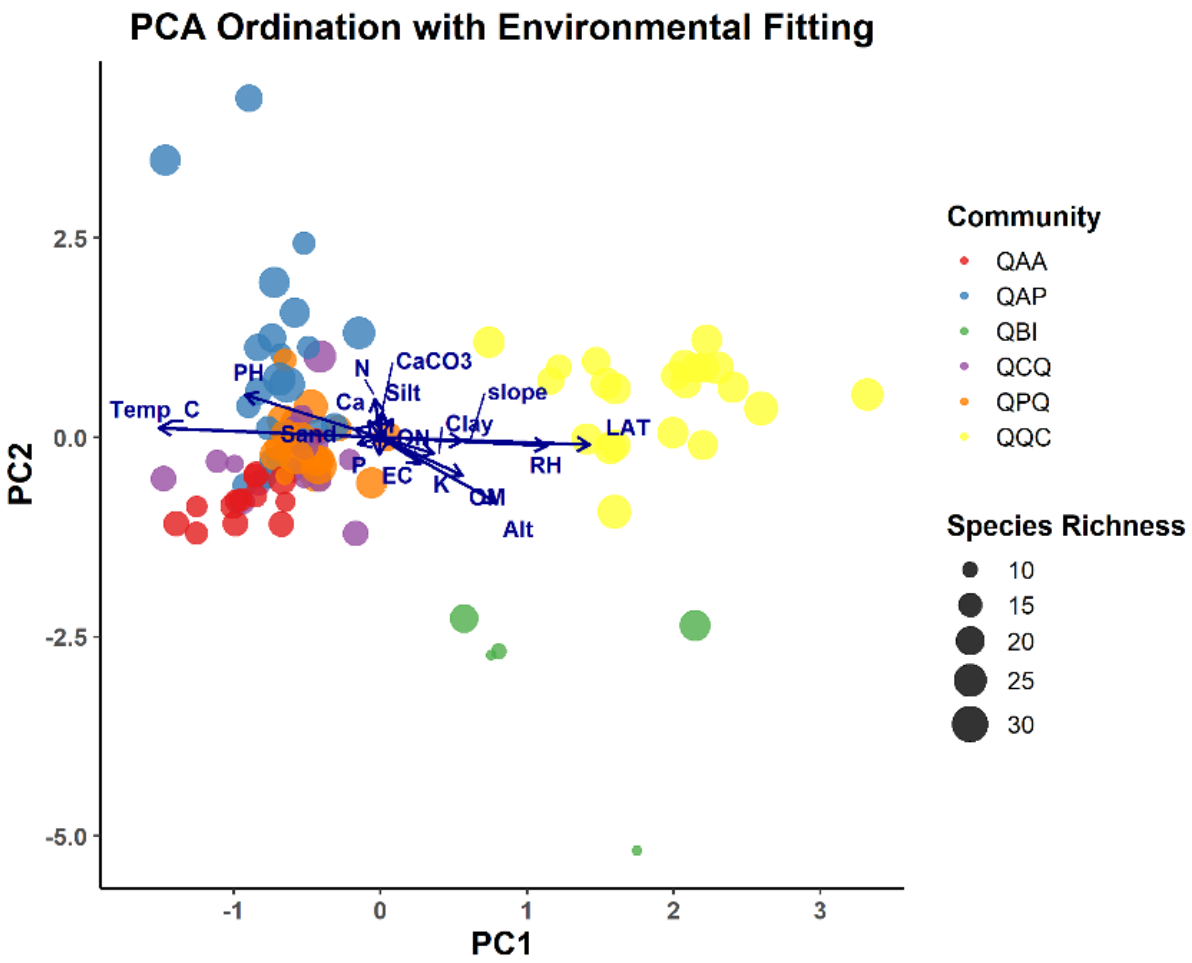

Figure 10: PCA biplot of 98 sampling stands (180 species) showing site distribution along environmental gradients; PC1 (30.2%) correlated positively with latitude, altitude, and relative humidity, and negatively with temperature and soil pH, while PC2 (12.3%) reflected variation in soil properties. The size of the circle shows the species richness while the color shows different communities. *Quercus incana-Asparagus officinalis-Avena fatua* (QAA), *Quercus incana-Aesculus indica-Phragmites communis* (QAP), *Quercus semecarpifolia-Bergenia stracheyi-Indigofera heterantha* (QBI), *Quercus dilatata-Cannabis sativa-Quercus glauca* (QCQ), *Quercus incana-Prunus vulgaris-Quercus dilatata* (QPQ), and *Quercus baloot-Quercus dilatata-Cynodon dactylon* (QQC).

Detrended correspondence analysis: The response data showed a gradient length of 4.20 SD units along axis 1, indicating a long ecological gradient. In DCA ordination, axis 1 had a gradient length of 4.20 and an eigenvalue of 0.53; axis 2, 2.89 and 0.30; and axis 3, 3.20 and 0.23. The eigenvalues of 0.53 and 0.30 on axes 1 and 2 indicated a strong species-habitat correlation, while the lower eigenvalue of 0.23 on axis 3 showed a weaker relationship. Total variance in the species data was 7.85 (Table 02). The dominant gradient along axis 1 suggested a resemblance in species composition.

DCA ordination grouped species by ecological affinities. *Taxus wallichiana*, *Quercus semecarpifolia*, *Bergenia stracheyi*, *Aquilegia nivalis*, and *Viburnum grandiflorum* showed strong positive correlation along axis 1. *Indigofera heterantha*, *Quercus dilatata*, *Rosa webbiana*, *Juglans regia*, and *Impatiens bicolor* were positively correlated on axis 2. *Mallotus philippensis* and *Olea ferruginea* were near the centroids of axes 1 and 2. *Cynodon dactylon* and *Chenopodium album* were positioned away from the centroid and showed negative correlations. *Alnus nitida* and *Ranunculus muricatus* were positively associated along axis 1, but negatively correlated with *Carissa opaca* and *Ziziphus jujuba*. Most species were centered in the ordination diagram, reflecting identical or overlapping communities and habitat preferences.

The ordination of stands also showed well-separated clusters based on species composition. Stand 27 (Dana) and stand 32 (Donga Galli) were closely related along axis 1, which represented similar vegetation structure. In contrast, stand 30 (Datal Banda) was inversely correlated with stands 26 (Dalola) and 28 (Danat). Stand 25 (Dabben) appeared at the upper end of the ordination space, indicating high species diversity, and showed a negative correlation with stands 27 and 32. Most

stands, including Banbaik (stand 8), Chorkalan (stand 24), and Surbanda (stand 94), are grouped at the center of the ordination diagram. They showed similar species composition, with some overlap in stands (Figure 11).

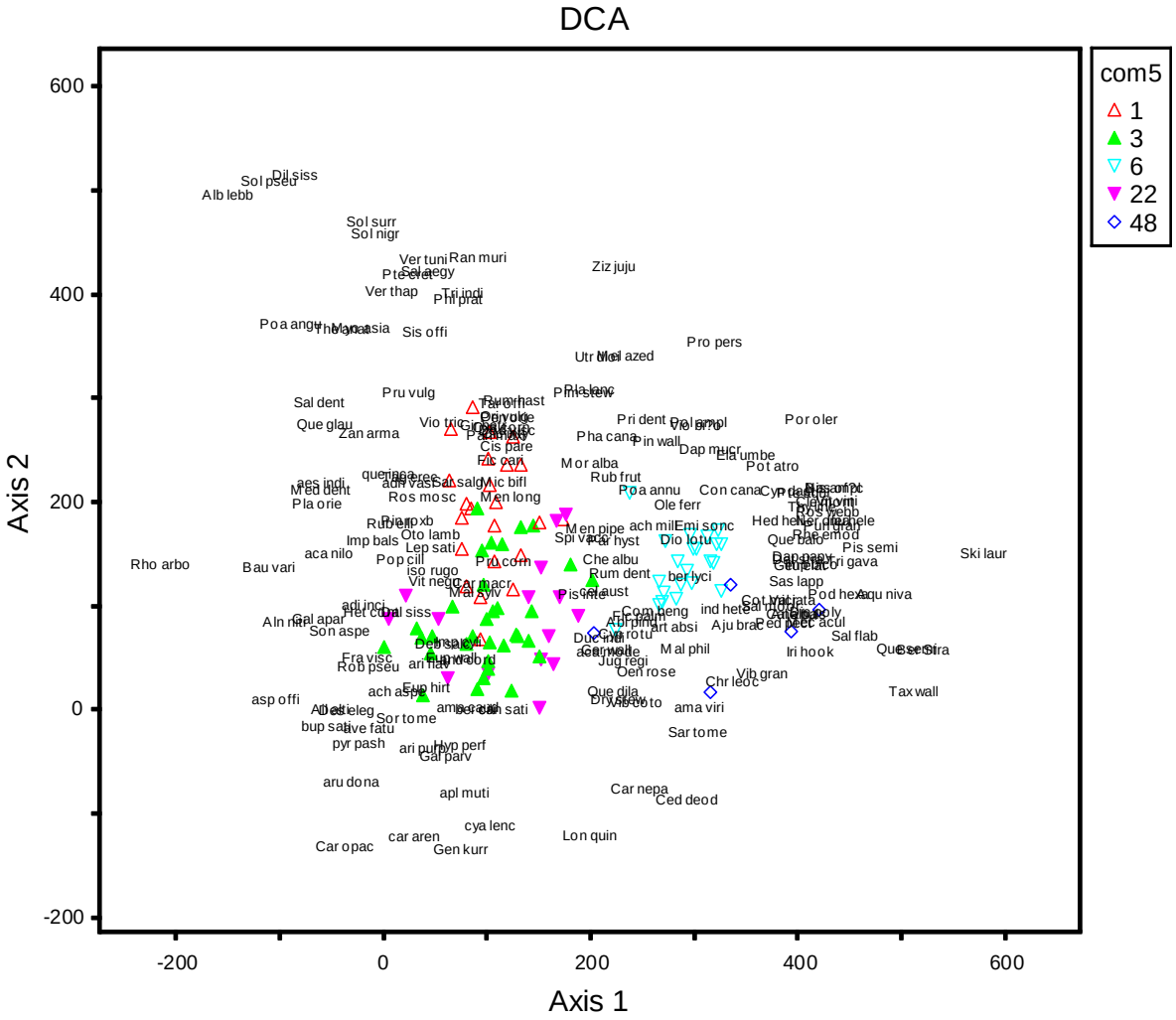

Figure 11: Illustrating DCA analysis of plant species and sites of the study area. The triangle shape shows the sites, and colours indicate distinct clusters based on species composition.

Table 2. Detrended Correspondence Analysis (DCA) summary showing eigenvalues and gradient lengths for the first three axes. Eigenvalues represent variance explained, while gradient lengths (SD units) indicate species turnover along ecological gradients.

Axis	Eigen value	Length of gradient
Axis1	0.52	4.2
Axis2	0.3	2.88
Axis3	0.23	3.19

Canonical Correspondence Analysis (CCA): CCA was applied to study the influence of environmental variables on plant species composition, especially *Quercus* species. The eigenvalues of the first three axes were 0.412, 0.298, and 0.192, corresponding to explaining 28.4%, 20.5% and 13.2% variance on the species–environment relationships (Table 03). Together, the two axes explained 48.9% of the variation and therefore should encompass most of the major ecological gradients accounting for species distribution.

The ordination biplot showed clearly differing ecological preferences of the *Quercus* species. *Q. semecarpifolia* was loaded on the positive side of axis 1 and strongly associated with higher elevation, lower temperature, and dense canopy cover. This indicates its preference to damp temperate forest environments. *Quercus dilatata*, in contrast, was clustered

toward the positive side of axis 2, where it was strongly correlated with soil moisture and organic matter, reflecting its affinity for relatively mesic habitats. *Quercus baloot* was separated toward the negative side of axis 1, indicating its preference for warmer, drier conditions and lower elevation sites, consistent with its distribution in dry temperate forests. *Q. incana* showed positive correlations with both Axis 1 and Axis 2, indicative of its mid-elevational distribution; conversely, *Q. glauca* exhibited a weaker positive correlation with Axis 1 alongside a slight negative correlation with Axis 2, which positions it at the lowest elevations and reflects its divergent moisture affinities compared to *Q. baloot* (Figure 13, 14).

Other co-occurring species further supported these habitat associations. *Taxus wallichiana* and *Indigofera heterantha* were closely aligned with *Q. semecarpifolia* along axis 1, reflecting shared preferences for high-altitude moist habitats. *Rosa webbiana* and *Berberis lycium* clustered near *Q. dilatata*, suggesting a common response to moisture gradients. On the other hand, *Cynodon dactylon* and *Chenopodium album* were positioned opposite *Q. baloot*, indicating their presence in disturbed and open habitats where *Q. baloot* was absent.

The ordination of stands further reflected these species–environment relationships. High-altitude stands such as Dana (stand 27) and Donga Gali (stand 32) grouped strongly with *Q. semecarpifolia*, while middle-elevation stands (e.g., Dabben - stand 25, Dalola -stand 26) were associated with *Q. dilatata*. Low elevation stands, including Datal Banda (stand 30) were positioned near *Q. baloot*, highlighting its adaptation to relatively dry and disturbed environments. Most stands were situated near the center of the ordination diagram, showing overlapping communities and transitional zones between *Quercus*-dominated habitats (Figure 12).

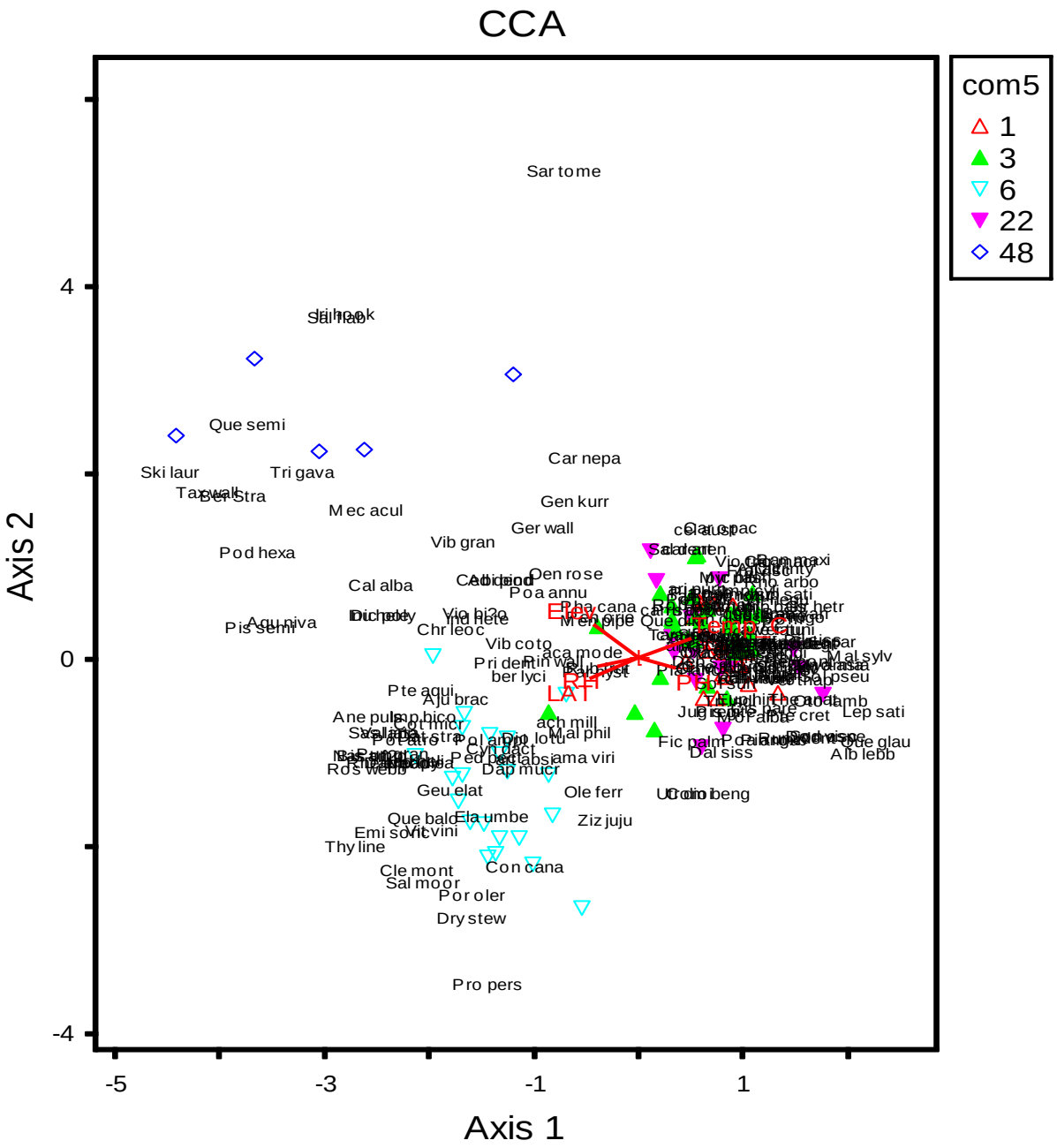

Figure 12: CCA Ordination of Species and Environmental Variables in the study area.

Table 3. Monte Carlo permutation test results for Canonical Correspondence Analysis (CCA) axes, showing eigenvalues, canonical correlations, percentage variance explained, and cumulative variance for the first four axes.

Axis	Eigenvalue	Canonical Correlation	% Variance Explained	Cumulative %
1	0.412	0.83	28.4%	28.4%
2	0.298	0.76	20.5%	48.9%
3	0.192	0.69	13.2%	62.1%
4	0.087	0.58	7.5%	69.6%

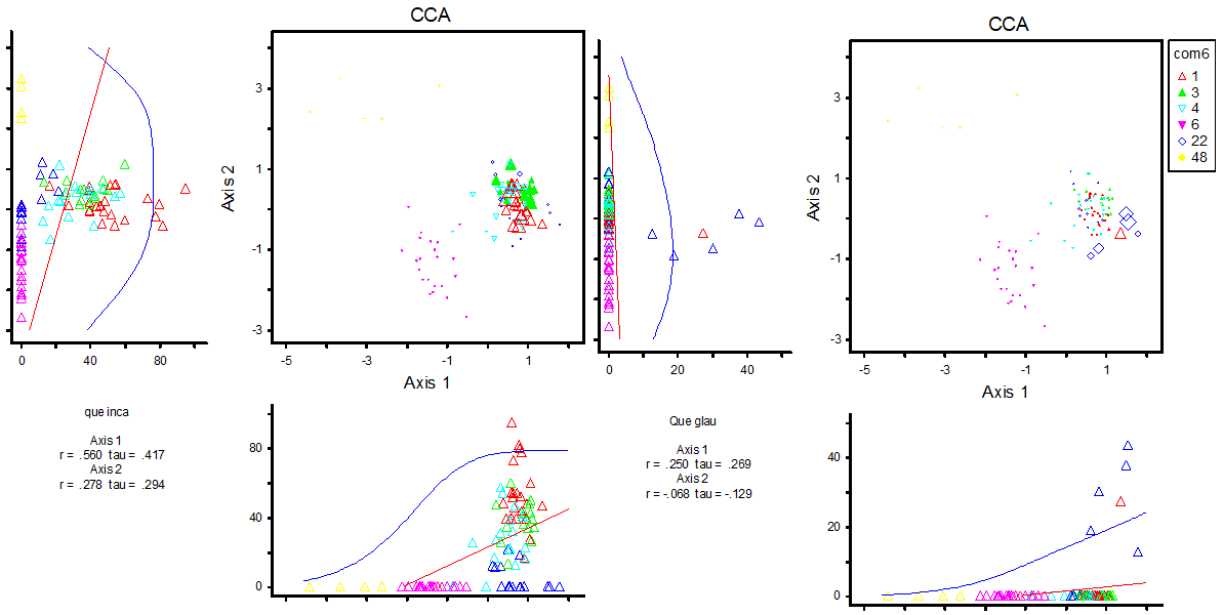

Figure 13: The species environment relationship of *Quercus incana* and *Quercus glauca*.

Quercus incana shows a positive correlation with CCA1 (r = 0.560, τ = 0.417) and CCA2 (r = 0.278, τ = 0.294). *Quercus glauca* shows a positive correlation with CCA1 (r = 0.250, τ = 0.269) and negative correlation CCA2 (r = -0.068, τ = -0.129).

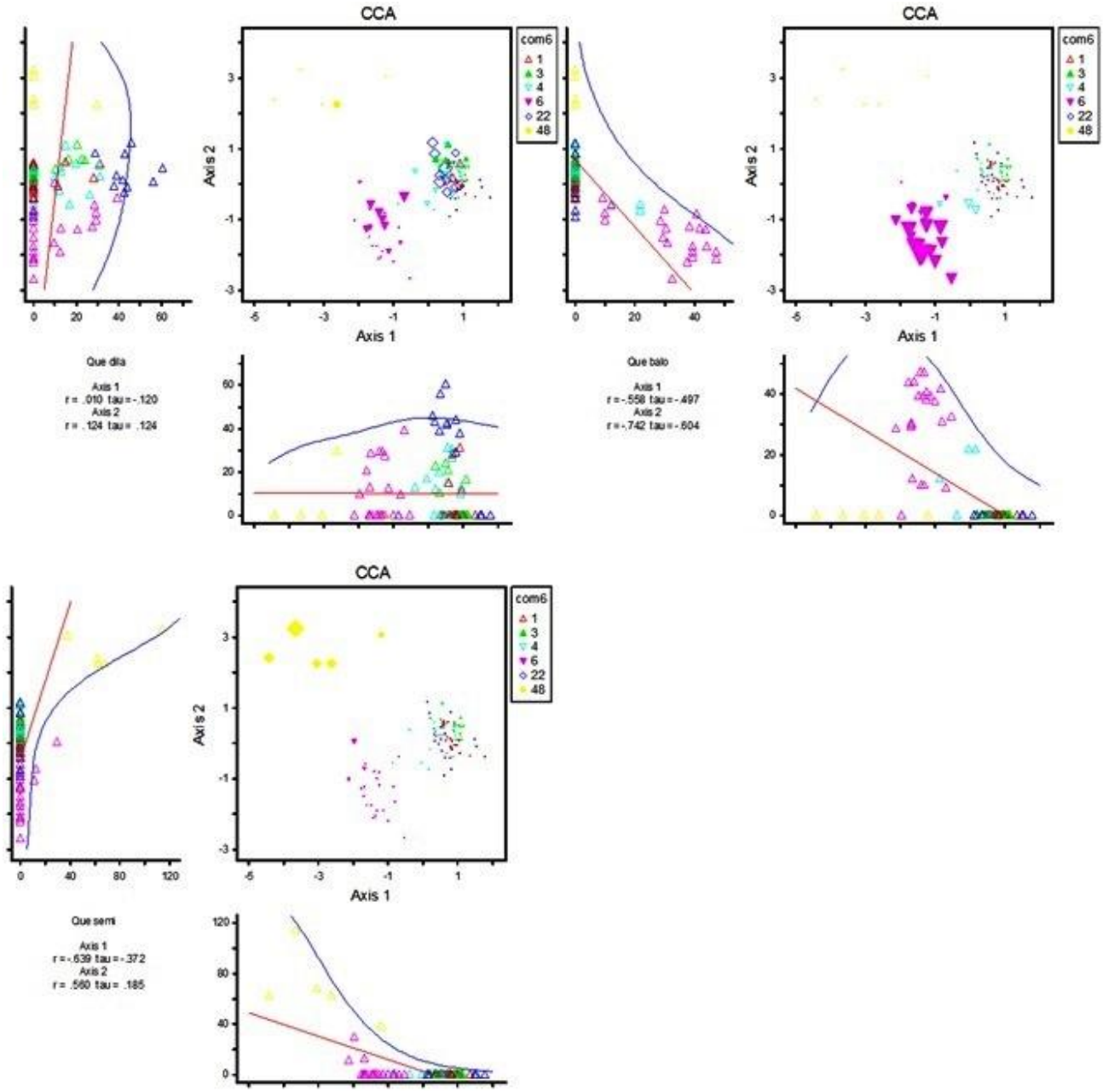

Figure 14: The species environment relationship of *Quercus dilatata*, *Quercus baloot*, and *Quercus semecarpifolia*.

Q. baloot shows strong negative correlations with both axes (r = –5.58 to –7.42), suggesting its association with the environmental gradient captured by the first two axes. *Q. semecarpifolia* also exhibits moderate negative correlations (r = –6.39 with Axis 1; –5.60 with Axis 2), whereas *Q. dilatata* displays weak correlations (r = –0.10 to –1.24). The eigenvalue for Axis 1 (0.53) and total explained variation (56–62%) indicate that the CCA model effectively captures the principal ecological gradients structuring *Quercus*-dominated forests in the study area.

DISCUSSION

The present study recorded 180 species from 142 genera and 65 families across *Quercus*-dominated forests of the western Himalayas, confirming the ecological richness of this region. Similar levels of diversity have been reported in other Himalayan forests, where altitudinal gradients, microclimate, and habitat heterogeneity create favorable conditions for diverse taxa (Rahman *et al.*, 2022; Singh and Negi, 2023; Yadav and Pandey, 2024).

Asteraceae, Rosaceae, Lamiaceae, and Poaceae were the dominant families, with Asteraceae alone contributing more than one-fifth of the flora. This pattern is consistent with earlier studies across Pakistan and Himalayan forests, where these families repeatedly dominate due to their broad ecological amplitude and adaptive dispersal mechanisms (Qazi *et al.*, 2023; Gillani *et al.*, 2024). Asteraceae and Lamiaceae have also been reported to dominate alpine vegetation, indicating that these species are adapted from forest regions to higher altitudes (Shaheen *et al.*, 2019; Qaiser *et al.*, 2025).

A pronounced elevational stratification of *Quercus* species was observed, highlighting the central role of environmental filtering in structuring forest communities. Species such as *Q. glauca* were confined to lower elevation, consistent with their affinity for warmer, subtropical conditions (Jin *et al.*, 2023), however, *Q. baloot* occupied the lower and mid altitudinal range as reported previously for this keystone dry temperate Himalayan forest tree species (Ahmad *et al.*, 2022). Intermediate species, including *Q. incana* and *Q. dilatata*, exhibited broader ecological amplitudes, spanning multiple elevational zones. This pattern is consistent with niche theory, where species distributions are governed by physiological tolerances and competitive abilities along environmental gradients (Rahman *et al.*, 2023), whereas *Q. semecarpifolia* was restricted to high-elevation subalpine zones, reflecting adaptations to cold, moist, and physiologically stressful environments (Rawat *et al.*, 2022; Shekhar *et al.*, 2022). The western Himalayas, situated at a biogeographic transition zone, further amplify these gradients, facilitating species turnover and elevational replacement (Singh *et al.*, 2009).

The results of multivariate classification (HCA and TCA) showed that there were separate vegetation assemblages and diagnostic species, which revealed a strong spatial structuring of vegetation communities. These curves are in line with the ecological theory which posits that montane ecosystems are gradients in moisture availability, light intensities, and disturbance regimes that drive species assembly (Rahman *et al.*, 2022). Identifying diagnostic species within these clusters is crucial, as these taxa define vegetation types and contribute to conservation priorities, as emphasized by (De Cáceres *et al.*, 2010).

Species accumulation and richness estimation further support the robustness of the sampling design. The species-area curve showed rapid initial accumulation followed by saturation beyond ~80 plots, indicating adequate sampling effort. Declining Sørensen dissimilarity with increased sampling suggests improved representation of compositional similarity across sites. Similar asymptotic patterns have been widely reported in floristic surveys, reflecting diminishing returns in species detection with increasing sampling intensity (Gray *et al.*, 2004). Nevertheless, the presence of undetected rare taxa, as indicated by Jackknife estimates, highlights the inherent limitations of field-based biodiversity assessments.

The results of the generalized linear model (GLM) revealed species-specific responses of *Quercus* taxa to environmental gradients, especially elevation, soil properties, and moisture. *Q. baloot* was associated with lower elevations, relatively fertile soils, and higher humidity, whereas *Q. dilatata* showed affinity for higher elevations and calcareous, nutrient-poor substrates. *Q. semecarpifolia* exhibited sensitivity to slope and temperature, suggesting a narrow ecological niche, while *Q. incana* displayed broad tolerance across environmental conditions. In contrast, *Q. glauca* showed weak statistical associations, which may reflect stochastic dispersal processes or the influence of unmeasured environmental drivers. While these relationships indicate strong ecological associations, they should not be interpreted as direct causal mechanisms, as observational data cannot fully disentangle complex biotic and abiotic interactions. Similar patterns emphasizing the role of altitude, moisture, and soil fertility in oak distribution have been reported in Himalayan systems (Singh *et al.*, 2009; Kumar *et al.*, 2013). Soil variables, although secondary to climatic gradients, contributed meaningfully to vegetation differentiation. Factors such as soil pH, organic matter, and texture influence nutrient availability, water retention, and rooting conditions, thereby shaping species establishment and persistence. For instance, the association of *Q. dilatata* with calcareous soils suggests adaptation to edaphic stress, whereas *Q. baloot* appears to prefer relatively fertile and moisture-retentive substrates. These findings are consistent with global montane studies where edaphic heterogeneity acts as a key modifier of vegetation patterns (Chai and Wang, 2016; Ahmad *et al.*, 2022).

The species assemblages described in this study illustrate how elevation, climate, and soil characteristics influence floristic composition and richness in *Quercus*-dominated forests of the Himalayas. Communities at the intermediate elevations (e.g., for QAA, QAP, QCQ, and QPQ) were also moderate to high in both diversity and evenness, indicating mild environment with continuous warm temperature, fertile soil including mesic surroundings for higher species richness of these communities. The high-elevation QBI community dominated by *Q. semecarpifolia* had lower richness and diversity. Due to the harsh environmental conditions, cold, moist, and acidic conditions (Chai and Wang, 2016; Fartyal *et al.*, 2022). The QQC community was characterized by being a biodiversity hotspot with the highest number of species and the greatest Shannon diversity, which may have resulted from fertile soils, lower temperature, and higher moisture conditions (factors favoring niche differentiation and coexistence) found there compared to other habitats (Khan, 2012; Gillani *et al.*, 2024). In summary, the results of this study are in accordance with ecological theory that community composition and diversity is largely determined by environmental gradients and resource availability (Kraft *et al.*, 2015), highlighting the significance of preserving the diversity of species across landscapes.

The NMDS and PCA results show that climatic and geographic profiles play a key role in the distribution of vegetation in the study area, and temperature, relative humidity, latitude, and elevation being more significant than soil factors.

Even though soil contains weak, yet dominant significant factors (soil pH, organic matter, and clay), indicating that soils contributed to the differentiation of the community, which is consistent with those so far observed in montane systems globally (Qian and Ricklefs, 2012). As higher-order components contributed little, the PCA results (first three axes) revealed the significance of large climatic and geographic gradients in structuring species assemblages. Similar results have been reported in temperate forest and Himalayan systems, which are primarily described by vegetation-environment relationships with temperature and moisture as primary characteristics, while edaphic features have a secondary influence (Rahman *et al.*, 2022; Alam *et al.*, 2023). Consequently, projected changes in climate may significantly alter species distributions and community composition in these forests.

The DCA results, with a gradient length exceeding 4 SD units, confirm high species turnover along environmental gradients, indicative of strong ecological differentiation (Jamil *et al.*, 2025). The clustering of species such as *Taxus wallichiana*, *Quercus semecarpifolia*, and Viburnum grandiflorum on the positive end of axis 1 indicated affinities with high elevation moist habitats while disturbance tolerant taxa such as *Cynodon dactylon* and *Chenopodium album* had a reversed position, indicating niche differentiation. linked to anthropogenically influenced environments (Bisht *et al.*, 2024). This pattern highlights the combined influence of environmental filtering and disturbance on community assembly.

The CCA additionally separated the life-form spectrum behind species-environment relationships by associating vegetation patterns to major ecological gradients. The first two axes accounted for almost half (48.9%) of the variability, with elevation, temperature, and soil moisture as important determinants in *Quercus*-dominated communities' structure. *Q. semecarpifolia* clustered on high-altitude cool and moist sites, whereas *Q. baloot* was strongly associated with lower, warmer, and drier habitats in line with its frequency dominance at dry temperate forest. *Q. dilatata* was associated with mid-elevation, reflecting its wide ecological amplitude. The presence of associated flora such as *Q. semecarpifolia* with *T. wallichiana*, and *Rosa webbiana* with *Quercus dilatata*, showed the same preference of habitat at mid altitude. While harsh environment-tolerant flora such as *Cynodon dactylon* are also present with oak species, they represent the anthropogenic pressure in the study area. Similarly, previous ordination-based studies documented similar climatic, edaphic, and anthropogenic pressure as the key ecological drivers of Himalayan Forest composition (Shaheen *et al.*, 2012; Siddiqui *et al.*, 2013).

Conclusion: The present study recorded 180 species from 142 genera and 65 families across *Quercus*-dominated forests of the western Himalayas, Hazara Division, Pakistan. Asteraceae, Rosaceae, Lamiaceae, and Poaceae were the dominant families, with Asteraceae alone contributing more than one-fifth of the flora of the study area. A pronounced elevational stratification of *Quercus* species was observed, highlighting the central role of environmental filtering in structuring forest communities. The results of multivariate classification (HCA and TCA) showed that there were separate vegetation assemblages and diagnostic species. Generalized linear model (GLM) revealed species-specific responses of *Quercus* taxa to environmental gradients, especially elevation, soil properties, and moisture.

Limitations of the study: The study is based on observational data, which restricts causal inference between environmental variables and species distribution. Important factors such as land-use history, grazing intensity, and biotic interactions were not explicitly quantified. Additionally, while soil variables were included, fine-scale edaphic variability may not have been fully captured. Future research integrating experimental approaches, high-resolution environmental data, and long-term monitoring would improve understanding of ecosystem dynamics under changing climatic conditions.

Author contribution: M. Ahmed performed specimen collection and investigation, performed data analysis, and prepared the 1st manuscript draft, and contributed to data visualization. Z. Iqbal conceived and designed the study, developed the methodology, performed validation, and supervised the research. G.M. Shah contributed to manuscript review and provided overall supervision. B. Alam participated in field visits, assisted with data analysis. S.A. Asad contributed to the conceptualization of the study, methodology development, and validation of the research framework and edited the final draft of manuscript before submission.

Ethics Declaration

Availability of Data/Materials: The datasets generated during this study are available in the manuscript.

Conflict of Interest: The author declares no conflict of interest

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