Environmental variables drive plant species composition and distribution in the moist temperate forests of Northwestern Himalaya, Pakistan

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Abstract

By assessing plant species composition and distribution in biodiversity hotspots influenced by environmental gradients, we greatly advance our understanding of the local plant community and how environmental factors are affecting these communities. This is a proxy for determining how climate change influences plant communities in mountainous regions ("space-for-time" substitution). We evaluated plant species composition and distribution, and how and which environmental variables drive the plant communities in moist temperate zone of Manoor valley of Northwestern Himalaya, Pakistan. During four consecutive years (2015–2018), we sampled 30 sampling sites, measuring 21 environmental variables, and recording all plant species present in an altitudinal variable range of 1932–3168 m.a.s.l. We used different multivariate analyses to identify potential plant communities, and to evaluate the relative importance of each environmental variable in the species composition and distribution. Finally, we also evaluated diversity patterns, by comparing diversity indices and beta diversity processes. We found that (i) the moist temperate zone in this region can be divided in four different major plant communities; (ii) each plant community has a specific set of environmental drivers; (iii) there is a significant variation in plant species composition between communities, in which six species contributed most to the plant composition dissimilarity; (iv) there is a significant difference of the four diversity indices between communities; and (v) community structure is twice more influenced by the spatial turnover of species than by the species loss. Overall, we showed that altitudinal gradients offer an important range of different environmental variables, highlighting the existence of micro-climates that drive the structure and composition of plant species in each micro-region. Each plant community
Introduction

Mountains are the most remarkable landforms on the earth, representing different vegetation zones based on environmental variations [1]. They offer habitat heterogeneity based on micro-environmental variation along the altitudinal gradient [2, 3], where environmental variables (including direct and indirect effects of abiotic and biotic effects) are important factors in determining altitudinal zone boundaries [4, 5]. It is well recognized that altitude is a dynamic gradient along which several environmental variables [6] and species diversity [7, 8] change concomitantly. Within this focus, plant biodiversity is strongly influenced by different environmental variables [9], and certain species can survive on the brink of extinction in high mountains across the world [10–12].

Many mountains across the globe are important hotspots of biodiversity [13–16], with roughly half of all plant species flourishing in hotspot areas [17, 18]. However, despite this high endemism of species greatly influenced by various environmental gradients, such as edaphic, climatic and physiographic variables [19], these areas suffer a major impact from climate change [20, 21]. Plant species present in these gradients have great adaptive power [22, 23]; however, the speed with which climate change is advancing might not be sufficiently achieved by plant species adaptation in these areas, leading to a strong impact on the biodiversity of these areas [24–26], ultimately leading to variations in the community structure [27].

In the face of the current climate change and considering the importance of phytosociological studies for the understanding of biodiversity and species distribution, the Himalayas represent a fundamental piece for these studies. This region is facing a marked increase in temperature [28], which is three times greater than the global average [29]. This unprecedented rise in temperature, and modification of various environmental variables as well, may lead to shifts in species composition [24–26] and variations in community structure [27]. Many researchers have explored the effect of altitude on species composition, diversity, and forests formation structure during the previous two decades, with around half of these studies indicating an inverse association between species richness and altitude. Rahbek [30], on the other hand, did a quantitative investigation of altitudinal gradients of species richness and discovered that among plants, hump-shaped patterns of species diversity with peaks at mid-elevation are the most typically recorded, followed by monotonically declining patterns. Kluge et al. [31] found a hump-shaped diversity pattern for seed plants in the Eastern Himalayas, even though endemic species richness peaks at higher elevations due to increasingly isolated habitats and smaller surface area in mountainous ecosystems, which promotes speciation [32]. Although there has been a considerable increase in the number of phytosociological studies in these altitudinal regions considered hotspots of biodiversity [7, 19, 22, 23, 33], there is still limited knowledge of how and which environmental variables drive the distribution and composition of plant species along altitudinal gradients in specific hotspots regions, such as the Northwestern Himalaya.

By assessing the patterns of composition and distribution of plant species in these biodiversity hotspots influenced by environmental gradients, we greatly advance our understanding of the local plant community and how environmental factors are affecting these communities, which is a proxy for assessing how impacts of climate change can affect plant communities...
located in mountainous regions [34]. In this context, we evaluated plant species composition and how and which environmental variables drive the plant species distribution of moist temperate zone of the Northwestern Himalaya, Pakistan. Briefly, we assessed (i) the potential plant communities present in the moist temperate zone; (ii) which are the environmental variables that most determine plant community structure in the moist temperate zone; (iii) whether there is variation in plant species composition between plant communities and which are the species that most contributed for species composition dissimilarity; (iv) whether there is variation of diversity indices among communities; and finally (v) which is the beta diversity process that most influence plant community structure in the moist temperate zone.

Materials and methods

Study area

The present study was carried out in the moist temperate zone of Manoor valley (District Mansehra, Khyber Pakhtunkhwa), which is a mountainous valley (34.68165 N to 34.83869 N latitude, and 73.57520 E to 73.73182 E longitude Fig 1) in the Northwestern Himalayan belt of Pakistan [35–39] along an altitudinal range of 1932–3168 m.a.s.l. Monsoon winds are the main source of precipitation as well as the primary force of controlling erosion, topography, climate and vegetation of the Northwestern Himalaya [1].

Ethics approval and consent to participate

This study was approved by the Board of Study (BoS), Committee, Department of Botany and Advanced Study Research Board (ASRB) of Hazara University, Mansehra 21300, KP, Pakistan.

Vegetation sampling and plant identification

In different growing seasons (from March to October), we evaluated 30 sampling sites per year, during four consecutive years, from 2015 to 2018. The line transect method (50 meters) we used for quantitative samplings [40–45], but we never repeated the same transects over years. The surveyed study area was subdivided into 30 stands and three points randomly selected were sampled within each sampling site along 50 meters transect (total = 90 transects).

Fig 1. Map of the study area showing Pakistan, Khyber Pakhtunkhwa (KP) province, and sampling sites for data collection. Points in the right figure represent stands of the four communities identified in the moist temperate zone, Northwestern Himalaya, Pakistan. CPI: Cedrus deodara-Pinus wallichiana-Isodon rugosus, IHC: Indigofera heterantha-Heraclium candidum-Cynodon dactylon, PCP: Pinus wallichiana-Cedrus deodara-Parrotiopsis jacquemontiana, and VIP: Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana.

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The distance between the sampling sites was kept at 200 meters, while the distance between the transects was kept at 100 meters. The individuals of plant species falling precisely on the line were recorded. The data from each sampling site was calculated using phytosociological characters (i.e., density, frequency, cover and their relative values, as well as importance value) [46–48]. The IV was further used to rank each plant species and species with the highest IV were considered as the dominant species [46, 47]. Similarly, each plant community was named based on three dominant species [49–52]. The slope angle, aspect and exposure were recorded using clinometer; and altitude, longitude and latitude were measured by geographical positioning system (GPS). Plants species collection, labelling, pressing and other herbarium methodology was adopted following Ijaz [53], Ijaz et al. [54], Amjad et al. [55] and Stefanaki et al. [56]. Identification was done with the aid of Flora of Pakistan [57–59] and submitted to the Herbarium of Hazara University, Mansehra (Pakistan).

**Environmental gradients**

Soil samples weighting 200 grams were collected (15-30cm depth) randomly from each transect of sampled vegetation site [60, 61]. The replicated samples of each sampling site were thoroughly mixed to form a composite sample [62], which was placed in a sterile polythene bag and labelled accordingly. Raw materials such as rocks, and stones were sieved out and the samples were then shade dried. Each dried soil sample was processed for physicochemical tests [62, 63] to determine soil texture (i.e., clay, sand, silt, loam), pH [64], electrical conductivity (EC) [65], organic matter (OM) [66], nitrogen (N), phosphorus (P), potassium (K) and calcium carbonate (CaCO$_3$) levels [60, 61, 67]. Other climatic variables such as barometric pressure, dew point, humidity, heat index, temperature, wet bulb (relative humidity and ambient air temperature) and wind speed were also determined using a small remote weather station (Kestrel weather tracker 4000) to record the data at each transect and then average values were calculated at sampling site level [19].

**Statistical analyses**

The recorded data of vegetation, edaphic, and other environmental variables of sampling sites were compiled in order to determine relationship among them [68, 69]. Matrixes of IV data of all the recorded plant species (244 species) from 30 sampling sites were used in the analyses. Analyses were conducted on PC-ORD [70] and R software 4.0.0 [71]. Packages used in R software are mentioned in each analysis. A georeferenced map was prepared to show the distribution pattern of distinct plant communities (Fig 1).

**Sampling effort and cluster analyses.** Species area curves (SAC) were used to check the efficiency of the sampling effort, where plant abundance data with Sørensen distance values were used to create species area curves [72]. For classification of the recorded plant species (244) and 30 sampling sites into different plant communities, we used three different cluster analyses: Two-way Indicator Species Analysis (TWINSPAN), and Cluster Analysis (CA). We identified and classified plant species and stands (sampling sites) into major plant communities [73], as well as assess the effects of various factors (such as environmental variables) on such communities by processing clustering method using TWINSPAN [19, 74].

**Plant communities and associated environmental variables.** Both species and stands (sampling sites) were constrained in relation with the environmental gradients [75, 76], which were divided into geographic, slope aspect, edaphic and climatic gradients. We used non-metric multidimensional scaling (NMDS) and Principal Component Analysis (PCA) ordination biplot to determine the relationship between vegetation communities and environmental gradients using the “vegan” package. In NMDS and PCA, arrows represent the environmental
gradients, in which the length shows the strength of the gradient, and the direction represent the degree of correlation. The direction of gradients on the same axis reveals a positive correlation.

In addition, we performed canonical correspondence analysis (CCA) and variation partitioning tests (partial CCA) [77] to observe how explanatory variables (climatic, edaphic, geographic, and slope) drive the plant species distribution. First we built the best model with the lowest number of variables (those that most explain variance), through the step function with permutation using the "stats" package [71]. Next, we also evaluated multicollinearity between variables of the final model using Variance Inflation Factor (VIF), and we removed any variable with VIF > 10, one at a time. Finally, with the final model, we carried out CCA and partial CCA to check how much each group of variables (geographic, edaphic, climatic, slope) explain in our model [77]. For these analysis, we used the “vegan” package [78].

Variation of plant species composition among plant communities. To compare whether there is difference in species composition between plant communities, we also used NMDS followed by a Permutational Multivariate Analysis of Variance (PERMANOVA) with Euclidean distance and 999 permutations. After PERMANOVA, we conducted pairwise comparisons between communities with corrections for multiple testing also using Euclidean distance and 999 permutations. We used false discovery rate (FDR) as p-value adjustment method. PERMANOVA and pairwise comparisons were conducted with "RVAideMemoire" package [79]. To observe the contribution of each plant species to overall dissimilarities, we used a similarity percentage analysis based on the decomposition of Bray-Curtis dissimilarity using the package "vegan" [78].

Variation of diversity indices among plant communities. To compare the diversity indices evaluated (species richness, Shannon, Simpson, and Pielou) among the four communities, we also conducted a GLM with Gaussian error distribution, except for species richness, in which we used Poisson distribution followed by Likelihood Ratio test. Pairwise comparisons were conducted with estimated marginal means using the package 'emmeans' [80].

Beta diversity. To evaluate which is the beta diversity process that most influence plant community structure in the moist temperate zone, we decomposed the Sørensen dissimilarity index (βsor), a measure of overall species replacement into two additive components: the spatial turnover (Simpson pairwise dissimilarity, βsim) and nestedness-resultant components (nestedness-fraction of Sorensen pairwise dissimilarity, βsne) [81–83]. Dissimilarity analysis was conducted in the package “betapart” [84].

Results

Sampling effort and plant communities

In total, 244 plant species belonging to 194 genera and 74 families (Table 1) were recorded in the moist temperate forests of the Manoor valley, Northwestern Himalaya, Pakistan. The moist temperate forests ranged from 1932.3m to 3168m. SAC analysis showed that the maximum number of plant species appeared up to stand 26 and the species curve became parallel after it, as no new species were recorded further (Fig 2).

Based on the TWINSPAN analysis (high cluster heterogeneity value–Lambda = 0.4045), we identified four different major plant communities (Fig 3), which were composed of different indicator species (IHC: Indigofera heterantha-Heracleum candicans-Cynodon dactylon; VIP: Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana, CPI: Cedrus deodara-Pinus wallichiana-Isodon rugosus, and PCP: Pinus wallichiana-Cedrus deodara- Parrotiopsis jacquiniana). The IHC community was primarily found in the lower mountainous ranges (1932.3–2338.4 m.a.s.l), where the dominating flora was a combination of shrub and herb
Table 1. Species composition and IV according to each sampling site and community found along four years of collection in moist temperate forests of Manoor valley, Northwestern Himalaya, Pakistan.

| Plant Species                        | Abbreviations | Family name    | Plant Communities |
|--------------------------------------|---------------|----------------|-------------------|
| Acer caesium (Wall. ex Brandis)      | Ace cae       | Sapindaceae    | 0.00 0.00 0.26 0.56 |
| Achyranthes aspera (L.)              | Ach asp       | Amaranthaceae  | 0.00 0.00 0.00 0.34 |
| Achyranthes bidentata Blume          | Ach bid       | Amaranthaceae  | 0.00 0.00 0.00 0.32 |
| Achillea millefolium (L.)            | Ach mil       | Astereae       | 0.87 0.50 0.00 0.00 |
| Adiantum capillus-veneris (L.)       | Adi cap-ven   | Adiantaceae    | 0.00 0.00 0.67 1.75 |
| Adiantum indicum J. Ghatak           | Adi ind       | Adiantaceae    | 0.00 0.00 0.96 1.84 |
| Adiantum venustum D. Don             | Adi ven       | Adiantaceae    | 0.00 0.00 0.49 1.30 |
| Aegopodium burttii (Nasir)           | Aeg bur       | Apiaceae       | 0.00 0.00 0.15 0.34 |
| Ainsliaea aptera (DC.)               | Ain apt       | Astereae       | 0.00 0.00 0.00 0.26 |
| Ajuga integrifolia (Buch.-Ham.)     | Aju int       | Lamiaeae       | 0.00 0.00 0.00 0.27 |
| Alchemilla cashmeriana (Rothum.)     | Alc cas       | Rosaceae       | 0.43 0.00 0.51 0.12 |
| Alcea rosea (L.)                     | Alc ros       | Malvacae       | 0.05 0.00 0.15 0.00 |
| Alnus nitida (Spach) Endl.           | Aln nit       | Betulaceae     | 0.45 0.00 0.00 0.29 |
| Amaranthus viridis (L.)              | Ama vir       | Amaranthaceae  | 0.00 0.00 0.00 0.24 |
| Anagallis arvensis (L.)              | Ana arv       | Primulaceae    | 0.00 0.00 0.08 1.15 |
| Anaphalis busua (Buch.-Ham.) DC.     | Ana bus       | Astereae       | 0.00 0.00 0.20 0.07 |
| Androsace hazarica R.R. Stewart ex Y. Nasir | And haz     | Primulaceae    | 0.00 0.00 0.30 0.39 |
| Androsace rotundifolia Hardw.        | And rot       | Primulaceae    | 0.00 0.00 0.06 0.54 |
| Arisaema flavum (Forssk.) Schott     | Ari fla       | Araceae        | 0.00 0.00 0.00 0.91 |
| Arisaema jacquemontii Blume          | Ari jac       | Araceae        | 0.00 4.24 0.00 0.91 |
| Artemisia absinthium (L.)            | Art abs       | Astereae       | 0.36 0.13 0.96 2.25 |
| Asplenium adiantum-nigrum (L.)       | Asp adi-nig   | Adiantaceae    | 0.00 0.00 0.20 0.41 |
| Asparagus fiicinus (Buch.-Ham.) DC.  | Asp fii       | Asparagaceae   | 0.00 0.00 0.00 0.16 |
| Avena sativa (L.)                    | Ave sat       | Poaceae        | 0.04 0.09 0.00 0.00 |
| Bauhinia variegata (L.)              | Bau var       | Caesalpiniaeae | 0.05 0.00 0.00 0.00 |
| Bergenia ciliata (Haw.) Sternb.      | Ber cil       | Saxifragiaeae  | 0.00 0.00 0.09 0.12 |
| Berberis lycium Royle                | Ber lyc       | Berberidaceae  | 0.00 1.42 1.55 0.49 |
| Berberis parkeriana C.K. Schneid.    | Ber pac       | Berberidaceae  | 0.00 0.00 0.00 0.24 |
| Bistorta amplexicaulis (D. Don) Greene | Bis amp      | Polygonaceae   | 5.17 1.64 0.00 0.00 |
| Brassica compestris (L.)             | Bra com       | Brassicaceae   | 0.52 0.00 0.00 0.00 |
| Bromus diandrus Roth.                | Bro dia       | Poaceae        | 2.00 1.64 0.39 0.19 |
| Bromus secalinus (L.)                | Bro sec       | Poaceae        | 1.83 1.49 0.67 0.59 |
| Bromus tectorum (L.)                 | Bro tec       | Poaceae        | 2.20 1.29 0.00 0.06 |
| Bupleurum longicaule Wall. ex DC.    | Bup lon       | Apiaceae       | 0.00 0.00 0.10 0.32 |
| Bupleurum nigrescens (E. Nasir)      | Bup nig       | Apiaceae       | 0.51 1.22 0.15 1.48 |
| Calitha palustris var. alba (Cambess) Hook.f. & Thomson | Cal pal | Ranunculaceae | 0.00 0.00 0.04 0.46 |
| Calamintha umbrosa (M. Bieb.) Hedge | Cal umb       | Lamiaceae      | 1.11 1.03 1.08 0.61 |
| Campylotropis meeboldii (Schindl.) Schindl. | Cam mee | Papilionaceae | 0.00 0.00 0.32 0.04 |
| Cannabis sativa (L.)                 | Can sat       | Cannabaceae    | 0.00 0.00 0.00 0.07 |
| Capsella bursa-pastoris (L.) Medik.  | Cap bur-pas   | Brassicaceae   | 0.18 0.97 0.53 1.47 |
| Castanea sativa (L.)                 | Cas sat       | Fagaceae       | 0.00 0.00 0.12 0.14 |
| Cedrus deodara (Roxb. ex Lamb.) G. Don | Ced deo     | Pinaceae       | 0.00 5.16 22.50 16.07 |
| Celosia argentea (L.)                | Cel arg       | Amaranthaceae  | 0.61 0.00 0.00 0.00 |
| Chenopodium album (L.)               | Che alb       | Chenopodiaceae | 0.75 0.41 0.00 0.24 |
| Chrysanthemum indicum (L.)           | Chr ind       | Astereae       | 0.00 0.00 0.00 0.64 |

(Continued)
### Table 1. (Continued)

| Plant Species | Abbreviations | Family name | Plant Communities |
|---------------|---------------|-------------|-------------------|
| Cichorium intybus L. | Cic int | Asteraceae | IHC 0.00 VIP 0.23 CPI 0.11 PCP 0.40 |
| Circaea alpina L. | Cir alp | Onagraceae | 0.00 0.00 0.00 0.00 0.40 |
| Cirsium arvense (L.) Scop. | Cir arv | Asteraceae | 0.79 0.79 0.24 0.15 0.55 |
| Circaea cordata Royle | Cir cor | Onagraceae | 0.79 0.79 0.24 0.15 0.55 |
| Cirsium falconeri (Hook.f.) Petr. | Cir fal | Asteraceae | 0.00 0.00 0.00 0.00 0.40 |
| Clematis grata Wall. | Cle gra | Ranunculaceae | 0.00 0.00 0.00 0.00 0.40 |
| Clinopodium vulgare L. | Cli vul | Lamiaceae | 1.54 1.10 1.67 3.68 |
| Colebrookea oppositifolia Sm. | Col opp | Lamiaceae | 0.00 0.00 0.00 0.00 0.40 |
| Commelina benghalensis L. | Com ben | Commelinaceae | 0.00 0.65 0.00 0.00 0.40 |
| Convolvulus arvensis L. | Con arv | Convolvulaceae | 0.00 0.00 0.00 0.00 0.40 |
| Conyza japonica (Thunb.) Less. ex Less. | Con jap | Asteraeae | 0.00 0.00 0.00 0.00 0.40 |
| Corydalis carinata Lide ´ n and Z.Y.Su | Cor car | Papaveraceae | 0.10 0.00 0.16 0.07 0.40 |
| Corylus colurna L. | Cor col | Betulaceae | 0.00 0.00 0.00 0.00 0.40 |
| Corydalis cornuta Royle [Syn. Corydalis stewartii Fedde] | Cor cor | Papaveraceae | 0.07 0.00 0.46 0.51 0.40 |
| Colebrookea oppositifolia Sm. | Col opp | Lamiaceae | 0.00 0.00 0.00 0.00 0.40 |
| Cyanthillium cinereum (L.)H.Rob. | Cya cin | Asteraeae | 0.00 0.00 0.08 0.10 0.40 |
| Cynoglossum apenninum L. | Cyn ape | Boraginaceae | 0.08 0.18 0.00 0.00 0.40 |
| Cynoglossum glochidiatum Wall. ex Benth. | Cyn glo | Boraginaceae | 1.58 0.25 0.33 1.52 0.40 |
| Cynoglossum microglochin Benth. | Cyn mic | Boraginaceae | 0.14 0.52 0.00 0.00 0.40 |
| Cuscuta reflexa Roxb. | Cus ref | Cuscutaceae | 0.00 0.00 0.08 0.34 0.40 |
| Cyperus odoratus L. | Cyp odo | Cyperaceae | 0.15 0.89 0.08 0.20 0.40 |
| Cyperus rotundus L. | Cyp rot | Cyperaceae | 0.59 1.09 0.91 0.53 0.40 |
| Dactylis glomerata L. | Dac glo | Poaceae | 0.41 1.40 0.47 0.40 0.40 |
| Desmodium elegans DC. | Des ele | Papilionaceae | 1.39 0.00 0.31 0.12 0.40 |
| Dicliptera bupleuroides Nees | Dic bup | Acanthaceae | 0.00 0.00 0.10 0.00 0.40 |
| Dioscorea deltoidea Wall. ex Griseb. | Dio del | Dioscoreaceae | 0.13 0.00 0.24 0.03 0.40 |
| Diospyros lotus L. | Dio lot | Ebenaceae | 0.00 0.00 0.16 0.00 0.40 |
| Dysphania ambrosioides (L.) Mosyakin & Clemants | Dys amb | Chenopodiaceae | 0.00 0.40 0.00 0.37 0.40 |
| Elsholtzia ciliata (Thunb.) Hyl. | Els cil | Lamiaceae | 0.00 0.16 0.18 0.04 0.40 |
| Epilobium hirsutum L. | Epi hir | Onagraceae | 0.04 0.00 0.17 0.12 0.40 |
| Epilobium latifolium L. | Epi lat | Onagraceae | 0.00 0.28 0.19 0.07 0.40 |
| Epimedium clatum C.Morrenan d Decne. | Epi ela | Berberidaceae | 0.03 0.18 0.14 0.07 0.40 |
| Equisetum arvense L. | Equ arv | Equisetaceae | 0.40 0.00 0.00 0.00 0.40 |
| Erigeron canadensis L. | Eri can | Asteraceae | 0.87 0.00 0.55 0.39 0.40 |
| Erysimum melicentae Dunn. | Ery mel | Brassicaceae | 0.15 0.12 0.00 0.00 0.40 |
| Euphorbia helioscopia L. | Eup hel | Euphorbiaceae | 0.11 0.00 0.00 0.05 0.40 |
| Euphrasia himalayica Wets. | Eup him | Orobanchaceae | 2.70 0.58 0.00 0.00 0.40 |

(Continued)
| Plant Species | Abbreviations | Family name     | Plant Communities |
|---------------|---------------|-----------------|-------------------|
| Euphorbia hirta L. | Eup hir | Euphorbiaceae | IHC 0.00  VIP 0.00  CPI 0.09  PCP 0.25 |
| Euphorbia prostrata Ait. | Eup pro | Euphorbiaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.07 |
| Euphorbia serpens Kunth | Eup ser | Euphorbiaceae | IHC 0.00  VIP 0.00  CPI 0.08  PCP 0.30 |
| Fagopyrum tataricum (L.) Gaertn. | Fag tat | Polygonaceae | IHC 0.00  VIP 0.21  CPI 0.00  PCP 0.06 |
| Filipendula vestita (Wall. ex G. Don.) Maxim. | Fil ves | Rosaceae | IHC 0.58  VIP 2.22  CPI 1.26  PCP 0.32 |
| Foeniculum vulgare Mill. | Foe vul | Apiaceae | IHC 0.70  VIP 1.00  CPI 0.00  PCP 0.68 |
| Fragaria nubicola (Hook. f.) Lindl. ex Lacaita | Fra nub | Rosaceae | IHC 0.15  VIP 1.95  CPI 0.36  PCP 4.11 |
| Fumaria indica (Hausskn ) Pugsley | Fum ind | Fumariaceae | IHC 0.00  VIP 0.21  CPI 0.00  PCP 0.13 |
| Galium aparine L. | Gal apa | Rubiaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.01 |
| Galium asparagifolium Wall. ex M.A.Lawson | Gal asp | Rubiaceae | IHC 0.00  VIP 0.21  CPI 0.05  PCP 0.13 |
| Galium elagans Wall. | Gal ela | Rubiaceae | IHC 0.00  VIP 0.04  CPI 0.00  PCP 0.02 |
| Geranimum clarkei (Kusn.) Omer | Gen cla | Gentianaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.10 |
| Gentianodes clarkei (Kusn.) Omer | Gen cla | Gentianaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.10 |
| Gerbera gossypina (Royle) Beauverd | Ger gos | Asteraeae | IHC 0.33  VIP 0.00  CPI 0.00  PCP 0.00 |
| Geranium nepalense Sweet. | Ger nep | Geraniaceae | IHC 2.94  VIP 3.09  CPI 1.04  PCP 2.16 |
| Geranium wallichianum D. Don ex Sweet | Ger wal | Geraniaceae | IHC 2.94  VIP 3.09  CPI 1.04  PCP 2.16 |
| Gymnosporia royleana Wall. ex M.A.Lawson | Gym roy | Celastraceae | IHC 0.00  VIP 0.46  CPI 0.00  PCP 0.00 |
| Hackelia uncinata (Benth.) C.E.C. Fisch. | Hac unc | Boraginaceae | IHC 5.89  VIP 1.79  CPI 0.00  PCP 0.00 |
| Hedera nepalensis K. Koch | Hed nep | Araliaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 2.61 |
| Helianthus annuus L. | Hel ann | Asteraeae | IHC 0.14  VIP 0.00  CPI 0.00  PCP 0.00 |
| Heracleum candicans Wall. ex DC. | Her can | Apiaceae | IHC 5.89  VIP 1.79  CPI 0.00  PCP 0.00 |
| Hyoscyamus niger L. | Hyo nig | Solanaceae | IHC 2.94  VIP 3.09  CPI 1.04  PCP 2.16 |
| Hypericum perforatum L. | Hyp perf | Clusiaceae | IHC 0.00  VIP 0.46  CPI 0.00  PCP 0.00 |
| Impatiens bicolor Royle. | Imp bic | Balsaminaceae | IHC 0.12  VIP 0.29  CPI 2.10  PCP 3.56 |
| Impatiens brachycentra Kar. & Kir. | Imp bra | Balsaminaceae | IHC 3.98  VIP 0.16  CPI 0.00  PCP 0.00 |
| Indigofera australis Willd. | Ind aus | Papilionaceae | IHC 1.15  VIP 1.27  CPI 0.00  PCP 0.00 |
| Indigofera hebehebe Baker | Ind heb | Papilionaceae | IHC 0.78  VIP 1.83  CPI 0.00  PCP 0.00 |
| Indigofera heterantha Brandis | Ind het | Papilionaceae | IHC 5.08  VIP 23.51  CPI 2.33  PCP 2.83 |
| Inula cuspidata (Wall. ex DC.) C.B. Clarke | Inu cus | Asteraceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.24 |
| Inula falconeri Hook.f. | Inu fal | Asteraceae | IHC 0.00  VIP 0.00  CPI 0.05  PCP 0.10 |
| Ipomoea nil (L.) Roth | Ipo nil | Convolvulaceae | IHC 0.00  VIP 0.00  CPI 0.26  PCP 0.50 |
| Isodon rugosus (Wall. ex Benth.) Codd | Iso rug | Lamiaceae | IHC 0.00  VIP 0.00  CPI 5.77  PCP 3.32 |
| Jugland regia L. | Jug reg | Juglandaceae | IHC 4.41  VIP 0.56  CPI 0.00  PCP 0.00 |
| Lactuca tatarica (L.) C.A. Mey | Lac tat | Asteraceae | IHC 0.35  VIP 0.48  CPI 0.41  PCP 0.41 |
| Lamium album L. | Lam alb | Lamiaceae | IHC 0.00  VIP 0.10  CPI 0.06  PCP 0.06 |
| Lamium amplexicaule L. | Lam amp | Lamiaceae | IHC 1.23  VIP 0.25  CPI 0.53  PCP 0.88 |
| Lathyrus aphaca L. | Lat aph | Papilionaceae | IHC 4.17  VIP 0.70  CPI 1.65  PCP 1.61 |
| Lathyrus odoratus L. | Lat odo | Papilionaceae | IHC 0.30  VIP 0.74  CPI 0.00  PCP 0.00 |
| Lathyrus sativa L. | Lat sat | Papilionaceae | IHC 0.34  VIP 0.90  CPI 0.00  PCP 0.00 |
| Launaea procumbens (Roxb.) Ramayya and Rajagopal | Lau pro | Asteraceae | IHC 0.00  VIP 0.00  CPI 0.91  PCP 0.40 |
| Lavatera cachemiriana Camb. in Jacq. | Lav cac | Malvaceae | IHC 0.04  VIP 0.00  CPI 0.00  PCP 0.00 |
| Leptodermis virgata Edgew. ex Hook.F. | Lep vir | Rubiaceae | IHC 1.36  VIP 0.63  CPI 1.24  PCP 1.67 |
| Ligularia amplexicaulis DC. | Lig amp | Asteraceae | IHC 0.00  VIP 0.34  CPI 0.00  PCP 0.11 |
| Lindelofia sp. | Lin sp | Boraginaceae | IHC 0.05  VIP 0.00  CPI 0.00  PCP 0.00 |
| Lomatogonium spathulatum (A. Kern.) Fernald | Lom spa | Gentianaceae | IHC 0.00  VIP 0.00  CPI 0.00  PCP 0.22 |
| Lonicera caerulea L. | Lon cae | Caprifoliaceae | IHC 0.05  VIP 0.28  CPI 0.07  PCP 0.17 |

(Continued)
| Plant Species | Abbreviations | Family name | Plant Communities |
|---------------|---------------|-------------|-------------------|
| *Lotus corniculatus* L. | Lot cor | Papilionaceae | 0.00  0.14  0.03  0.07 |
| *Luffa sp.* | Lufsp | Cucurbitaceae | 0.00  0.00  0.39  0.37 |
| *Lyonia ovalifolia* (Wall.) Drude | Lyo ova | Ericaceae | 0.00  0.00  0.00  0.22 |
| *Malus domestica* Borkh. | Mal dom | Rosaceae | 0.27  0.35  0.05  0.22 |
| *Medicago sativa* L. | Med sat | Papilionaceae | 0.86  0.27  1.04  1.95 |
| *Mentha piperita* L. | Men pip | Lamiaceae | 0.00  0.00  0.00  0.64 |
| *Mentha royleana* Wall. ex Benth. | Men roy | Lamiaceae | 0.00  0.00  0.00  0.63 |
| *Micromeria biflora* (Ham.) Bth. | Mic bif | Lamiaceae | 0.00  0.00  2.17  0.88 |
| *Minuartia kashmirica* (Edgew.) Mattf. | Min kas | Caryophyllaceae | 0.00  0.00  0.00  0.12 |
| *Nepeta graciliflora* Benth. | Nep gra | Lamiaceae | 1.90  0.87  0.00  0.00 |
| *Nepeta laevigata* (D. Don) Hand.-Mazz | Nep lae | Lamiaceae | 1.00  2.07  0.00  0.00 |
| *Oenothera rosea* L. Her ex Aiton | Oen ros | Onagraceae | 1.36  0.46  0.26  0.44 |
| *Onopordum acanthium* L. | Ono aca | Asteraceae | 0.00  1.57  0.00  0.00 |
| *Parrotiopsis jacquemontiana* (Decne.) Rehder | Par jac | Hamamelidaceae | 0.43  0.00  4.69  10.33 |
| *Paspalum dilatatun* Poir. | Pas dil | Poaceae | 0.40  0.00  0.09  0.00 |
| *Pedicularis punctata* Decne | Ped pun | Orobanchaceae | 2.09  1.10  0.00  0.00 |
| *Pennisetum orientale* Rich. | Pen ori | Poaceae | 2.78  2.83  0.69  0.31 |
| *Periploca aphylla* Decne. | Per aph | Asclepiadaceae | 0.04  0.15  0.13  0.11 |
| *Persicaria capitata* (Buch.-Ham. ex D.Don) H.Gross | Per cap | Polygonaceae | 0.00  0.81  0.31  1.73 |
| *Pilea umbrosa* Blume | Pil umb | Urticaceae | 0.00  0.00  0.27  0.21 |
| *Pimpinella stewartii* (Dunn) Nasir | Pim ste | Apiaceae | 2.11  2.72  0.00  0.40 |
| *Pinus wallichiana* A.B. Jacks | Pin wal | Pinaceae | 0.00  5.30  20.28  16.24 |
| *Piptatherum aequiglume* (Duthie ex Hook.f.) Roshev. | Pip aeq | Poaceae | 0.13  0.00  0.00  0.00 |
| *Plantago lanceolata* L. | Pla lan | Plantaginaceae | 0.85  2.76  0.07  0.36 |
| *Plantago major* L. | Pla maj | Plantaginaceae | 2.06  4.64  0.71  0.79 |
| *Pleurospermum stellatum* (D. Don) Benth. ex C.B. Clarke | Ple ste | Apiaceae | 0.00  0.00  0.21  0.00 |
| *Pleurospermum stylosum* C.B. Clarke | Ple sty | Apiaceae | 0.00  0.00  0.24  0.04 |
| *Poa alpina* L. | Poa alp | Poaceae | 0.00  0.00  0.30  0.00 |
| *Poa annua* L. | Poa ann | Poaceae | 0.45  1.99  0.75  0.00 |
| *Poa infirma* Kunth | Poa inf | Poaceae | 3.08  3.03  1.11  0.03 |
| *Polygonum plebeium* R.Br. | Pol ple | Convallariaceae | 0.49  1.51  0.62  0.60 |
| *Polygonatum sp.* | Pol sp. | Convallariaceae | 0.00  0.00  0.00  0.13 |
| *Portulaca oleracea* L. | Por ole | Portulacaceae | 0.07  0.00  0.00  0.00 |
| *Potentilla anserina* L. | Pot ans | Rosaceae | 0.00  0.67  0.00  0.26 |
| *Potentilla nepalensis* Hook. | Pot nep | Rosaceae | 2.15  1.59  0.00  0.12 |
| *Prunus armeniaca* L. | Pru arm | Rosaceae | 0.07  0.00  0.00  0.00 |
| *Prunus domestica* L. | Pru dom | Rosaceae | 0.25  0.00  0.00  0.00 |
| *Prunus vulgaris* L. | Pru vul | Lamiaceae | 3.11  4.20  0.00  0.00 |
| *Pteridium aquilinum* (L.) Kuhn | Pte aqu | Pteridaceae | 0.29  0.00  0.00  0.00 |

(Continued)
Table 1. (Continued)

| Plant Species | Abbreviations | Family name       | Plant Communities |
|---------------|---------------|-------------------|-------------------|
| *Pterocanthus urticifolius* (Wall. ex Kuntze) Bremek. | Pte urt | Verbenaceae | IHC: 0.00 0.00 0.07 0.05 |
| *Pteris vittata* L. | Pte vit | Pteridaceae | IHC: 1.34 0.00 0.51 0.49 |
| *Pyrus pashia* Buch.-Ham. ex D.Don | Pyr pas | Rosaceae | IHC: 0.69 0.00 0.00 0.00 |
| *Ranunculus laetus* Wall. ex Hook. f. and J.W. Thompson | Ran lae | Ranunculaceae | IHC: 0.00 0.00 0.00 0.07 |
| *Ranunculus muricatus* L. | Ran mur | Ranunculaceae | IHC: 1.61 0.94 0.00 0.23 |
| *Reinwardtia trigyna* Planch. | Rei tri | Linaceae | IHC: 0.00 0.00 0.04 0.04 |
| *Rhamnus purpurea* Edgew. | Rha pur | Rhamnaceae | IHC: 0.00 0.00 0.09 0.16 |
| *Rhynchosia pseudo-cajan* Cambess. | Rhy pse | Papilionaceae | IHC: 0.23 0.00 0.00 0.06 |
| *Rosa brunonii* Lindl. | Ros bru | Rosaceae | IHC: 0.00 0.00 0.15 0.07 |
| *Rosa webbiana* Wall. ex. Royle | Ros web | Rosaceae | IHC: 0.00 0.00 0.04 0.00 |
| *Rubus fruticosus agg.* | Rub fru | Rosaceae | IHC: 0.00 0.00 0.24 0.16 |
| *Rubus sanctus* Schreber | Rub san | Rosaceae | IHC: 0.00 0.00 0.00 0.12 |
| *Rumex dentatus* L. | Rum den | Polygonaceae | IHC: 0.47 0.00 0.00 0.00 |
| *Rumex nepalensis* Sprenge | Rum nep | Polygonaceae | IHC: 0.42 0.77 0.00 0.00 |
| *Rydingia limbata* (Benth.) Scheen & V.A. Albert [Syn. *Otostegia limbata* (Benth.) Boiss.] | Ryd lim | Lamiaceae | IHC: 0.00 1.24 0.28 0.00 |
| *Saccharum spontaneum* L. | Sac spo | Poaceae | IHC: 0.00 0.00 0.00 0.28 |
| *Salvia lanata* Roxb. | Sal lan | Lamiaceae | IHC: 0.15 0.00 0.00 0.00 |
| *Salvia nubicola* Wall. ex Sweet | Sal nub | Lamiaceae | IHC: 0.12 0.00 0.00 0.00 |
| *Sanicula elata* Buch.-Ham. ex D.Don | San ela | Apiaceae | IHC: 0.00 0.00 0.10 0.25 |
| *Sambucus wightiana* Wall. ex Wight and Arn | Sam wig | Sambucaceae | IHC: 1.34 0.00 0.54 0.00 |
| *Sarcoccoa saligna* Müll.Arg. | Sar sal | Buxaceae | IHC: 0.00 0.00 0.00 1.54 |
| *Saussurea venosum* (Dryand. ex Aiton) Kunth | Sau ven | Araceae | IHC: 0.00 0.00 0.00 0.11 |
| *Schismus arabicus* Nees. | Sch ara | Poaceae | IHC: 0.00 0.00 0.46 1.24 |
| *Senecio analogous* DC. | Sen ana | Asteraceae | IHC: 0.00 0.00 0.05 0.03 |
| *Senecio chrysanthemoides* DC. | Sen chr | Asteraceae | IHC: 0.00 0.00 0.15 0.57 |
| *Seseli libanotis* (L.) W.D.J. Koch | Ses lib | Apiaceae | IHC: 0.00 0.00 0.04 0.31 |
| *Sida cordata* (Burm.f.) Borss.. | Sid cor | Malvaceae | IHC: 0.16 0.00 0.05 0.07 |
| *Silene conoidea* L. | Sil con | Caryophyllaceae | IHC: 0.37 0.00 0.00 0.05 |
| *Silene vulgaris* (Moench) Garcke | Sil vul | Caryophyllaceae | IHC: 0.37 0.23 0.00 0.17 |
| *Sisymbrium irio* L. | Sis iri | Brassicaceae | IHC: 0.03 0.32 0.05 0.00 |
| *Smilax glaucophylla* Koltzsch | Smi glau | Smilacaceae | IHC: 0.00 0.00 0.00 0.01 |
| *Solena amplexicaulis* (Lam.) Gandhi | Sol amp | Cucurbitaceae | IHC: 0.00 0.00 0.05 0.04 |
| *Sonchus asper* (L.) Hill | Son asp | Asteraceae | IHC: 0.00 0.00 0.00 0.00 |
| *Sorghum halepense* (L.) Pers. | Sor hal | Poaceae | IHC: 0.00 0.00 0.00 0.47 |
| *Sorbus tomentosa* Hedl. | Sor tom | Rosaceae | IHC: 0.00 0.00 0.00 0.06 |
| *Sorbaria tomentosa* (Lindl.) Rehder | Sorb tom | Rosaceae | IHC: 0.57 3.04 0.00 0.12 |
| *Spiraea affinis* R.Parker | Spi aff | Rosaceae | IHC: 0.00 0.00 0.00 0.12 |
| *Spiranthes sinensis* (Pers.) Ames | Spi sin | Orchidaceae | IHC: 0.00 0.00 0.00 0.02 |
| *Sparaxis taxa* J. Breck. | Spi tax | Caryophyllaceae | IHC: 0.00 0.00 0.00 0.02 |
| *Sporobolus diandrus* (Retz.) P.Beauv. | Spo dia | Poaceae | IHC: 2.48 0.00 0.75 0.26 |
| *Stellaria media* (L.) Vill. | Ste med | Caryophyllaceae | IHC: 0.11 0.00 0.00 0.18 |
| *Stellaria monosperma* Buch.-Ham. ex D. Don | Ste mon | Caryophyllaceae | IHC: 0.00 0.00 0.00 0.08 |
| *Swertia cordata* (Wall. ex G. Don) C.B. Clarke | Swc cor | Gentianaceae | IHC: 0.00 0.00 0.00 0.03 |
| *Tagetes minuta* L. | Tag min | Asteraceae | IHC: 0.00 0.00 0.70 2.22 |
| *Taraxacum officinale* agg. F.H. Wigg. | Tar off | Asteraceae | IHC: 0.14 0.66 0.17 0.56 |
| *Thalictrum pedunculatum* Edgew. | Tha ped | Ranunculaceae | IHC: 0.00 0.00 0.13 0.05 |

(Continued)
Table 1. (Continued)

| Plant Species | Abbreviations | Family name | Plant Communities |
|---------------|---------------|-------------|-------------------|
| *Torilis japonica* (Houtt.) DC. | Tor jap | Apiaceae | IHC 0.00 VIP 0.00 CPI 0.05 PCP 0.08 |
| *Trachyspermum ammi* (L.) Sprague | Tra am | Apiaceae | IHC 0.00 VIP 0.00 CPI 0.05 PCP 0.18 |
| *Trifolium repens* L. | Tri rep | Papilionaceae | VIP 1.55 CPI 0.31 PCP 0.14 0.69 |
| *Urochloa panicoides* P. Beauv. | Uro pan | Poaceae | CPI 0.61 PCP 0.43 0.30 0.00 |
| *Urtica dioica* L. | Urt dio | Urticaceae | CPI 1.52 PCP 0.00 0.21 0.53 0.34 |
| *Valeriana jatamansi* Jones | Val jat | Caprifoliaceae | CPI 0.00 1.10 PCP 0.00 0.00 |
| *Verbascum thapsus* L. | Ver tha | Scrophulariaceae | CPI 1.34 PCP 0.00 0.00 0.73 |
| *Veronica anagallis* L. | Ver ana | Plantaginaceae | CPI 0.00 2.12 PCP 0.23 0.24 |
| *Viburnum grandiflorum* Wall. ex DC. | Vib gra | Adoxaceae | CPI 0.00 24.43 PCP 0.00 1.45 |
| *Vicia sativa* L. | Vic sat | Papilionaceae | CPI 0.36 PCP 0.99 0.17 0.00 |
| *Vincetoxicum petrense* (Hemsl. & Lace) Rech. f. | Vinc pet | Asclepiadaceae | CPI 0.00 PCP 0.00 0.09 0.13 |
| *Viola odorata* L. | Vio odo | Violaceae | CPI 0.42 PCP 0.70 0.15 0.51 |
| *Viola serpens* Wall. Ex Ging | Vio ser | Violaceae | CPI 0.19 PCP 0.92 0.38 0.11 |
| *Vitex negundo* L. | Vit neg | Vitaceae | CPI 0.00 PCP 0.80 0.00 0.12 |
| *Wulfenia amherstiana* (Benth.) D.Y. Hong | Wul amh | Plantaginaceae | CPI 0.00 PCP 0.00 0.04 0.34 |

IHC: *Indigofera heterantha-Heracleum candicans-Cynodon dactylon*, VIP: *Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana*, CPI: *Cedrus deodara-Pinus wallichiana-Isodon rugosus* and PCP: *Pinus wallichiana-Cedrus deodara-Parrotiopsis jacquemontiana*.

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species owing to the existence of a substantial herbaceous layer of *Cynodon dactylon*, which carpeted the landscape alongside *Indigofera heterantha* patches (Table 1). The VIP community was recognized mainly in the foothills and adjacent plains (2390.5–2437.8 m.a.s.l), where the predominant vegetation was shrubland with abundant patches of *Viburnum grandiflorum* and

![Species-Area Curve (SAC) of 244 plant species distributed among 30 sampling sites.](https://doi.org/10.1371/journal.pone.0260687.g002)
Indigofera heterantha, accompanied by the co-dominant Pinus wallichiana (tree species). Nonetheless, the other two plant communities, i.e., PCP and CPI, were significantly dominated by the tree species layer at the middle (2292–2947 m.a.s.l) and higher (2048.2–3168 m.a.s.l) altitudinal ranges alongside shrubby associates (Table 1).

**Plant communities and associated environmental variables**

NMDS and PCA were used to show the relationship between the plant communities of moist temperate forests and environmental variables (Fig 4A–4D) and PCA (Fig 4E). The ecological and environmental variables like geographic, slope, edaphic, and climatic variables were used to correlate communities (Table 2). The most representative environmental variables that drive the community structure and diversity were altitude, slope angle and aspects (SE, NE, ES, WN), potassium (K), pH, organic matter, loam, silt, sand, clay, temperature, heat index, wind speed and barometric pressure. Environmental variables classify 30 sampling sites into four major plant communities, as shown by the cluster analysis (Fig 3). In constrained PCA ordination, the PC1 axis accounted for the most explanatory variance (20%), while the PC2 axis accounted for the least (14.2%). The profound influence of the environmental variables was revealed by classifying the moist temperate forests vegetation into four communities (Fig 4E), as also shown by CA, TWCA and NMDS.

The PCP community showed positive and significant correlation with northern aspect, silty loamy soil texture, humidity and altitude (Fig 4B and 4C). In contrast, CPI community showed positively significance with southern slope, wind speed, dew point and wet bulb. IHC community showed positive correlation with silty soil texture, electric conductivity and pH. And
Fig 4. Non-Multidimensional Scaling (NMDS) between plant communities in moist temperate forests and environmental gradients. a) geographic, b) slope, c) edaphic and d) climatic. e) Principle Component Analysis (PCA) illustrating the relationship between various measured environmental variables and communities indicated by coloured circles. Large coloured circles show the centroid of each community. NMDS-PCA: Species contribution analysis for community ordination in NMDS is depicted in Table 2. IHC: Indigofera heterantha- Heracleum candicans- Cynodon
finally, VPI community revealed positively significant correlation with north-western slope, CaCO$_3$ and pH. Thus, all the four communities were found separately in clumps with clear differences based on the environmental variables (Fig 4).

The CCA and variation partitioning tests showed that the total inertia results of CCA was 3.023, where our final variables (altitude, temperature, humidity, wind speed, slope angle, slope N, slope NW, slope SW, pH, EC, OM, CaCO$_3$, K, P, sand, and loam) together explained 66.5% of variation (sum of canonical eigenvalues was 2.011). The first two canonical axes explained 37.1% of variation. CCA model was significant ($\chi^2 = 2.010$; pseudo-F value = 1.613; $p<0.001$; df = 16; permutations = 999). For the 16 explanatory variables, we tested simple term dactylon, VIP: Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana, CPI: Cedrus deodara-Pinus wallichiana-Isodon rugosus and PCP: Pinus wallichiana-Cedrus deodara-Parrotiopsis jacquemontiana.

Table 2. Mean (SD) of environmental variables and plant species richness per community found along four years of collection in moist temperate forests of Manoor valley, Northwestern Himalaya.

| Communities | IHC | VIP | CPI | PCP |
|-------------|-----|-----|-----|-----|
| Species Richness | 51(8) | 53(10) | 40(12) | 68(13) |
| Altitude | 2251.7(13 2.7) | 2413(19 4) | 2588.8(408.8) | 2609(167.6) |
| Latitude | 34.7(0) | 34.8(0) | 34.7(0) | 34.7(0) |
| Longitude | 73.6(0) | 73.6(0) | 73.6(0) | 73.6(0) |
| Temp | 23.4(2) | 20.7(0.5) | 20.8(3.2) | 21(3) |
| Humidity | 56.8(6) | 54.6(3.7) | 54.7(3.6) | 56.7(3.7) |
| Heat index | 23.9(2.2) | 23.3(2.2) | 22.6(2.9) | 22.8(3.1) |
| Wind speed | 1.6(0.3) | 1.7(0.2) | 1.7(0.5) | 1.6(0.5) |
| Dew point | 16(0.9) | 16.3(0.5) | 16.5(1.5) | 16.6(2) |
| Wet bulb | 18.2(1.3) | 17.3(0.2) | 18.2(1.5) | 17.3(2.1) |
| Baro Press | 770.2(12.8) | 754.6(1.8) | 750.4(31.2) | 752.9(18.3) |
| Slope Angle | 47.9(16.9) | 35.4(1) | 56.6(31.7) | 46.7(22.2) |
| Slope ES | 0(0) | 0(0) | 0.3(0.5) | 0(0) |
| Slope N | 0(0) | 0(0) | 0(0) | 0.7(0.4) |
| Slope NW | 0.1(0.3) | 0(0) | 0(0) | 0(0) |
| Slope S | 0(0) | 0(0) | 0.7(0.5) | 0.3(0.4) |
| Slope SW | 0.9(0.3) | 0.7(0.5) | 0(0) | 0(0) |
| Slope W | 0(0) | 0.3(0.5) | 0(0) | 0(0) |
| pH | 5.8(0.2) | 5.6(0.2) | 5.6(0.5) | 5.4(0.5) |
| EC | 2.4(1.1) | 2(0.6) | 1.7(0.8) | 1.7(0.9) |
| OM | 1.2(0.3) | 1.3(0.3) | 1.3(0.5) | 1(0.4) |
| CaCO$_3$ | 63.1(6.6) | 9.3(1.9) | 6.6(2.4) | 5.6(2.4) |
| K | 210.9(5.6) | 220.3(5) | 210.9(3.1) | 216(5.2) |
| P | 13.4(3.2) | 11.7(0.5) | 11.9(3.2) | 10.5(3.8) |
| Sand | 31.2(3.6) | 27.6(2.8) | 30.5(8.3) | 35.2(6.9) |
| Silt | 46.5(6.1) | 46.7(3.5) | 44.7(3.5) | 41.7(7.6) |
| Clay | 22.4(4.1) | 25.7(1) | 25.2(2.4) | 23.2(4) |
| Loam | 0.6(0.5) | 0.3(0.5) | 0.6(0.5) | 0.5(0.5) |
| Sandy clay loam | 0(0) | 0(0) | 0(0) | 0.1(0.3) |
| Silt loam | 0.4(0.5) | 0.7(0.5) | 0.4(0.5) | 0.5(0.5) |

IHC: Indigofera heterantha- Heracleum candicans-Cynodon dactylon, VIP: Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana, CPI: Cedrus deodara-Pinus wallichiana-Isodon rugosus and PCP: Pinus wallichiana-Cedrus deodara-Parrotiopsis jacquemontiana.
effects. Simple term effects showed that Altitude, Slope SW, Slope NW, Slope N, Slope Angle, K, and Humidity (decreasing order of importance) were significant (p < 0.05; Table 3). The 16 explanatory variables were grouped into four classes: Climatic (Humidity, Temperature, Wind speed); Edaphic (pH, EC, OM, CaCO$_3$, K, P, Sand, Loam); Geographic (Altitude); and Slope (Slope Angle, Slope N, Slope NW, Slope SW), and then, we performed variation partitioning tests (partial CCA) for all 15 possible classes (Table 4). Class [b] was the most explanatory variable (104.6%) followed by class [m] (7.2%) (Fig 5).

Variation of plant species composition among plant communities and beta diversity

We found a significant variation in plant species composition among communities (Table 5; Fig 6), in which all communities showed a significant difference in species composition between each other (Table 6). Out of 244 species, six species greatly contributed to the variation in plant species composition between communities, namely *Viburnum grandiflorum*, *Indigofera heterantha*, *Heracleum candicans*, *Cedrus deodara*, *Pinus wallichiana*, and *Parrotiopsis jacquemontiana* (Table 6). Overall, the three species that most contributed for the variation in species composition between communities showed 13.7–29.7% of cumulative contribution (Table 6).

The total beta diversity ($\beta$sr) showed a value of 54.7% dissimilarity, of which spatial turnover ($\beta$sim) made up 40.5% and nestedness-resultant components ($\beta$sne) made up 14.2%. In $\beta$sim cluster, we observed 47.8% dissimilarity between PCP-CPI cluster and VIP-IHC cluster (Fig 7). PCP showed a dissimilarity of 9.4% with CPI, and VIP showed a dissimilarity of 21.5% with IHC (Fig 7). In $\beta$sne cluster, we found 24.5% dissimilarity between PCP and VIP-CPI-IHC cluster (Fig 7). VIP showed a dissimilarity of 11.3% with IHC-CPI, and IHC had 4.1%

| Variables       | Df | ChiSquare | F     | p-value |
|-----------------|----|-----------|-------|---------|
| Altitude        | 1  | 0.251     | 3.229 | 0.001   |
| Slope.SW        | 1  | 0.245     | 3.146 | 0.001   |
| Slope.NW        | 1  | 0.178     | 2.297 | 0.001   |
| Slope.N         | 1  | 0.214     | 2.748 | 0.002   |
| Slope.Angle     | 1  | 0.163     | 2.097 | 0.009   |
| K               | 1  | 0.140     | 1.798 | 0.018   |
| Humidity        | 1  | 0.119     | 1.538 | 0.039   |
| Wind.speed      | 1  | 0.114     | 1.472 | 0.069   |
| CaCO$_3$        | 1  | 0.098     | 1.270 | 0.151   |
| Temp            | 1  | 0.081     | 1.049 | 0.376   |
| OM              | 1  | 0.079     | 1.017 | 0.401   |
| EC              | 1  | 0.066     | 0.976 | 0.474   |
| P               | 1  | 0.070     | 0.907 | 0.578   |
| Sand            | 1  | 0.069     | 0.895 | 0.590   |
| Loam            | 1  | 0.056     | 0.724 | 0.864   |
| pH              | 1  | 0.050     | 0.647 | 0.922   |
| P               | 1  | 0.088     | 0.7295| 0.820   |
| K               | 1  | 0.075     | 0.6191| 0.922   |

Significant variables are displayed in **bold**.
dissimilarity with CPI (Fig 7). Thus, plant community structure is twice more influenced by the spatial turnover of species ($\beta$sim) than by the species loss (nestedness-resultant, $\beta$sne).

Variation of diversity indices among plant communities

We found a significant difference of four diversity indices, species richness (GLM $\chi^2 = 73.113$, df = 3, p < 0.001; Fig 8A), Shannon (GLM $\chi^2 = 35.797$, df = 3, p < 0.001; Fig 8B), Simpson

| Individual Fraction | Adjusted R$^2$ | Variation explained (%) | % of all | Df |
|---------------------|---------------|-------------------------|----------|----|
| [a]                 | 0.020         | 5.5                     | 0.1      | 1  |
| [b]                 | 0.370         | 104.6                   | 2.3      | 4  |
| [c]                 | 0.004         | 1.2                     | 0.0      | 8  |
| [d]                 | 0.015         | 4.3                     | 0.1      | 3  |
| [e]                 | 0.020         | 5.7                     | 0.1      | 0  |
| [f]                 | -0.091        | -25.6                   | -0.6     | 0  |
| [g]                 | -0.005        | -1.5                    | 0.0      | 0  |
| [h]                 | -0.001        | -0.3                    | 0.0      | 0  |
| [i]                 | -0.045        | -12.9                   | -0.3     | 0  |
| [j]                 | -0.002        | -0.6                    | 0.0      | 0  |
| [k]                 | 0.011         | 3.1                     | 0.1      | 0  |
| [l]                 | 0.019         | 5.3                     | 0.1      | 0  |
| [m]                 | 0.026         | 7.2                     | 0.2      | 0  |
| [n]                 | 0.006         | 1.7                     | 0.0      | 0  |
| [o]                 | 0.008         | 2.3                     | 0.1      | 0  |
| Total explained     | 0.354         | 100.0                   | 2.2      | 18 |
| All variation       | 15.835        | /                       | 100      |    |

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Fig 5. The Venn diagram shows variation partitioning results (partial CCA model) and the contribution [77] of the four studied environmental variable groups (i.e., climatic, edaphic, geographic, and slope) that drive the plant species distribution. Each letter code indicates the individual fraction.

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Table 5. PERMANOVA results comparing species composition between the four communities found in Moist temperate forest. This analysis was made with Euclidean distance and 999 permutations. Pairwise comparisons between communities are depicted in Table 6.

|                      | Df | Sums of Sqs | Mean Sqs | F      | R²     | Pr(>F) |
|----------------------|----|-------------|----------|--------|--------|--------|
| Communities          | 3  | 9961.1      | 3320.4   | 13.324 | 0.6059 | 0.001  |
| Residuals            | 26 | 6479.1      | 249.2    |        | 0.3941 |        |
| Total                | 29 | 16440.2     |          |        | 1      |        |

(GLM $\chi^2 = 46.465$, df = 3, $p < 0.001$; Fig 8C), and Pielou (GLM $\chi^2 = 44.093$, df = 3, $p < 0.001$; Fig 8D), between the four communities. PCP showed the highest average number of species (68.1±4.2; mean±SE) followed by VIP (53.3±7.5) and IHC (51.1±3.5), and finally by CPI, with the lowest number of species (40.2±4.5) (Fig 8A). PCP showed a Shannon’ value of 3.62±0.08 (mean±SE), followed by IHC (3.53±0.07), VIP (3.29±0.1), and CPI (2.9±0.1) respectively (Fig 8B). IHC showed the highest Simpson’ value (0.959±0.01; mean±SE), followed by PCP (0.954±0.01), VIP (0.930±0.01), and CPI (0.898±0.01) respectively (Fig 8C). Finally, IHC showed the highest Pielou’ value (0.901±0.01; mean±SE), followed by PCP (0.862±0.01), VIP (0.830±0.01), and CPI (0.797±0.01) respectively (Fig 8D).

Discussion

Mountain ecosystems are characterized by dramatic changes in temperature and abiotic properties over short altitudinal and geographical distances, making them ideal natural laboratories for studying vegetation response to environmental changes [85]. In this study, we evaluated the plant species composition and distribution in a hotspot of biodiversity, the Northwestern Himalayan mountains, Pakistan, assessing how environmental gradients, source of habitat heterogeneity, influence plant community structure and diversity, which might be a proxy for assessing how climate change impacts on plant communities located in mountainous regions.
Table 6. Pairwise comparisons with FDR p-value adjustment method of species composition and contrast results of the contribution of individual species to the overall Bray-Curtis dissimilarity of species composition between the four communities found in moist temperate forest. We displayed only the three species that most contributed.

| Communities | P-value | Species     | Av dis | SD  | Ratio | Av Com1 | Av Com2 | Cum | Cum % | Cont % |
|-------------|---------|-------------|--------|-----|-------|---------|---------|-----|-------|--------|
| IHC-VIP     | 0.011   | Vib.gra     | 0.1    | 0   | 5     | 0       | 24.4    | 0.1 | 12.2  | 12.2   |
|             |         | Ind.het     | 0.1    | 0   | 1.9   | 8.8     | 23.5    | 0.2 | 20.1  | 7.9    |
|             |         | Her.can     | 0.1    | 0   | 1.3   | 6.9     | 1.8     | 0.2 | 22.8  | 2.7    |
| IHC-CPI     | 0.002   | Ced.deo     | 0.1    | 0   | 3.8   | 0       | 22.5    | 0.1 | 10.9  | 10.9   |
|             |         | Ind.het     | 0.1    | 0   | 0.9   | 8.8     | 2.3     | 0.2 | 20.8  | 9.9    |
| IHC-PCP     | 0.002   | Pin.wal     | 0.1    | 0   | 2.7   | 0       | 16.2    | 0.1 | 6.9   | 6.9    |
|             |         | Ced.deo     | 0.1    | 0   | 3     | 0       | 16.1    | 0.1 | 13.8  | 6.9    |
|             |         | Par.jac     | 0.1    | 0   | 5.8   | 0.4     | 10.3    | 0.2 | 18.5  | 4.2    |
| VIP-CPI     | 0.011   | Vib.gra     | 0.1    | 0   | 5.1   | 0       | 24.4    | 0.1 | 11.6  | 11.6   |
|             |         | Ind.het     | 0.1    | 0   | 3.3   | 23.5    | 2.3     | 0.2 | 21.5  | 9.9    |
|             |         | Ced.deo     | 0.1    | 0   | 1.9   | 5.2     | 22.5    | 0.3 | 29.7  | 8.3    |
| VIP-PCP     | 0.006   | Vib.gra     | 0.1    | 0   | 3.3   | 24.4    | 1.4     | 0.2 | 17.9  | 8.4    |
|             |         | Ind.het     | 0.1    | 0   | 6.6   | 23.5    | 2.8     | 0.2 | 22.8  | 4.9    |
| CPI-PCP     | 0.002   | Ced.deo     | 0.1    | 0   | 1.2   | 22.5    | 0.1     | 5.4  | 5.4   | 5.4    |
|             |         | Par.jac     | 0.1    | 0   | 1.8   | 4.7     | 0.1     | 9.6  | 4.2   |        |
|             |         | Pin.wal     | 0.1    | 0   | 1.1   | 20.3    | 0.1     | 13.7 | 4     |        |

Av. dis.–Average dissimilarity; SD–Standard deviation; Av Com1 –Average Community 1; Av Com2 –Average community 2; Cum.–Cumulative; Cont.–Contribution.

Vib.gra: Viburnum grandiflorum, Ind.het: Indigofera heterantha, Her.can: Heracleum candicans, Ced.deo: Cedrus deodara, Pin.wal: Pinus wallichiana, Par.Jac: Parrotiopsis jacquemontiana.

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Fig 7. Dissimilarity cluster based on spatial turnover ($\beta_{sim}$) and nestedness-resultant components ($\beta_{sne}$) of beta diversity components of species dissimilarity between four plant communities of moist temperate forests. IHC: Indigofera heterantha-Heracleum candicans-Cynodon dactylon, VIP: Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana, CPI: Cedrus deodara-Pinus wallichiana-Isodon rugosus, and PCP: Pinus wallichiana-Cedrus deodara-Parrotiopsis jacquemontiana.

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We found that (i) the moist temperate zone in this region can be divided in four different major plant communities; (ii) each plant community has a specific set of environmental drivers; (iii) there is a significant variation in plant species composition between communities, in which six species contributed most to the plant composition dissimilarity; (iv) there is a significant difference of the four diversity indices (species richness, Shannon, Simpson, Pielou) between communities; and finally (v) plant community structure is twice more influenced by the spatial turnover of species ($\beta$sim) than by the species loss (nestedness-resultant, $\beta$sne). Overall, we showed that altitudinal gradients offer an important range of different environmental variables, highlighting the existence of micro-climates that drive the structure and composition of plant species in each micro-region. In addition, each plant community along the altitudinal gradient has a set of environmental drivers, which lead to the presence of indicator species in each micro-region.

Mountain plant communities are thought to be sensitive to climate change and, thus, able to reveal its effects sooner than others [34, 88]. The four communities found showed a wide range of environmental drivers; however, altitude and temperature showed great prominence, probably making up the main environmental drivers in mountainous plant communities. Similar pattern was observed in the allied area (Nandiar catchment, Battagram) of Northwestern

Fig 8. Variation of diversity indices between the four plant communities of moist temperate forests in the Northwestern Himalaya, Pakistan. Figures represent ridgeline plots with raw data (black dots below each density distribution) and the first, second and third quartiles (vertical red lines). Lowercase letters on the left differ from each other by an estimated marginal mean. The Y-axis is displayed in an ascendant altitudinal gradient. **IHC**: *Indigofera heterantha-Heracleum candicans-Cynodon dactylon*, **VIP**: *Viburnum grandiflorum-Indigofera heterantha-Pinus wallichiana*, **CPI**: *Cedrus deodara-Pinus wallichiana-Isodon rugosus*, and **PCP**: *Pinus wallichiana-Cedrus deodara- Parrotiopsis jacquemontiana*. 

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Himalaya by stating altitude and temperature as the governing gradient [74]. Such variables, which can be strongly correlated [89], modify the diversity and structure of plant communities by creating local micro-climates [90], directly influencing plant community composition and diversity [19, 26, 91, 92].

Indeed, there is no order of importance of environmental variables, but studies are unanimous in showing that there is a consensus on the explanations for the variables' influences. For instance, in two recent studies we showed that the altitude-temperature relationship significantly influenced the physiological attributes of some plant species in the Northwestern Himalayan region [22, 23], which can be a proxy for understanding plant adaptation to climate change. Any change in soil parameters has a significant effect on the growth of plant communities [19]. The studies on mountain forests habitats around the world have also revealed the role of soil structure on species zonation [72, 93, 94]. Furthermore, both chemical and physical attributes of the soil are related to natural soil characteristics, with an impact on plant species composition and distribution of higher vascular plants [95–97]. For instance, some soil variables can have great influence on plant composition and distribution, such as pH. Some studies have shown that pH level on soil can influence nutrient availability, ultimately influencing nutrient uptake for growth [98–100]. However, the availability of some nutrients as a result of pH levels can be detrimental for some plants, since some nutrients are toxic to some plants [98, 101]. Considering that there is a great variability of pH levels and nutrient availability and concentration along altitudinal variables, it is expected a great variability of plant species composition which can be more or less related to specific soil parameters. Since plants are sensitive to small variations of soil characteristics such as pH, minerals, organic matter, among others, and these variables are constantly changing along altitudinal gradients directly and indirectly influencing the presence and availability of other organisms and resources, some plant species might have adapted to specific set of variables.

Variability in plant species diversity is an outcome of species interaction with particular set of environment variables either abiotic and biotic [102, 103], which can occur in both space and time [104, 105]. The concept of changing species composition and vegetation continuum along the ecological gradients emerged as an antithesis model for distinct units [106, 107]. In our study, the moist temperate forest of the studied Northwestern Himalayan region is comprised in an altitudinal gradient of approximately 1500 m. This gradient is subject to strong micro-climatic variation, which results in a set of micro-regions (better discussed above). Each micro-region has certain characteristics, which will influence the set of species that will inhabit these spaces [24–26]. In this sense, it is expected that the plant community structure is more influenced by the spatial turnover of species ($\beta_{\text{sim}}$) than by the species loss (nestedness-resultant, $\beta_{\text{sne}}$), i.e., that there are different plant communities along the altitudinal gradient, as shown by our results. The differentiation of species diversity was mainly a consequence of environmental variables which is due to soil factors [108]. Therefore, in addition to the influence of edaphic factors in space on species composition and vegetation continuum, as shown in our study, results from similar studies have shown that the altitude is also important in driving vegetation structure and diversity in plant communities.

We found that environmental heterogeneity among plant communities have significant effects on beta diversity, particularly the spatial turnover. These results indicate that there is not a significant loss of the number of species between the plant community, but a variation in the species composition. This variation may be closely linked to the environmental effects in the area, which induces the appearance of species adapted to environmental variables [109]. The local community composition replacement implied the simultaneous loss and gain of species due to immigration–extinction dynamics and trait-based environmental filtering [110, 111]. This indicates the relationship among plant community types and among species based
on multiple factors. Although we did not find a large variation in βsne (loss of species between plant communities), it is important to note that temporal analysis might be important to consider a notable variation in this component of beta diversity; and βsne variations will be better observed in long-term analysis in future studies. In this sense, it is expected that the plant community structure is more influenced by the spatial turnover of species (βsim) than by the species loss (nestedness-resultant, βsne), i.e., that there are different plant communities along the altitudinal gradient, as shown by our results. Similarly, results were report by Haq et al. [112] from forests of Kashmir Himalaya, India.

We observed a significant variation in plant species composition between communities, in which all communities showed a significant difference in species composition between each other. The measure of Bray-Curtis dissimilarity shows that species composition change that is influenced mainly by abundant species, in our study six species (Viburnum grandiflorum, Indigofera heterantha, Heracleum candicans, Cedrus deodara, Pinus wallichiana, and Parrotiopsis jacquemontiana) contributed most to the plant composition dissimilarity. These results suggest that the richness and turnover patterns we observed were driven primarily by rare species, which comprise most of the local species pools at these forest communities [113]. These findings are consistent with the idea that less abundant species are more sensitive to climate variability than longer lived and more abundant species [114]. The high level of turnover is common and is an important mechanism by which a large regional species pool buffers site level diversity from interannual variation in climate [115].

Current study provides the baseline and first insights of spatial distribution, vegetation pattern and species contribution in response to environmental gradients in a moist temperate forests, Northwestern Himalaya, Pakistan. Studies that evaluate the distribution and composition of the plant community are fundamental for a better understanding of the local plant community, the conservation status and protection of these communities, as well as providing support for mitigation measures. Especially in the case of Northwestern Himalaya, which represents a biodiversity hotspot, it is even more important that we conduct phytosociological studies in these areas to document and preserve the biodiversity there. In the face of current climate changes, these regions are being heavily impacted [28, 29], where the probability of species extinction may be higher than elsewhere, as these regions are rich in endemic species. Finally, we need to consider that phytosociological studies consider a general profile of the first trophic chains level, i.e., to evaluate the composition, distribution and diversity of plants is to indirectly assess the first level of trophic chains.

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References

1. Khan SM. Plant communities and vegetation ecosystem services in the Naran Valley, Western Himalaya. PhD Dissertation, University of Leicester, UK. 2012.

2. Luo Z, Tang S, Li C, Fang H, Hu H, Yang J, et al. Environmental effects on vertebrate species richness: testing the energy, environmental stability and habitat heterogeneity hypotheses. PLoS One. 2012/04/18. 2012; 7: e35514–e35514. https://doi.org/10.1371/journal.pone.0035514

3. Yang Z, Liu X, Zhou M, Ai D, Wang G, Wang Y, et al. The effect of environmental heterogeneity on species richness depends on community position along the environmental gradient. Sci Rep. 2015; 5: 15723. https://doi.org/10.1038/srep15723 PMID: 26508413

4. Shipley B, Keddy PA. The individualistic and community-unit concepts as falsifiable hypotheses. Theory and models in vegetation science. Springer; 1987. pp. 47–55.

5. Frahm J-P, Gradients SR. An altitudinal zonation of tropical rain forests using byrophytes. J Biogeogr. 1991; 669–678.

6. Givnish TJ. On the causes of gradients in tropical tree diversity. J Ecol. 1999; 87: 193–210.

7. Iqbal Z, Zeb A, Abd_Allah EF, Rahman IU, Khan SM, Ali N, et al. Ecological assessment of plant communities along the edaphic and topographic gradients of biha valley, District Swat, Pakistan. Appl Ecol Environ Res. 2018; 16. https://doi.org/10.15666/aeer/1605_56115631

8. Paul H, Gottfried M, Dullinger S, Abduladze O, Akhalkatsi M, Alonso JLB, et al. Recent Plant Diversity Changes on Europe’s Mountain Summits. Science (80-). 2012; 336: 353 LP–355. https://doi.org/10.1126/science.1219033 PMID: 22517860

9. Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F. Impacts of climate change on the future of biodiversity. Ecol Lett. 2012; 15: 365–377.

10. Kullman L. Alpine flora dynamics—a critical review of responses to climate change in the Swedish Scandes since the early 1950s. Nord J Bot. 2010; 28: 398–408. https://doi.org/10.1111/j.1756-1051.2010.00812.x

11. Jabis MD. Climate Change Impacts in Alpine Plant Communities. UC Berkeley; 2018.

12. Malanson GP, Nelson EL, Zimmerman DL, Fagre DB. Alpine plant community diversity in species–area relations at fine scale. Arctic, Antarct Alp Res. 2020; 52: 41–46. https://doi.org/10.1080/15230430.2019.1698894

13. Cañadas EM, Fenu G, Peñas J, Lorite J, Mattana E, Bacchetta G. Hotspots within hotspots: Endemic plant richness, environmental drivers, and implications for conservation. Bioll Conserv. 2014; 170: 282–291. https://doi.org/10.1016/j.biocon.2013.12.007

14. Noroozi J, Talebi A, Doostmohammadi M, Rumpf SB, Linder HP, Schneeweiss GM. Hotspots within a global biodiversity hotspot—areas of endemism are associated with high mountain ranges. Sci Rep. 2018; 8: 10345. https://doi.org/10.1038/s41598-018-28504-9 PMID: 29985437

15. Kidane YO, Steinbauer MJ, Beierkuhnlein C. Dead end for endemic plant species? A biodiversity hotspot under pressure. Glob Ecol Conserv. 2019; 19: e00670. https://doi.org/10.1016/j.gecco.2019.0e00670

16. Noroozi J, Najinezhad A, Talebi A, Doostmohammadi M, Plutzar C, Rumpf SB, et al. Hotspots of vascular plant endemism in a global biodiversity hotspot in Southwest Asia suffer from significant conservation gaps. Bioll Conserv. 2019; 237: 299–307. https://doi.org/10.1016/j.biocon.2019.07.005

17. Motiekaitė V. Conservation diversity of vascular plants and their communities in situ, applying the conception of ecosystem pool. Ekologia. 2006; 2: 1–7.

18. Myers N, Mittermeier RA, Mittermeier CG, Fonseca GAB da, Kent J. Biodiversity hotspots for conservation priorities. Nature. 2000; 403: 853–858. https://doi.org/10.1038/35002501 PMID: 10706275
19. Rahman IU, Afzal A, Iqbal Z, Bussmann RW, Alsamadany H, Calixto ES, et al. Ecological gradients hosting plant communities in Himalayan subalpine pastures: Application of multivariate approaches to identify indicator species. Ecol Inform. 2020; 60: 101162. https://doi.org/10.1016/j.ecoinf.2020.101162

20. Baldwin AH, Jensen K, Schönfeldt M. Warming increases plant biomass and reduces diversity across continents, latitudes, and species migration scenarios in experimental wetland communities. Glob Chang Biol. 2014; 20: 835–850. https://doi.org/10.1111/gcb.12378 PMID: 2396933

21. Rudgers JA, Kivlin SN, Whitney KD, Price M V, Waser NM, Harte J. Responses of high-altitude graminoids and soil fungi to 20 years of experimental warming. Ecology. 2014; 95: 1918–1928. https://doi.org/10.1890/13-1454.1 PMID: 25163124

22. Rahman IU, Afzal A, Iqbal Z, Hart R, Abd-Allah EF, Alqarawi AA, et al. Response of plant physiological attributes to altitudinal gradient: Plant adaptation to temperature variation in the Himalayan region. Sci Total Environ. 2020; 706: 135714. https://doi.org/10.1016/j.scitotenv.2019.135714 PMID: 31940726

23. Rahman IU, Hart R, Afzal A, Iqbal Z, Alqarawi AA, Abd-Allah EF, et al. Ecophysiological plasticity and cold stress adaptation in Himalayan alpine herbs: Bistorta affinis and Sibbaldia procumbens. Plants. 2019; 8: 378–386. https://doi.org/10.3390/plants8100378

24. Schuur EAG, Crummer KG, Vogel JG, Mack MC. Plant species composition and productivity following permafrost thaw and thermokarst in Alaskan tundra. Ecosystems. 2007; 10: 280–292.

25. Weltzin JF, Bridgham SD, Pastor J, Chen J, Harth C. Potential effects of warming and drying on peatland plant community composition. Glob Chang Biol. 2003; 9: 141–151.

26. Rahman IU, Hart R, Afzal A, Iqbal Z, Abdallah EF, Alqarawi AA, et al. Phenological plasticity in Berberis lycium Royle along temporal and altitudinal gradients. Appl Ecol Environ Res. 2019; 17: 331–341. https://doi.org/10.15666/aer/1701_331341

27. Walker MD, Wahren CH, Hollister RD, Henry GHR, Ahlquist LE, Alatalo JM, et al. Plant community responses to experimental warming across the tundra biome. Proc Natl Acad Sci. 2006; 103: 1342–1346. https://doi.org/10.1073/pnas.0503198103 PMID: 16428292

28. Shrestha UB, Gautam S, Bawa KS. Widespread climate change in the Himalayas and associated changes in local ecosystems. PLoS One. 2012; 7: e36741. https://doi.org/10.1371/journal.pone.0036741 PMID: 22615804

29. Xu J, Grumbine RE, Shrestha A, Eriksson M, Yang X, Wang Y, et al. The melting Himalayas: Cascading effects of climate change on water, biodiversity, and livelihoods. Conserv Biol. 2009; 23: 520–530. https://doi.org/10.1111/j.1523-1739.2009.01237.x PMID: 22748090

30. Rahbek C. The role of spatial scale and the perception of large-scale species-richness patterns. Ecology Letters. 2005. pp. 224–239. https://doi.org/10.1111/j.1461-0248.2004.00701.x

31. Kluge J, Worm S, Lange S, Long D, Boehner J, Yangzom R, et al. Elevated seed plants richness patterns in Bhutan, Eastern Himalaya. J Biogeogr. 2017; 44: 1711–1722.

32. Trigas P, Panitsa M, Tsiftsis S. Elevational gradient of vascular plant species richness and endemism in Crete—the effect of post-isolation mountain uplift on a continental island system. PLoS One. 2013; 8: e59425. https://doi.org/10.1371/journal.pone.0059425 PMID: 23555031

33. Khan AM, Qureshi R, Saqib Z. Multivariate analyses of the vegetation of the western Himalayan forests of Muzaffarabad district, Azad Jammu and Kashmir, Pakistan. Ecol Indic. 2019; 104: 723–736.

34. Niu Y, Yang S, Zhou J, Chu B, Ma S, Zhu H, et al. Vegetation distribution along mountain environmental gradient predicts shifts in plant community response to climate change in alpine meadow on the Tibetan Plateau. Sci Total Environ. 2019; 650: 505–514. https://doi.org/10.1016/j.scitotenv.2018.08.390 PMID: 3205341

35. Rahman IU, Ijaz F, Afzal A, Iqbal Z, Ali N, Khan SM. Contributions to the phytotherapies of digestive disorders: Traditional knowledge and cultural drivers of Manoor Valley, Northern Pakistan. J Ethnopharmacol. 2016; 192: 30–52. https://doi.org/10.1016/j.jep.2016.06.049 PMID: 27353866

36. Rahman IU, Ijaz F, Iqbal Z, Afzal A, Ali N, Afzal M, et al. A novel survey of the ethno medicinal knowledge of dental problems in Manoor Valley (Northern Himalaya), Pakistan. J Ethnopharmacol. 2016; 194: 877–894. https://doi.org/10.1016/j.jep.2016.06.068 PMID: 27794507

37. Rahman IU, Afzal A, Iqbal Z, Ijaz F, Ali N, Bussmann RW. Traditional and ethnomedicinal dermatology practices in Pakistan. Clin Dermatol. 2018; 36: 310–319. https://doi.org/10.1016/j.cldermatol.2018.03.016 PMID: 29908573

38. Rahman IU, Afzal A, Iqbal Z, Hart R, Abd-Allah EF, Hashem A, et al. Herbal teas and drinks: Folk medicine of the Manoor valley, Lesser Himalaya, Pakistan. Plants. 2019; 8: 1–18. https://doi.org/10.3390/plants8120581 PMID: 31817913

39. Rahman IU, Afzal A, Iqbal Z, Ijaz F, Ali N, Asif M, et al. First insights into the floristic diversity, biological spectra and phenology of Manoor valley, Pakistan. Pakistan J Bot. 2018; 50: 1113–1124.
40. Buckland ST, Anderson DR, Burnham KP, Laake JL, Borchers DL, Thomas L. Introduction to distance sampling: estimating abundance of biological populations. 2001.
41. Buckland ST, Anderson DR, Burnham KP, Laake JL, Borchers DL, Thomas L. Advanced distance sampling. Oxford University Press; Oxford; 2004.
42. Buckland ST, Newman KB, Fernández C, Thomas L, Harwood J. Embedding population dynamics models in inference. Stat Sci. 2007; 44–58.
43. Anderson DR, Burnham KP, Laake JL. Distance sampling: estimating abundance of biological populations. Chapman & Hall, London, United Kingdom; 1993.
44. Sprent P. Distance Sampling-Estimating Abundance of Biological Populations. JSTOR; 1994.
45. Le Moullec M, Pedersen ÅØ, Yoccoz NG, Aanes R, Tufto J, Hansen BB. Ungulate population monitoring in an open tundra landscape: distance sampling versus total counts. Wildlife Biol. 2017; 2017.
46. Curtis JT, McIntosh R. The interrelations of certain analytic and synthetic phytosociological characters. Ecology. 1950; 31: 434–455.
47. Curtis JT. The vegetation of Wisconsin: an ordination of plant communities. University of Wisconsin Press; 1959.
48. Jayasuriya AHM, Pemadasa MA. Factors affecting the distribution of tree species in a dry zone montane forest in Sri Lanka. J Ecol. 1983; 571–583.
49. Son H-J, Park S-H, Lee D-H, Song J-H, Park H-W, Park W-G. Growing environment characteristics and vegetation structure of Vaccinium Oldhamii Miq. native habitats in Korea. Forest Sci Technol. 2019; 15: 33–43.
50. Tian Z, Li H, Li W, Gan X, Zhang X, Fan Z. Structural characteristics and niches of dominant tree populations in Tetracentron sinense communities: implications for conservation. Bot Sci. 2018; 96: 157–167.
51. Lou Y, Pan Y, Gao C, Jiang M, Lu X, Xu YJ. Response of plant height, species richness and above-ground biomass to flooding gradient along vegetation zones in floodplain wetlands, Northeast China. PLoS One. 2016; 11: e0153972. https://doi.org/10.1371/journal.pone.0153972 PMID: 27097325
52. Song JH, Cheong EJ, Kim H, Kim MS, Kim SH. Variation of morphological characteristics and anthocyanin contents from fruit of Vaccinium oldhamii in Korea. J Korean Soc For Sci. 2015; 104: 193–197.
53. Biodiversity Ijaz F. and traditional uses of plants of Sarban Hills, Abbottabad. M.Phil Dissertation, Hazara University Manehra-21300, Khyber Pakhtunkhwa, Pakistan; 2014.
54. Ijaz F, Rahman I., Iqbal Z, Alam J, Ali N, Khan S. Ethno-ecology of the healing forests of Sarban Hills, Abbottabad, Pakistan: an economic and medicinal appraisal. 1st ed. In: Ozturk KRH M., editor. Plant and Human Health. 1st ed. Springer International Publishing AG; 2018. pp. 675–706. https://doi.org/10.1007/978-3-319-93997-1_19.
55. Amjad MS, Qaeem MF, Ahmad I, Khan SU, Chaudhari SK, Zahid Malik N, et al. Descriptive study of plant resources in the context of the ethnomedicinal relevance of indigenous flora: A case study from Toli Peer National Park, Azad Jammu and Kashmir, Pakistan. PLoS One. 2017; 12: e0171896. https://doi.org/10.1371/journal.pone.0171896 PMID: 28192466
56. Stefanaki A, Porck H, Grimaldi IM, Thurn N, Pugliano V, Kardinaal A, et al. Breaking the silence of the 500-year-old smiling garden of everlasting flowers: The En Tibi book herbarium. PLoS One. 2019; 14: e0217779. https://doi.org/10.1371/journal.pone.0217779 PMID: 31242215
57. Nasir E, Ali SI. Flora West of Pakistan. Nasir E, Ali SI, editors. Karachi: National Herbarium; 1971.
58. Ali SI, Nasir YJ. Flora of Pakistan. Ali SI, Nasir YJ, editors. Islamabad: Department of Botany, University of Karachi, Karachi and National Herbarium; 1989.
59. Ali SI, Daiser M. Flora of Pakistan. Karachi: Department of Botany, University of Karachi; 1995.
60. Rahman IU, Ijaz F, Afzal A, Iqbal Z. Effect of foliar application of plant mineral nutrients on the growth and yield attributes of chickpea (Cicer aritinum L.) Under nutrient deficient soil conditions. Bangladesh J Bot. 2017; 46: 111–118.
61. Rahman IU, Afzal A, Iqbal Z, Ijaz F, Khan SM, Khan SA, et al. Influence of different nutrients application in nutrient deficient soil on growth and yield of onion. Bangladesh J Bot. 2015; 44: 613–619.
62. Ravindranath NH, Ostwald M. Carbon inventory methods: handbook for greenhouse gas inventory, carbon mitigation and roundwood production projects. Springer International Publishing AG; 2007.
63. Haq F, Ahmad H, Iqbal Z. Vegetation description and phytoclimatic gradients of subtropical forests of Nandiar Khuwar catchment District Battagram. Pakistan J Bot. 2015; 47: 1399–1405.
64. Mc Lean EO. Soil pH and Lime requirement. 2nd ed. In: Page AL, Miller RH, Keeney DR, editors. Methods of soil analysis Part 2 Chemical and Microbiological Properties. 2nd ed. Madison, Wisconsin, USA: American Society of Agronomy, Inc. Soil Science Society of America, Inc.; 1982. pp. 199–223.
65. Wilson MJ, Bayley SE. Use of single versus multiple biotic communities as indicators of biological integrity in northern prairie wetlands. Ecol Indic. 2012; 20: 187–195.

66. Nelson DW, Sommers LE. Total carbon, organic carbon, and organic matter. 5th ed. In: Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, et al., editors. Methods of Soil Analysis Part 3 Method Chemical. 5th ed. Madison, WI 53711, USA: Soil Science Society of America and American Society of Agronomy; 1996. pp. 961–1010. https://doi.org/10.2136/sssabooks5.3.c34

67. Soltanpour PN. Determination of nutrient availability and elemental toxicity by AB-DTPA soil test and ICPS. 16th ed. Advances in soil science. 16th ed. NY: Springer, New York; 1991. pp. 165–190. https://doi.org/10.1007/978-1-4612-3144-8_3

68. Šmilauer P, Jan L. Multivariate analysis of ecological data using CANOCO. 2nd ed. Cambridge CB2 8BS, United Kingdom: Cambridge University Press; 2014. https://doi.org/10.1017/CBO9781139627061

69. Mayor JR, Sanders NJ, Classen AT, Bardgett RD, Clément JC, Fajardo A, et al. Elevation alters ecosystem properties across temperate treelines globally. Nature. 2017; 542: 91–95. https://doi.org/10.1038/nature21027 PMID: 28117440

70. CCone B, Mefford M. PC-ORD. Multivariate Analysis of Ecological Data. Version 6. Gleneden Beach, Oregon, USA: MJM Software Design; 2011.

71. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. 2020.

72. Rahman IU. Ecophysiological plasticity and Ethnobotanical studies in Manoor Area, Kaghan Valley, Pakistan. PhD Dissertation, Hazara University, Mansehra 21300, Khyber Pakhtunkhwa, Pakistan. 2020.

73. Hill MO. TWINSPLAN: a FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Cornell Univ. 1979.

74. Haq F, Ahmad H, Iqbal Z, Alam M, Aksoy A. Multivariate approach to the classification and ordination of the forest ecosystem of Nandiar valley western Himalayas. Ecol Indic. 2017; 80: 220–225. https://doi.org/10.1016/j.ecolind.2017.05.047

75. Knapp AK, Fay PA, Blair JM, Collins SL, Smith MD, Carlisle JD, et al. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science (80-). 2002; 298: 2202–2205. https://doi.org/10.1126/science.1076347

76. McCune B. PC-ORD: an integrated system for multivariate analysis of ecological data. Abstr Bot. 1986; 10: 221–225.

77. Legendre P. Studying beta diversity: ecological variation partitioning by multiple regression and canonical analysis. J Plant Ecol. 2008; 1: 3–8. https://doi.org/10.1093/jpe/rtm001

78. Oksanen J, Blanchet F, Friendly M, Kindt R, Legendre P, Minchin D, et al. vegan: Community Ecology Package (R package Version 2.5–5). Accessed; 2019.

79. Hervé M. RVAideMemoire: Testing and Plotting Procedures for Biostatistics. 2020.

80. Lenth R. emmeans: Estimated Marginal Means, aka Least-Squares Means. 2020.

81. Baselga A, Orme CDL. betapart: an R package for the study of beta diversity. Methods Ecol Evol. 2012; 3: 808–812.

82. Baselga MA. Package `betapart.` 2013.

83. Baselga A. Partitioning the turnover and nestedness components of beta diversity. Glob Ecol Biogeogr. 2010; 19: 134–143. https://doi.org/10.1111/j.1466-8238.2009.00490.x

84. Bas A, Orme D, Villeger S, De Bortoli J, Leprieur F, Logez M, et al. Partitioning Beta Diversity into Turnover and Nestedness Components. Cran. 2018; 1–42.

85. Anslan S, Azizi Rad M, Buckel J, Echeverria Galindo P, Kai J, Kang W, et al. Reviews and syntheses: How do abiotic and biotic processes respond to climatic variations in the Nam Co catchment (Tibetan Plateau)? Biogeosciences. 2020; 17: 1261–1279.

86. McCarty JP. Ecological consequences of recent climate change. Conserv Biol. 2001; 15: 320–331.

87. Hansen AJ, Neilson RP, Dale VH, Flather CH, Iverson LR, Currie DJ, et al. Global change in forests: responses of species, communities, and biomes: interactions between climate change and land use are projected to cause large shifts in biodiversity. Bioscience. 2001; 51: 765–779.

88. Malanson GP, Resler LM, Butler DR, Fagre DB. Mountain plant communities: Uncertain sentinels? Prog Phys Geogr Earth Environ. 2019; 43: 521–543. https://doi.org/10.1177/0309133119843873

89. Cantonati M, Gerecke R, Bertuzzi E. Springs of the Alps-sensitive ecosystems to environmental change: from biodiversity assessments to long-term studies. Hydrobiologia. 2006; 562: 59–96.
90. Adair KL, Lindgreen S, Poole AM, Young LM, Bernard-Verdier M, Wardle DA, et al. Above and below-ground community strategies respond to different global change drivers. Sci Rep. 2019; 9: 1–11. https://doi.org/10.1038/s41598-018-37186-2 PMID: 30626917

91. Conti L, de Bello F, Lepi J, Acosta ATR, Carboni M. Environmental gradients and micro-heterogeneity shape fine-scale plant community assembly on coastal dunes. J Veg Sci. 2017; 28: 762–773. https://doi.org/10.1111/jvs.12533

92. Rahman I-U, Afzal A, Abd_Allah EF, Iqbal Z, Alqarawi AA, Hashem A, et al. Composition of plant communities driven by environmental gradients in alpine pastures and cold desert of northwestern Himalaya, Pakistan, Pakistan J Bot. 2021; 53: 655–664. https://doi.org/10.30848/pjb2021-2(35)

93. Rawat M, Arunachalam K, Arunachalam A, Alatalo JM, Kumar U, Simon B, et al. Relative contribution of plant traits and soil properties to the functioning of a temperate forest ecosystem in the Indian Himalayas. Catena. 2020; 194: 104671.

94. Hegazy AK, El-Demerdash MA, Hosni HA. Vegetation, species diversity and floristic relations along an altitudinal gradient in south-west Saudi Arabia. J Arid Environ. 1998; 38: 3–13.

95. Marini L, Scotton M, Klimek S, Isselstein J, Pecile A. Effects of local factors on plant species species-richness and composition of Alpine meadows. Agric Ecosyst Environ. 2007;119.

96. Oduor C, Karanja N, Onwonga R, Mureithi S, Pelster D, Nyberg G. Enhancing soil organic carbon, particulate organic carbon and microbial biomass in semi-arid rangeland using pasture enclosures. BMC Ecol. 2018;18. https://doi.org/10.1186/s12898-018-0174-z PMID: 29890975

97. Yang Y, et al. Soil physicochemical properties and vegetation structure along an elevation gradient and implications for the response of alpine plant development to climate change on the northern slopes of the Qilian Mountains. J Mt Res. 2018; 15: 1006–1019.

98. Vichérova E, Hájek M, Hájek T. Calcium intolerance of fen mosses: physiological evidence, effects of nutrient availability and successional drivers. Perspect Plant Ecol Evol Syst. 2015; 17: 347–359.

99. Audorff V, Kapfer J, Beierkuhnlein C. The role of hydrological and spatial factors for the vegetation of Central European springs. J Limnol. 2011; 70: 9–22.

100. Strohbach M, Audorff V, Beierkuhnlein C. Drivers of plant species composition in siliceous spring ecosystems: groundwater chemistry, catchment traits or spatial factors? J Limnol. 2009; 68: 375–384.

101. Tyler T, Olsson PA. Substrate pH ranges of south Swedish bryophytes—Identifying critical pH values and richness patterns. Flora. 2016; 223: 74–82.

102. Ricklefs RE. Evolutionary diversification and the origin of the diversity–environment relationship. Ecology. 2006; 87: S3–S13. https://doi.org/10.1890/0012-9658(2006)87[3:edatoo]2.0.co;2 PMID: 16922298

103. Gauthray-Guyénet V, Schneider R, Paré D, Achim A, Loi C, Sirois L. Influence of shifts over an 80-year period in forest composition on soil properties. Plant Soil. 2018; 433: 111–125.

104. Suding KN, Lavorel S, Chapin FS, Cornelissen JHC, Díaz S, Garnier E, et al. Scaling environmental change through the community-level: A trait-based response-and-effect framework for plants. Glob Chang Biol. 2008; 14: 1125–1140. https://doi.org/10.1111/j.1365-2486.2008.01587.x

105. Nicotra AB, Atkin OK, Bone SP, Davidson AM, Finnegan EJ, Mathesius U, et al. Plant phenotypic plasticity in a changing climate. Trends Plant Sci. 2010; 15: 684–692. https://doi.org/10.1016/j.tplants.2010.09.008 PMID: 20970368

106. Vleminkx J, Schimann H, Decaëns T, Fichaux M, Vedel V, Jaouen G, et al. Coordinated community strategies respond to different global change drivers. Sci Rep. 2019; 9: 1–11. https://doi.org/10.1038/s41598-018-37186-2 PMID: 30626917

107. Hu A, Wang J, Lu X, Zhou J. Mountain biodiversity and ecosystem functions: interplay between geology and contemporary environments. ISME J. 2019. https://doi.org/10.1038/s41396-019-0574-x

108. Kang S, Niu J, Zhang Q, Zhang X, Han G, Zhao M. Niche differentiation is the underlying mechanism maintaining the relationship between community diversity and stability under grazing pressure. Glob Ecol Conserv. 2020; 24: e01246.

109. Rahman IU, Afzal A, Iqbal Z, Hashem A, Al-Arjani A-BF, Alqarawi AA, et al. Species Distribution Pattern and Their Contribution in Plant Community Assembly in Response to Ecological Gradients of the Ecolonal Zone in the Himalayan Region. Plants. 2021; 10: 2372. https://doi.org/10.3390/plants10112372 PMID: 34834735

110. Matthews TJ, Whittaker RJ. Neutral theory and the species abundance distribution: recent developments and prospects for unifying niche and neutral perspectives. Ecol Evol. 2014; 4: 2263–2277. https://doi.org/10.1002/ece3.1082 PMID: 25360266

111. Filgueiras BKC, Peres CA, Melo FPL, Leal IR, Tabarelli M. Winner–Loser Species Replacements in Human-Modified Landscapes. Trends Ecol Evol. 2021. https://doi.org/10.1016/j.tree.2021.02.006 PMID: 33859560
112. Haq SM, Calixto ES, Kumar M. Assessing Biodiversity and Productivity over a Small-scale Gradient in the Protected Forests of Indian Western Himalayas. J Sustain For. 2021; 40: 675–694. https://doi.org/10.1080/10549811.2020.1803918

113. Cleland EE, Collins SL, Dickson TL, Farrer EC, Gross KL, Gherardi LA, et al. Sensitivity of grassland plant community composition to spatial vs. temporal variation in precipitation. Ecology. 2013; 94: 1687–1696. https://doi.org/10.1890/12-1006.1 PMID: 24015513

114. Bisbing SM, Urza AK, Buma BJ, Cooper DJ, Matocq M, Angert AL. Can long-lived species keep pace with climate change? Evidence of local persistence potential in a widespread conifer. Divers Distrib. 2021; 27: 296–312.

115. Burrows MT, Hawkins SJ, Moore JJ, Adams L, Sugden H, Firth L, et al. Global-scale species distributions predict temperature-related changes in species composition of rocky shore communities in Britain. Glob Chang Biol. 2020; 26: 2093–2105.