Composition and structure of forests in the Jumla-Dolpa region, western Nepal

Hisashi Sugita[1,*], Chuh Yonebayashi[2], Satoshi Tsuda[3] and Hiroshi Ikeda[4]

[1]Tateyama Caldera Sabo Museum, Tateyama Town, Toyama 930-1405, Japan
[2]Rissho University, Kumagaya, 360-0194 Japan
[3]Nature & Science Koshimizu, Koshimizu, Hokkaido, 099-3698 Japan
[4]The University Museum, The University of Tokyo, Hongo, Tokyo, 113-0033 Japan
* Corresponding author: sugitahisasi@gmail.com (H. Sugita).

Abstract The Jumla-Dolpa region of western Nepal including northern Dolpa, one of the driest regions in this country, experiences a relatively to markedly dry climate compared with eastern Nepal due to the rain-shadow effect of the Himalayas. Because the information about the vegetation of this region is lacking, we report community classification and ordination, species richness and diversity, population structures of canopy species, and spatial vegetation patterns across slope aspects of this region. Vegetation was classified into five community types based on the species composition and into six dominance types based on relative basal areas. In this region, principal tree species typical of the forest zones of eastern Nepal did not grow, except for *Abies spectabilis* and *Betula utilis* in the subalpine zone, and species rare or absent in eastern Nepal such as *Quercus semecarpifolia*, *Pinus wallichiana*, *Picea smithiana*, *Cupressus torulosa*, *Juniperus indica*, *Cedrus deodara*, and *Pinus roxburghii* commonly grew instead. The NMDS ordination showed that the west-east position reflecting climatic dryness mainly determines vegetation. The DBH distribution of canopy species exhibited unimodal to inverse-J patterns, indicating various regeneration traits from pioneer to late successional. Both Gleason's and Fisher's indices did not differ from those reported in eastern Nepal and indicated an existence of comparable species richness in this region despite the drier conditions. The Shannon-Wiever index, however, was lower than those in eastern Nepal and indicated reduced diversity among canopy species. Spatial vegetation pattern in the subalpine zone of relatively wet areas within the surveyed region showed a striking contrast across slope aspects, *Abies spectabilis* and *Betula utilis* forests on north-facing slopes, whereas *Quercus semecarpifolia* forests and meadows on south-facing slopes. This difference suggested that vegetation patterns are shaped by the amount of direct sunlight and the grazing pressures across slope aspects.
Keywords: DBH distribution, elevation, species composition, species richness and diversity, slope aspect, western Nepal, wet-dry gradient

Introduction

The Himalayas are an extensive mountain range stretching over 2400 km, characterized by highly diverse environment and vegetation. The eastern part of the range that includes eastern Nepal, Bhutan, and Assam is remarkably wet due to the summer monsoon. Contrastingly, the western part extending from western Nepal to Kashmir is very dry (Nayava 1980; Kansakar et al. 2004; Sharma et al. 2020, 2021).

Jumla and Dolpa Districts are located in the northern part of Karnali Province in western Nepal, ca. 300 km northwest of Kathmandu. The mountainous regions above 2000 m asl in these districts experience a relatively to markedly dry climate (Khatiwada et al. 2016; Sharma et al. 2020). Particularly, the northern part of Dolpa District lies in the rain-shadow of the Himalayas, whose high peaks such as Mt. Dhaulagiri (8167 m) block monsoon rain, and has a semi-arid climate. Such dry conditions strongly influence forest extent, dominant canopy species, and species richness and diversity.

The forest vegetation of the Jumla-Dolpa region has been surveyed, for example, by Stainton (1972), Shrestha (1982), Shrestha et al. (2005), and Ghimire et al. (2006), and its broad outlines, such as vegetation zones and main forest types, have been clarified (Barnekow Lillesø et al. 2005; Acharya & Paudel 2020). Vegetation types characteristic of dry climate have been noted particularly in northern Dolpa (Shrestha et al. 2005; DNPWC 2007; Acharya & Paudel 2020). Information on the vegetation of the Jumla-Dolpa region, however, remains insufficient, such as species composition including herbaceous plants, relationships between vegetation types and environmental conditions, and forest structures.

We carried out an ecological research of the floristic composition and structure of representative forests in the Jumla-Dolpa region in 1991. Within the limited time frame, we established several plots in a small portion of extant forest types. Although the number of plots is insufficient due to the accessing difficulty of this area and species identification in the studied plots has not been finished, our findings in this region provide important information about the scarcely studied ecology of this region. We aimed to clarify, on a regional scale, the species composition and dominant trees of plant communities, to examine species richness and biodiversity, and to assess regeneration traits of major canopy tree species based on their size structure. Moreover, we examined local scale spatial patterns of plant communities with special reference to the slope aspect.

Study region

We surveyed three areas of the Jumla-Dolpa region (Fig. 1): the Jumla-south mountain area (highest peak: 4740 m), the Phoksundo area around Phoksundo Lake, and the Dunai-south mountain area along the route to Jangla Bhanjyan (4523 m).

The annual precipitation at Jumla (2363 m) is 803 mm (1991–2020). This is relatively high for this region, but is still lower than the national average of 1500 mm. The annual precipitation at Dunai (2090 m), the headquarter of Dolpa District, is less than 500 mm and was 411 mm in 2023 (DHM 2024). The annual precipitation at Phoksundo Lake (3612 m) is presumed to be even lower, ca. 300–400 mm.

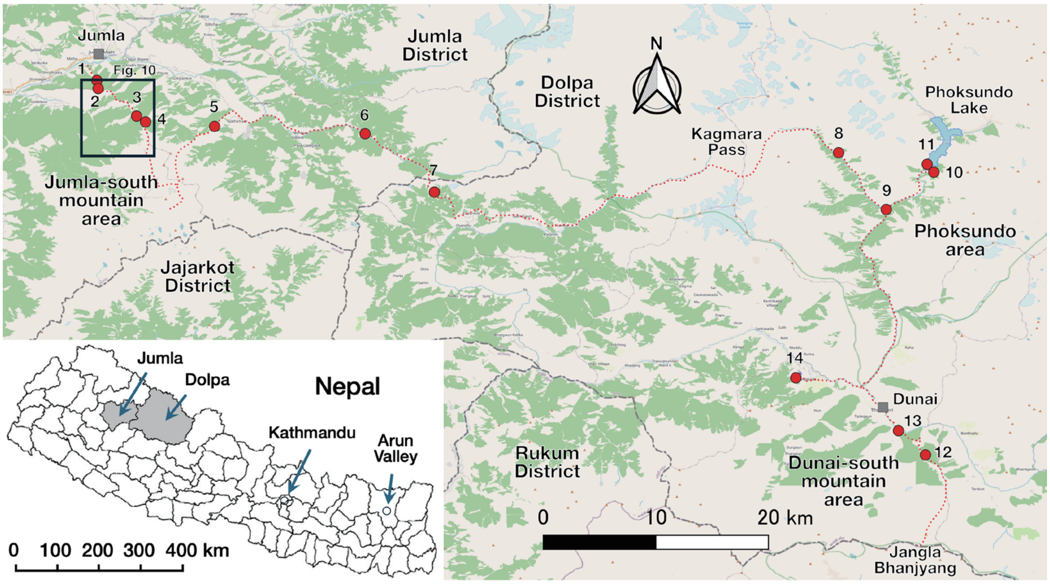

Fig. 1. Map of surveyed region (map data from OpenStreetMap). Red dotted line: expedition route, circles: surveyed plots with plot numbers, light green parts: forest areas, rectangle: area of vegetation map (Fig. 10).

Most areas of Jumla District are covered by forests, but, in Dolpa District, only a small portion of the southern region is forested (ICIMOD 2010). Among our survey areas, the Jumla-south and Dunai-south mountain areas are largely forested, whereas the Phoksundo area is sparsely forested, mostly covered with scrub and meadow vegetation. Local people residing in these areas use scrubs and meadows for livestock grazing, including the alpine zone (DNPWC 2007), and it is often unclear whether such vegetation is natural one or secondary one resulting from human activity.

Bio-climatic zones and forest types in the mountainous regions (higher than 1000 m asl) in Karnali Province are described as follows (Acharya & Paudel 2020):

A. Subtropical zone (1000–2000 m)

(1) *Pinus roxburghii* forest, (2) *Pinus roxburghii* and broad-leaved (*Quercus incana, Q. lanata*) forest, (3) *Alnus nepalensis* forest

B. Temperate zone (2000–3000 m)

(1) *Pinus wallichiana* forest, (2) *Picea smithiana* forest, (3) *Abies pindrow*, *Tsuga dumosa* and *Quercus semecarpifolia* forest, (4) *Cedrus deodara* forest, (5) *Cupressus torulosa* forest, (6) *Pinus wallichiana* and oaks (*Quercus lanata* and *Q. dilatate*) forest, (7) oaks (*Quercus lanata* and *Q. dilatate*) forest, (8) deciduous walnut-maple-alder forest (*Aesculus, Juglans, Acer, Populus, Betula, Corylus Ulmus*, etc.), and (9) *Olea cuspidata* and *O. glanulifera* forest

C. Subalpine zone (3000–4000 m)

(1) *Betula utilis* forest, (2) *Abies spectabilis* forest, (3) *Abies spectabilis*, *Tsuga dumosa* and *Quercus semecarpifolia* forest, (4) *Quercus semecarpifolia* forest,

D. Alpine zone (4000–5000 m)

(1) Upper alpine meadows (*Carex* sp., *Calamogrostis* sp., *Agrotis micanth*a, etc.) and (2) moist alpine scrub (*Rhododendron anthopogon*, *R. setosum*, *Juniperus indica*, *Potentilla fructicosa*, etc.)

The scrub and meadow vegetation in the arid areas of the northern part of Dolpa including the Phoksundo area is described as follows (Shrestha et al. 2005):

A. Xerophile formation (3000–3600 m asl)

Juniperus indica, *Rosa sericea*, *Berberis aristata*, *Lonicera hispida*, *Salix scerophylla*, etc.

B. Alpine Zone (3600–6400 m asl)

1. Alpine scrubs
   (1) Dry alpine scrubs (*Caragana brevifolia*, *Lonicera spinosa*, etc.)
   (2) Moist alpine scrubs (*Myricaria squamosa*, *Salix calyculata*, *S. lindleyana*, etc.)
2. Alpine meadows/Grasslands (*Carex* sp., *Deyeuxia holiciformis*, *D. pulchella*, etc.)

To protect the unique landscape and ecosystems of this area, Shey-Phoksundo National Park was established in 1984, presently the largest national park in Nepal.

Methods

Field survey

We established 14 plots across various forest and shrub types during the expedition from 16 September to 15 October 1991 (Minaki 1992, Fig. 1). After starting from Jumla, we established seven plots (P1–P7) in the Jumla-south mountain area. After crossing Kagmara Pass (5114 m), we established four plots (P8–P11) in the Phoksundo area, and three plots (P12–P14) in the Dunai-south mountain area. General characteristics of the plots are presented in Tables 1 and 2.

Plot size was usually 10 × 50 m, except for P9 (10 × 40 m), P11 (2 × 10 m), and P14 (10 × 35 m). We identified and measured diameters at breast height (DBH) and heights (H)

Table 1. General description of the plots.

Plot no	Latitude	Longitude	Location	Elevation (m)	Aspect (degree)	Inclination (degree)	Forest type	Plot size (m)
1	N29°15′04″	E82°10′44″	Jumla–Bibeya	2910	N35E	33	*Picea smithiana* forest	10 × 50
2	N29°14′38″	E82°10′49″	Bibeya	3510	N30E	25	*Abies spectabilis* forest	10 × 50
3	N29°13′08″	E82°12′54″	Chakare pani	3660	S22W	31	*Quercus semecarpifolia* forest	10 × 50
4	N29°12′49″	E82°13′24″	Deula Deuli	3840	N80E	35	*Betula utilis* forest	10 × 50
5	N29°12′34″	E82°17′10″	above Gothichaur	3340	S20W	25	*Abies spectabilis-Betula utilis* forest	10 × 50
6	N29°12′10″	E82°25′23″	Chota	3100	N60W	40	*Q. semecarpifolia-Pinus wallichiana* forest	10 × 50
7	N29°08′59″	E82°29′10″	Naat	3510	N60W	28	*A. spectabilis-Q. semecarpifolia* forest	10 × 50
8	N29°11′8″”	E82°51′14″	Daja	3620	S10W	35	*Juniperus indica* forest	10 × 50
9	N29°08′02″	E82°53′50″	Sumduwa	3090	N10E	25	*Cupressus torulosa-P. smithiana* forest	10 × 40
10	N29°10′30″	E82°56′04″	Phoksundo Tal	3660	N75W	25	*Pinus wallichiana* forest	10 × 50
11	N29°10′04″	E82°56′26″	Phoksundo Tal	3640	N10W	15	*Caragana gerardiana* scrub	2 × 10
12	N28°54′39″	E82°55′59″	Lunkhor	3040	W	25	*P. smithiana-Q. semecarpifolia* forest	10 × 50
13	N28°55′58″	E82°54′30″	Dunai	2180	N50E	40	*Pinus roxiburghii* forest	10 × 50
14	N28°58′51″	E82°48′54″	Juphal	2680	N60E	22	*Cedrus deodara* forest	10 × 35

of all trunks taller than 1.3 m in all the plots except P11, and carried out a phytosociological survey: all vascular plant species within each plot were identified, and their coverage ranks were measured.

Spatial patterns of forest types

Spatial patterns of forest types across topography were examined by preparing a vegetation map. The subject area was in the Jumla-south mountain area and included P2–P4 (Fig. 1). The area covered approximately 1300 ha with an elevational range of 3000–4300 m. Physiognomical vegetation types (including meadow vegetation) were determined based on the interpretation of 1:50,000 aerial photographs taken in 1978 by the Survey Department of His Majesty's Government of Nepal, supplemented by photographs taken on the site and field observations during the survey. A 125 m mesh grid was applied to the vegetation map. For each grid cell, elevation at the center, slope aspect, and dominant vegetation type were recorded. The relationships between the vegetation types and slope aspect and altitude were examined using these data.

Data analysis

Community classification was conducted using the two-way indicator species analysis (TWINSPAN, Hill 1979) based on the species coverage data.

Ordination of all plots was performed using the non-metric multidimensional scaling (NMDS) based on the species coverage in each plot. The resulting diagram shows a biplot of sample scores along the two principal axes. Statistically significant ($p < 0.05$) environmental variables were plotted as vectors on the NMDS diagram. Elevation (*ELV*) and eastward distance from P1 (*EAST*) of each plot were examined as environmental factors.

Cluster analysis was conducted to describe dominance types among plots except P11. The Euclidean distances among plots were calculated based on the relative basal areas of tree species in the plots, using the group-average method.

To compare species richness including herbaceous plants among plots of different sizes, the Gleason index was calculated using the formula $d = S / \ln(A)$, where d is the Gleason index, S is the number of species in a plot, and A is the plot area (m^2). To compare diversity of woody plants, Fisher's and Shannon-Wiever's diversity indices were calculated using the formulae, $S = \alpha \times \ln(1 + N / \alpha)$ and $H' = -\Sigma(P_i \times \ln(P_i))$, respectively, where α is Fisher's index, S is the number of species, N is the number of stems taller than 1.3 m, H' is the Shannon-Wiever index, and P_i is the relative basal area of species i. The

Table 2. Component species of the plots.

Result of TWINSPAN	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	0	0	0	0	0	0	0	0	0	0	0	1	1	
	0	0	0	0	0	0	0	0	0	1	1			
	0	0	0	0	1	1	1	1	1					
Community type	A				B					C		D		E
Species / Plot no	2	3	4	5	1	6	7	12	9	14	8	10	11	13
Betula utilis D.Don	1	·	4	2	·	·	·	·	·	·	·	·	·	·
Arundinaria sp.	2	2	+	+	+	·	·	1	·	·	·	·	·	·
Sorbus microphylla Wenz.	1	+	3	+	·	·	+	·	·	·	·	·	·	·
Cacalia sp.	1	+	+	·	·	·	·	·	·	·	·	·	·	·
sp49 (*Lepisorus*)	+	+	·	+	·	·	·	·	·	·	·	·	·	·
Smilacina purpurea Wall.	+	·	+	+	·	·	+	·	·	·	·	·	·	·
Rhododendron campanulatum D.Don	·	·	3	·	·	·	·	·	·	·	·	·	·	·
Poa sp.	·	·	2	·	·	·	·	·	·	·	·	·	·	·
Oryzopsis sp.	·	1	+	·	·	·	·	·	·	·	·	·	·	·
Aruncus sp.	·	·	1	·	·	·	·	·	·	·	·	·	·	·
sp65 (*Athyrium*)	·	·	1	·	·	·	·	·	·	·	·	·	·	·
Dipsacus sp.	·	·	·	1	·	·	·	·	·	·	·	·	·	·
sp18 (*Acer caesium* Wall. ex Brandis ?)	·	·	·	1	·	·	·	·	·	·	·	·	·	·
Spiraea micrantha Hook.f.	+	+	·	·	·	·	·	·	·	·	·	·	·	·
sp54 (Polypodiaceae)	·	+	+	·	·	·	·	·	·	·	·	·	·	·
Myriactis sp.	+	·	·	·	·	·	·	·	·	·	·	·	·	·
Smilax menispermoidea A.DC.	+	·	·	·	·	·	·	·	·	·	·	·	·	·
Sorbus foliolosa (Wall.) Spach	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp 9 (Poaceae)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp10 (Poaceae)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp11 (Poaceae)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp12 (*Polystichum*)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp17 (Apiaceae)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp47 (*Viola* ?)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp69 (Asteraceae)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
sp70 (*Pteridium*)	+	·	·	·	·	·	·	·	·	·	·	·	·	·
Stellaria monosperma Buch.-Ham. ex D.Don	+	·	·	·	·	·	·	·	·	·	·	·	·	·
Festuca ovina L.	·	+	·	·	·	·	·	·	·	·	·	·	·	·
Lonicera myrtilloides Purpus	·	+	·	·	·	·	·	·	·	·	·	·	·	·
Rhodiola chrysanthemifolia (H.Lev.) S.H.Fu	·	+	·	·	·	·	·	·	·	·	·	·	·	·
Senecio chrysanthemoides DC.	·	+	·	·	·	·	·	·	·	·	·	·	·	·
Bistorta vaccinifolia (Wall. ex Meisn.) Greene	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Cotoneaster sp.	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Koenigia delicatula (Meisn.) H.Hara	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Pleurospermum dentatum (DC.) C.B.Clarke	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Rhodiola wallichiana (Hook.) S.H.Fu	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Saxifraga moorcroftiana (Ser.) Wall. ex Sternb.	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Selinum tenuifolium Wall. ex C.B.Clarke	·	·	+	·	·	·	·	·	·	·	·	·	·	·
sp 4 (*Sausurea* ?)	·	·	+	·	·	·	·	·	·	·	·	·	·	·
sp20 (*Polystichum* ?)	·	·	+	·	·	·	·	·	·	·	·	·	·	·
sp57 (*Athyrium*)	·	·	+	·	·	·	·	·	·	·	·	·	·	·
sp61 (*Polystichum* ?)	·	·	+	·	·	·	·	·	·	·	·	·	·	·
sp64 (*Dryopteris*)	·	·	+	·	·	·	·	·	·	·	·	·	·	·
Balanophora involucrata Hook.f.	·	·	·	+	·	·	·	·	·	·	·	·	·	·
Oxalis acetosella L. subsp. *acetosella*	·	·	·	+	·	·	·	·	·	·	·	·	·	·
Persicaria nepalensis (Meisn.) H.Gross	·	·	·	+	·	·	·	·	·	·	·	·	·	·
Sanguisorba diandra (Hook.f.) Nordborg	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp 7 (*Athyrium* ?)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp 8 (Poaceae)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp27 (*Carpesium*)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp34 (*Cimicifuga* ?)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp36 (Lamiaceae)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp50 (*Sonchus* ?)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
sp56 (Asteraceae)	·	·	·	+	·	·	·	·	·	·	·	·	·	·
Picea smithiana (Wall.) Boiss.	·	·	·	·	4	+	·	3	1	·	·	·	·	·
Quercus semecarpifolia Sm.	·	5	·	·	·	4	3	4	·	·	·	·	·	·
sp63 (Asteraceae)	·	·	·	+	·	+	1	1	1	·	·	·	·	·
Geranium wallichianum D.Don ex Sweet	·	+	·	·	+	+	+	+	·	·	+	·	·	·
Viburnum nervosum D.Don	+	·	·	·	1	+	+	·	·	·	·	·	·	·
Circaea alpina L. subsp. *imaicola* (Asch. & Magnus) Kitam.	·	·	·	·	+	·	+	+	·	·	+	·	·	·
Jasminum humile L.	·	·	·	·	+	+	·	·	+	·	·	·	·	+
Bistorta amplexicaulis (D.Don) Greene var. *amplexicaulis*	·	·	+	+	+	+	+	·	·	·	·	·	·	·
Senecio sp1	·	·	·	·	+	·	·	+	+	·	·	·	·	·
Podophyllum hexandrum Royle	·	·	·	·	·	·	+	+	+	·	·	·	·	·
Euonymus fimbriatus Wall.	·	·	·	·	+	·	·	+	+	·	·	·	·	·
Viburnum mullaha Buch.-Ham. ex D.Don var. *glabrescens* (C.B.Clarke) Kitam.	·	·	·	·	1	·	·	2	·	·	·	·	·	·
sp67 (*Athyrium*)	·	·	·	·	1	·	·	1	·	·	·	·	·	·
Helictotrichon virescens (Nees ex Steud.) Henrard	·	·	·	·	·	1	·	·	1	·	·	·	·	·
Caragana brevispina Royle	·	·	·	·	+	·	·	1	·	·	·	·	·	·
Lonicera lanceolata Wall.	·	·	·	·	·	·	·	+	2	·	·	·	·	·
Dipsacus inermis Wall. var. *inermis*	·	·	·	·	+	+	·	·	·	·	·	·	·	·
Leptodermis kumaonensis Parker	·	·	·	·	·	+	·	+	·	·	·	·	·	·
Parietaria micrantha Ledeb.	·	·	·	·	+	·	+	·	·	·	·	·	·	·
sp59 (*Athyrium*)	·	·	·	·	·	+	+	·	·	·	·	·	·	·
Erigeron sp.	·	·	·	·	·	·	+	·	+	·	·	·	·	·
Salvia nubicola Wall. ex Sweet	·	·	·	·	+	·	·	·	+	·	·	·	·	·
Viburnum erubescens Wall. ex DC. var. *erubescens*	·	·	·	·	·	+	·	·	+	·	·	·	·	·
Corylus jacquemontii Decne.	·	·	·	·	2	·	·	·	·	·	·	·	·	·
Desmodium elegans DC. subsp. *elegans* var. *elegans*	·	·	·	·	1	·	·	·	·	·	·	·	·	·
Agrimonia pilosa Ledeb. var. *japonica* (Miq.) Nakai	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Carpesium sp.	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Clinopodium umbrosum (M.Bieb.) C.Koch	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Galium asperifolium Wall.	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Parthenocissus himalayana (Royle) Planch.	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Philadelphus tomentosus Wall. ex G.Don forma *nepalensis* (Koehne) H.Hara	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Rubus hoffmeisterianus Kunth & Bouché	·	·	·	·	+	·	·	·	·	·	·	·	·	·
sp22 (Polypodiaceae)	·	·	·	·	+	·	·	·	·	·	·	·	·	·
sp28 (*Dryopteris*)	·	·	·	·	+	·	·	·	·	·	·	·	·	·
sp46 (*Carex*)	·	·	·	·	+	·	·	·	·	·	·	·	·	·
sp62 (*Carex*)	·	·	·	·	+	·	·	·	·	·	·	·	·	·

Table 2. (continued)

Community type	A				B					C		D		E
Species / Plot no	2	3	4	5	1	6	7	12	9	14	8	10	11	13
Triplostegia sp.	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Vincetoxicum hirundinaria Medik. subsp. *glaucum* (Wall. ex Wight) H.Hara	·	·	·	·	+	·	·	·	·	·	·	·	·	·
Androsace hookeriana Klatt	+	·	·	·	·	1	·	·	·	·	·	·	·	·
Corydalis pseudolongipes Lidén	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Epilobium royleanum Hausskn.	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Euphorbia sp.	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Halenia elliptica D.Don	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Malaxis monophyllos (L.) Sw.	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Nepeta laevigata (D.Don) Hand.-Mazz.	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Pleurospermum angelicoides (DC.) C.B.Clarke	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Saxifraga brachypoda D.Don var. *brachypoda*	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Saxifraga parnassifolia D.Don	·	·	·	·	·	+	·	·	·	·	·	·	·	·
sp33 (*Athyrium*)	·	·	·	·	·	+	·	·	·	·	·	·	·	·
sp52 (*Adiantum*)	·	·	·	·	·	+	·	·	·	·	·	·	·	·
sp60 (Asteraceae)	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Stachys sericea Wall. ex Benth.	·	·	·	·	·	+	·	·	·	·	·	·	·	·
Aconitum sp.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Anthogonium gracile Wall. ex Lindl.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Cardamine yunnanensis Franch.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Delphinium sp.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Juncus sp.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Saxifraga diversifolia Wall. ex Ser.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
sp21 (Polypodiaceae)	·	·	·	·	·	·	+	·	·	·	·	·	·	·
sp53 (*Cheilanthes* ?)	·	·	·	·	·	·	+	·	·	·	·	·	·	·
sp55 (*Thelypteris* ?)	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Triosteum himalayanum Wall.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Viola glaucescens Oudem.	·	·	·	·	·	·	+	·	·	·	·	·	·	·
Taxus baccata L. subsp. *wallichiana* (Zucc.) Pilg.	·	·	·	·	·	·	·	2	·	·	·	·	·	·
Strobilanthes sp.	·	·	·	·	·	·	·	1	·	·	·	·	·	·
Cephalanthera sp.	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Euonymus amygdalifolius Franch.	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Geum sikkimense Prain	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Jasminum officinale L. var. *officinale*	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Leycesteria formosa Wall.	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Ophiopogon parviflorus (Hook.f.) H.Hara	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Polygonatum sp.	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Prunus cornuta (Hook.f.) H.Hara	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Smilax minutiflora A.DC.	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp 2 (*Aster* ?)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp13 (*Polystichum*)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp14 (Apiaceae)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp15 (*Coniogramme* ?)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp16 (*Sanicula* ?)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp41 (*Carex*)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp42 (*Carex*)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
sp58 (*Dryopteris*)	·	·	·	·	·	·	·	+	·	·	·	·	·	·
Cupressus torulosa D.Don	·	·	·	·	·	·	·	·	4	·	·	·	·	·
Berberis sikkimensis Ahrendt var. *baileyi* Ahrendt	·	·	·	·	·	·	·	·	1	·	·	·	·	·
Leptodermis lanceolata Wall.	·	·	·	·	·	·	·	·	1	·	·	·	·	·
Juniperus squamata Buch.-Ham. ex D.Don	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Chenopodium badachschanicum Tzvelev	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Ephedra gerardiana Wall. ex Stapf	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Euonymus sp.	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Lactuca sp.	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Populus ciliata Wall. ex Royle	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Prunus persica (L.) Batsch	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Ribes alpestre Wall. ex Decne	·	·	·	·	·	·	·	·	+	·	·	·	·	·
sp26 (*Euonymus* ?)	·	·	·	·	·	·	·	·	+	·	·	·	·	·
sp35 (*Angelica* ?)	·	·	·	·	·	·	·	·	+	·	·	·	·	·
sp38 (*Artemisia* ?)	·	·	·	·	·	·	·	·	+	·	·	·	·	·
sp48 (Amaryllidaceae ?)	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Taraxacum sp.	·	·	·	·	·	·	·	·	+	·	·	·	·	·
Abies spectabilis (D.Don) Mirb.	4	·	·	4	·	+	3	·	·	·	·	·	·	·
Impatiens spp.	+	2	+	·	+	+	+	+	+	·	·	·	·	·
sp24 (*Dryopteris*)	+	·	+	1	·	+	+	+	·	·	·	·	·	·
sp37 (*Davallia* ?)	+	+	·	+	+	·	+	·	·	·	·	·	·	·
Fragaria nubicola Lindl. ex Lacaita	1	·	·	+	+	1	+	·	·	·	·	·	·	·
Senecio sp.2	3	·	·	+	2	1	·	·	·	·	·	·	·	·
Adenostema sp.	·	1	·	·	+	+	+	·	·	+	·	·	·	·
Polygonatum verticillatum (L.) All.	+	+	·	·	·	+	·	·	+	·	+	·	·	·
Acanthopanax cissifolius (Griff. ex Seem.) Harms	+	·	·	·	·	+	·	·	·	·	·	·	·	·
Centella sp.	·	·	·	+	·	·	+	·	·	·	·	·	·	·
Parochetus communis Buch.-Ham. ex D.Don	+	·	·	·	·	+	·	·	·	·	·	·	·	·
Polygonatum singalilense H.Hara	·	·	+	·	+	·	·	·	·	·	·	·	·	·
Saussurea sp.	·	·	+	·	·	+	·	·	·	·	·	·	·	·
Cotoneaster microphyllus Wall. ex Lindl.	·	·	·	·	·	·	·	·	·	+	+	·	·	·
Cedrus deodara (Roxb. ex D.Don) G.Don	·	·	·	·	·	·	·	·	·	4	·	·	·	·
Colquhounia coccinea Wall. var. *coccinea*	·	·	·	·	·	·	·	·	·	2	·	·	·	·
Iris decora Wall.	·	·	·	·	·	·	·	·	·	2	·	·	·	·
sp40 (*Carex*)	·	·	·	·	·	·	·	+	+	2	·	·	·	·
Andropogon trigtis	·	·	·	·	·	·	·	·	·	1	·	·	·	·
Desmodium elegans DC. subsp. *elegans* var. *nutans* (Hook.) H.Ohashi	·	·	·	·	·	·	·	·	·	1	·	·	·	·
Elsholtzia fruticosa (D.Don) Rehder	·	·	·	·	+	·	·	·	·	1	·	·	·	·
Asparagus filicinus Buch.-Ham. ex D.Don	·	·	·	·	·	·	·	·	+	1	·	·	·	·
Herminium lanceum (Thunb.) Vuijk	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Potentilla griffithii Hook.f.	·	·	·	·	·	·	·	·	·	+	·	·	·	·
sp19 (*Polypodium* ?)	·	·	·	·	·	·	·	·	·	+	·	·	·	·
sp45 (*Onychium* ?)	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Swertia ciliata (D.Don ex G.Don) B.L.Burtt	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Arisaema flavum (Forssk.) Schott	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Arundinella hookeri Munro ex Keng	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Bromus sp.	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Buddleja crispa Benth.	·	·	·	·	·	·	·	·	·	+	·	·	·	·
Cotoneaster rotundifolius Wall. ex Lindl.	·	·	·	·	·	·	·	·	·	·	3	·	·	·
Valeriana hardwickii Wall.	+	+	·	·	·	+	·	·	·	·	1	·	·	·
Festuca sp.	+	·	·	·	·	·	+	·	·	·	1	·	·	·

Table 2. (continued)

Community type	A				B					C		D		E
Species / Plot no	2	3	4	5	1	6	7	12	9	14	8	10	11	13
sp44 (*Swertia*)	·	·	·	·	·	·	·	·	·	·	1	·	·	·
sp66 (*Athyrium*)	·	·	·	·	·	·	·	·	·	·	1	·	·	·
Syringa emodi Wall. ex Royle	·	·	·	·	·	·	·	·	·	·	1	·	·	·
Triplostegia glandulifera Wall. ex DC.	·	·	·	·	·	+	·	·	·	·	1	·	·	·
Astragalus chlorostachys Lindl.	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Erigeron multiradiatus (Lindl. ex DC.) C.B.Clarke	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Galium asperifolium Wall. var. *sikkimense* (Gand.) Cufod.	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Heradeum sp.	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Meconopsis paniculata Prain	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Pedicularis mollis Wall. ex Benth.	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Salvia campanulata Wall. ex Benth.	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Silene waltonii F.N.Williams	·	·	·	·	·	·	·	·	·	·	+	·	·	·
sp 5 (*Sonchus* ?)	·	·	·	·	·	·	·	·	·	·	+	·	·	·
sp23 (*Anaphalis* ?)	·	·	·	·	·	·	·	·	·	·	+	·	·	·
sp29 (*Primula* ?)	·	·	·	·	·	·	·	·	·	·	+	·	·	·
sp30 (*Polystichum* ?)	·	·	·	·	·	·	·	·	·	·	+	·	·	·
sp32 (*Aster* ?)	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Viburnum cotinifolium D.Don	·	·	·	·	·	·	·	·	·	·	+	·	·	·
Cotoneaster acuminatus Lindl.	+	+	·	·	1	1	+	+	·	2	1	·	·	·
Rosa macrophylla Lindl.	1	·	·	·	1	+	·	+	+	·	2	·	·	·
Ribes sp.	+	1	+	·	·	·	·	·	·	·	2	·	·	·
Aconitum spicatum (Bruhl) Stapf	·	+	·	·	·	·	·	·	·	·	+	·	·	·
Anaphalis contorta (D.Don) Hook.f.	·	·	·	·	·	+	·	·	·	·	+	·	·	·
Lonicera angustifolia Wall. ex DC.	·	·	·	·	·	+	·	·	·	·	+	·	·	·
sp51 (*Aster* ?)	·	·	·	·	·	·	·	·	+	·	+	·	·	·
Spiraea canescens D.Don	·	·	·	·	·	·	·	·	·	+	·	1	2	·
Androsace strigillosa Franch.	+	·	+	·	·	+	+	·	+	·	+	1	1	·
Anaphalis sp.	·	+	·	·	·	·	·	·	·	·	·	+	1	·
Elymus sp.	·	·	·	·	·	·	·	·	·	·	·	+	1	·
Koeleria cristata (L.) Pers.	·	·	·	·	·	·	·	·	·	·	·	+	+	·
Pinus wallichiana A.B.Jacks.	·	·	·	·	+	2	·	·	+	·	·	3	·	·
Danthonia jacquemontii Bor	·	·	·	·	·	·	·	·	·	·	·	2	·	·
Juniperus indica Bertol.	·	·	·	·	·	·	·	·	·	·	4	1	·	·
Trigonella emodii Benth. subsp. *emodii*	·	·	·	·	·	·	·	·	·	·	·	1	·	·
Aster sp.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Bupleurum falcatum L. subsp. *marginatum* (Wall. ex DC.) H.Wolff	·	·	·	·	·	·	·	·	+	+	·	+	·	·
Calamagrostis sp.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Cotoneaster integrifolius (Roxb.) Klotz	·	·	·	·	·	·	·	·	+	·	·	+	·	·
Epilobium angustifolium L. subsp. *circumvagum* Mosquin	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Gentiana sp.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Geranium lambertii Sweet	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Malaxis sp.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Monotropa hypopithys L.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Origanum vulgare L.	·	·	·	·	·	·	·	·	·	+	·	+	·	·
Pedicularis sp.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Pedicularis hoffmeisteri Klotzsch	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Polygonatum cirrhifolium (Wall.) Royle	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Pterocephalus hookeri (C.B.Clarke) Diels	·	·	·	·	·	·	·	·	·	·	·	+	·	·
sp 6 (*Swertia*)	·	·	·	·	·	·	·	·	·	·	·	+	·	·
sp43 (*Swertia*)	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Stellera chamaejasme L.	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Thermopsis barbata Royle	·	·	·	·	·	·	·	·	·	·	·	+	·	·
Carex sp.	·	·	+	·	·	·	·	·	+	·	·	+	·	·
Epipactis helleborine (L.) Crantz	·	·	·	·	+	+	·	·	+	·	·	+	·	·
Caragana gerardiana Royle	·	·	·	·	·	·	·	·	·	·	·	·	4	·
Danthonia schneideri Pilg.	·	·	·	·	·	·	·	·	·	·	·	·	2	·
Thalictrum sp.	·	·	·	·	+	+	+	+	1	·	1	·	1	·
Thymus sp.	·	·	·	·	·	·	·	·	·	·	·	·	1	·
Androsace sp.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Arnebia sp.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Bupleurum dalhousieanum (Clarke) K.-Pol.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Gentianella paludosa (Clarke) K.-Pol.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Pedicularis gracilis Wall. ex Benth.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
sp 1 (*Aster* ?)	·	·	·	·	·	·	·	·	·	·	·	·	+	·
sp 3 (*Gentiana* ?)	·	·	·	·	·	·	·	·	·	·	·	·	+	·
sp31 (*Senecio* ?)	·	·	·	·	·	·	·	·	·	·	·	·	+	·
sp39 (*Carex*)	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Swertia gracilescens H.Sm.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Thesium himalense Royle ex Edgew.	·	·	·	·	·	·	·	·	·	·	·	·	+	·
Rosa sericea Lindl.	1	1	+	·	·	·	1	·	·	1	·	1	·	·
Selinum sp.	·	+	·	·	+	+	+	·	+	·	1	+	·	·
Lonicera myrtillus Hook.f. & Thomson	+	·	·	+	+	·	+	·	+	+	·	+	·	·
Clematis sp.	+	+	·	+	·	·	·	+	+	·	+	+	·	·
Anemone sp.	+	+	+	+	·	·	·	·	·	·	·	+	·	·
Berberis sp.	·	·	·	+	+	·	+	·	·	1	1	1	·	+
Artemisia sp.	·	·	·	·	·	+	·	+	+	1	+	·	+	+
Gerbera sp.	·	·	·	·	·	+	·	·	·	+	·	·	·	+
Galium acutum Edgew.	·	·	·	·	·	·	·	·	·	+	·	+	·	+
Indigofera cylindracea Graham ex Baker	·	·	·	·	·	·	·	·	·	1	·	·	·	+
sp25 (*Artemisia*)	·	·	·	·	·	·	·	·	·	+	·	·	·	+
Themeda anathera (Nees ex Steud.) Hack.	·	·	·	·	·	·	·	·	·	·	·	·	·	4
Pinus roxiburghii Sarg.	·	·	·	·	·	·	·	·	·	·	·	·	·	3
Apluda mutica L.	·	·	·	·	·	·	·	·	·	·	·	·	·	1
Chrysopogon sp.	·	·	·	·	·	·	·	·	·	·	·	·	·	1
Chrysopogon gryllus (L.) Trin. ?	·	·	·	·	·	·	·	·	·	·	·	·	·	1
Lespedeza juncea (L.f.) Pers.	·	·	·	·	·	·	·	·	·	·	·	·	·	1
Anaphalis triplinervis (Sims) C.B.Clarke	·	·	·	·	+	·	·	·	·	·	·	·	·	+
Anemone vitifolia Buch.-Ham. ex DC.	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Coriaria napalensis Wall.	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Juglans regia L. var. *kamaonia* C.DC.	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Micromeria sp.	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Polygala longifolia Poir.	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Sopubia trifida Buch.-Ham. ex D.Don	·	·	·	·	·	·	·	·	·	·	·	·	·	+
Swertia racemosa (Griseb.) C.B.Clarke	·	·	·	·	·	·	·	·	·	·	·	·	·	+
sp68 (*Lapsanastrum* ?)	·	·	·	·	·	·	·	·	·	·	·	·	·	+

relationship between the elevation and the index was examined using Spearman's rank correlation coefficient. Difference in index values between groups was examined using Mann-Whitney test.

These analyses were performed with a programming language R 4.2.2 (R Core Team 2022). The packages "twinspan" and "vegan" were used for TWINSPAN and NMDS, respectively.

Results

Species composition, and classification and ordination of community types

The species composition of each plot is shown in Table 2 with the TWINSPAN results shown in the upper part. Fourteen plots were classified into five groups (A–E).

Type A (plot nos. 2, 3, 4, 5): characterized by *Betula utilis*, *Arundinaria* sp., *Sorbus microphylla*, *Cacalia* sp., etc.

Type B (plot nos. 1, 6, 7, 9, 12): characterized by *Picea smithiana*, *Quercus semecarpifolia*, *Geranium wallichianum*, etc. *Abies spectabilis*, *Fragaria nubicola*, etc. were common to Types A–B.

Type C (plot nos. 8, 14): characterized by *Cotoneaster microphyllus*, etc. *Cotoneaster acuminatus*, *Rosa macrophylla*, etc. were common to Types A-C.

Type D (plot nos. 10, 11): characterized by *Spiraea canescens*, *Androsace stri-*

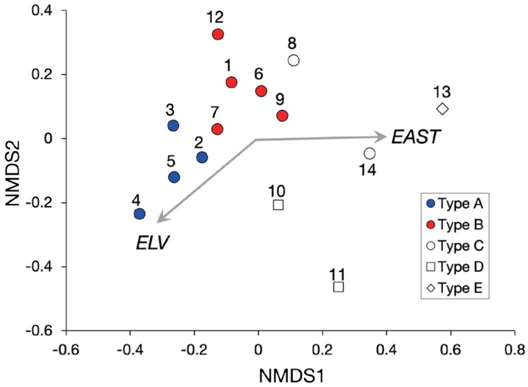

Fig. 2. NMDS ordination biplot of sample scores and significant environmental variables for 14 plots. Samples are represented by their community types (A–E), as identified by TWINSPAN classification. Arrows indicate the directions of the environmental variables. *ELV*: elevation, *EAST*: distance along the east direction from Plot 1.

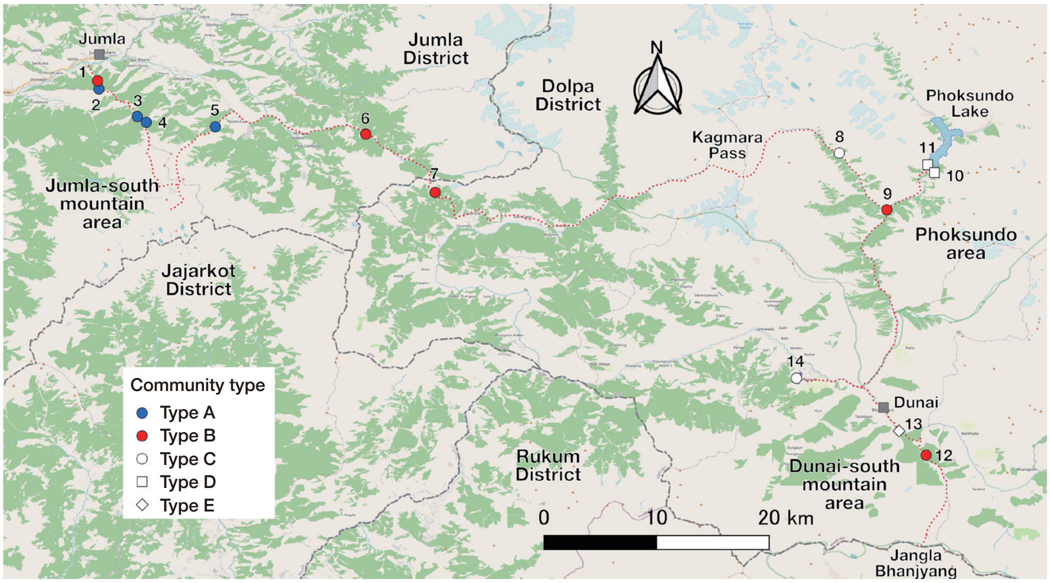

Fig. 3. Geographical distribution of the community types (A–E) identified by TWINSPAN classification (map data from OpenStreetMap). Light green parts: natural forests.

Table 3. General description of the forest structures in the plots surveyed.

Plot no	Forest type	Height (m) H	Height (m) S	Height (m) T2	Height (m) T1	Coverage (%) H	Coverage (%) S	Coverage (%) T2	Coverage (%) T1	Max. DBH (cm)	Basal area (m^2/ha)	Dominance type*	Community type **
1	*Picea smithiana* forest	0–0.3	0.5–3	3–8	24–32	40	50	30	70	125	148.9	b	B
2	*Abies spectabilis* forest	0–0.5	2–4	10–15	18–23	60	20	20	60	88	88.3	a	A
3	*Quercus semecarpifolia* forest	0–0.8	0.8–3		9–21	30	10		80	83	67.5	b	A
4	*Betula utilis* forest	0–1	1–5		7–11	70	60		60	85	37.0	a	A
5	*Abies spectabilis–Betula utilis* forest	0–0.5	0.5–2	2–7	9–24	20	20	10	70	71	57.2	a	A
6	*Q. semecarpifolia–Pinus wallichiana* forest	0–0.5	0.5–4	4–15	15–18	30	15	60	15	43	33.4	b	B
7	*A. spectabilis–Q. semecarpifolia* forest	0–0.5	0.5–4	4–22	22–32	15	30	60	10	97	72.8	a	B
8	*Juniperus indica* forest	0–1	1–3		3–13	30	50		60	75	42.2	d	C
9	*Cupressus torulosa–P. smithiana* forest	0–0.7	0.7–4		4–24	20	30		70	151	194.1	b	B
10	*Pinus wallichiana* forest	0–0.5	0.5–5		5–15	30	10		30	61	41.7	c	D
11	*Caragana gerardiana* scrub	0–0.3	0.3–1			20	70						D
12	*P. smithiana–Q. semecarpifolia* forest	0–0.5	0.5–5	5–10	10–32	20	30	30	85	101	84.1	b	B
13	*Pinus roxburghii* forest	0–0.8			21–26	80			45	57	24.3	f	E
14	*Cedrus deodara* forest	0–0.6	0.6–4		6–24	40	30		60	95	75.6	e	C

T1: tree layer, T2: subtree layer, S: shrub layer, H: herb layer

* classified by cluster analysis (Fig. 4), ** classified by TWINSPAN (Table 2)

Table 4. Relative basal area (%) of tree species and the diversity indices in each plot

Dominance type	a				b					c	d	e	f
Species / Plot no	P2	P5	P7	P4	P1	P12	P9	P3	P6	P10	P8	P14	P13
Abies spectabilis	87	73	62										
Betula utilis	11	26		85									
Sorbus microphylla	1		0	7				0					
Rhododendron campanulatum				9									
Picea smithiana					96	53	24		0				
Quercus semecarpifolia			37			43		100	61				
Cupressus torulosa							75						
Pinus wallichiana					1				39	100			
Juniperus indica										0	99		
Cedrus deodara												100	
Pinus roxburghii													100
Fisher's diversity index (α)	3.057	0.63	2.033	0.836	3.62	3.00	3.544	0.921	1.688	0.512	0.992	2.019	0.343
Shannon-Wiever's diversity index (H')	0.469	0.651	0.691	0.529	0.21	0.878	0.581	0.00	0.681	0.028	0.036	0.007	0.00

Species less than 5 % in maximum value of relative basal area are omitted.

gillosa, etc. *Rosa sericea*, *Selinum* sp., *Lonicera myrtillus*, etc. were common to Types A–D.

Type E (plot no. 13): dominated by *Themeda anathera, Pinus roxburghii*, etc., and shared few species with the other types.

The NMDS ordination results are shown in Fig. 2. Types A and E were positioned at opposite ends along the axis NMDS1, while Types B, C, and D occupied intermediate positions. Both environmental variables, *ELV* (p = 0.006) and *EAST* (p = 0.020), were significant. Types C, B, and A were arranged along the vector *ELV*. The vector *EAST* was parallel to the axis NMDS1.

Geographical distribution of community types is shown in Fig. 3. Type A occurred in the Jumla-south mountain area. Type B occurred mainly in the Jumla-south mountain area, but also in parts of the Dunai-south mountain and Phoksundo areas. Types C–E occurred in the Dunai-south mountain and Phoksundo areas.

Forest dominant types and size structures of canopy species

Dominant canopy species, stratification, maximum DBH, and total basal area are shown in Table 3, and the relative basal areas of tree species in each plot are shown in Table 4. Six dominance types (Type a–f) were recognized by the cluster analysis using relative basal area (Fig. 4). Type a was dominated by *Abies spectabilis* and *Betula utilis*; Type b by *Picea smithiana*, *Quercus semecarpifolia,* and *Cupressus torulosa*; Type c by *Pinus wallichi-*

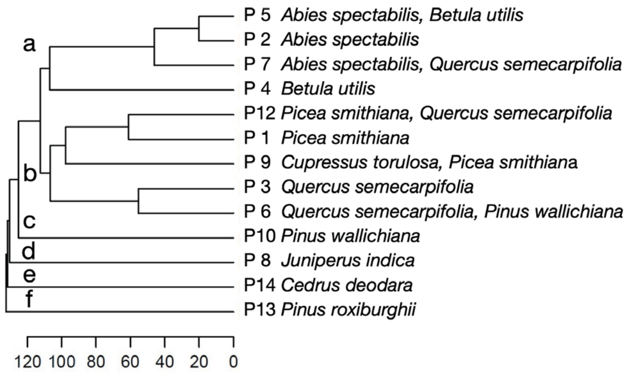

Fig. 4. Dominance type classification of the plots by cluster analysis using the relative basal area of each tree species. Euclidean distances among plots were calculated by the group average method. Dominant species are shown for each plot.

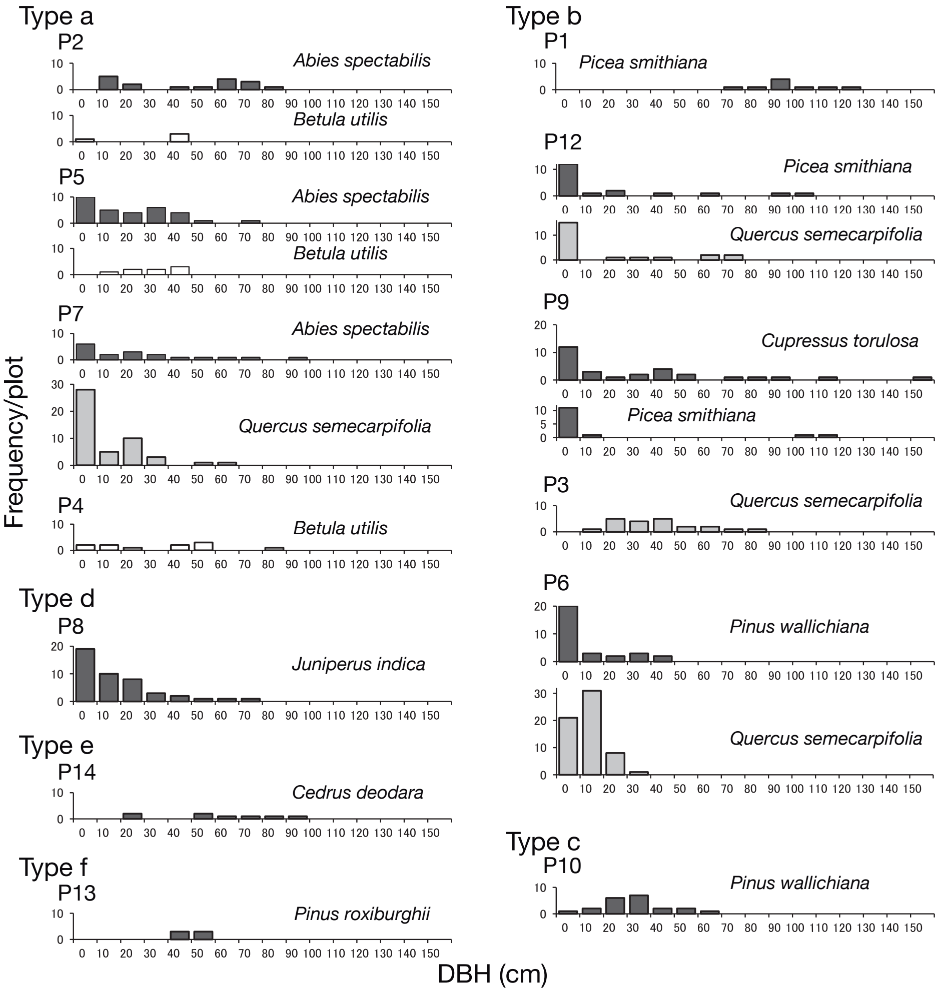

Fig. 5. DBH frequency distribution of major canopy species. Solid bar: evergreen conifer, grey bar: evergreen broadleaved tree, open bar: deciduous broadleaved tree.

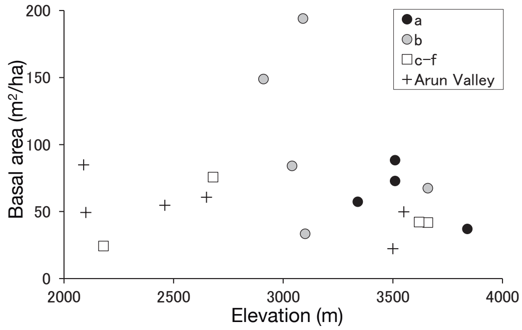

Fig. 6. Elevational variation in total basal areas. Circle or square: Jumla-Dolpa region, western Nepal (present study); cross: Arun Valley, eastern Nepal (Sugita et al. 1994).

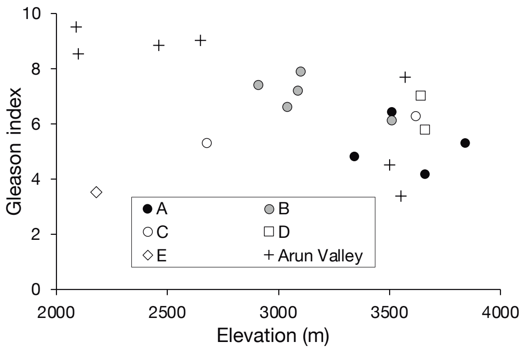

Fig. 7. Elevational variation in Gleason's index. Circle or square: Jumla-Dolpa region, western Nepal (present study); cross: Arun Valley, eastern Nepal (Sugita et al. 1994).

ana; Type *d* by *Juniperus indica*; Type e by *Cedrus deodara*; Type f by *Pinus roxburghii*. Type a corresponded closely to community Type A, Type b to Type B, Types c–f to Types C–E (Table 3). Types c–f were almost composed of only one canopy species (Table 4).

The DBH frequency distributions of major canopy species are shown in Fig. 5. Maximum DBH reached 151 cm for *Cupressus torulosa*, 125 cm for *Picea smithiana*, 97 cm for *Abies spectabilis*, 95 cm for *Cedrus deodara*, 85 cm for *Betula utilis*, 83 cm for *Quercus semecarpifolia*, 75 cm for *Juniperus indica*, 61 cm for *Pinus wallichiana*, 57 cm for *Pinus roxburghii*. *Cedrus deodara*, *Pinus roxburghii*, and *Betula utilis* showed unimodal distributions with few slender stems (< 10 cm DBH). In contrast, *Cupressus torulosa*, *Abies spectabilis*, and *Juniperus indica* showed bimodal, trimodal, or inverse-J distributions with abundant slender stems. *Picea smithiana*, *Quercus semecarpifolia*, and *Pinus wallichiana* exhibited both distribution types depending on the plots.

The elevational variation in total basal area is shown in Fig. 6. It showed maximum values at ca. 3000 m, reflecting huge DBH of *Cupressus torulosa* and *Picea smithiana*. Types a–b often had higher basal areas than Types c–f and exceeded values reported from Arun Valley, eastern Nepal (Sugita et al. 1994), but the differenes were not statistically significant (p = 0.190, p = 0.512, respectively, Mann-Whitney test).

Species richness and tree species diversity

The elevational variation in Gleason index representing species richness including herbaceous species is shown in Fig. 7. The index showed maximum species richness at ca. 3000 m. Differences between Types A–B and Types C–E were not significant (p = 0.39, Mann-Whitney U-test). Gleason index values were comparable to those reported from the Arun Valley, eastern Nepal (Sugita et al. 1994) above 2700 m asl, although, below that elevation, the values for P13 and P14 were lower.

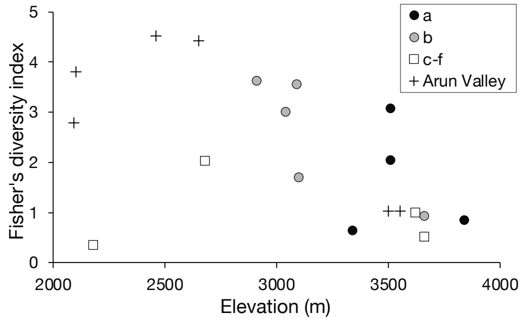

Fig. 8. Elevational variation in Fisher's diversity index. Circle or square: Jumla-Dolpa region, western Nepal (present study); cross: Arun Valley, eastern Nepal (Sugita et al. 1994).

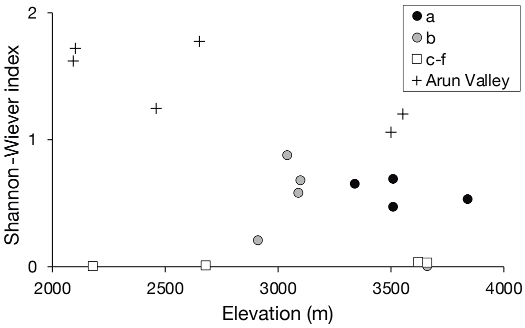

Fig. 9. Elevational variation in Shannon-Wiever's diversity indices. Circle or square: Jumla-Dolpa region, western Nepal (present study); cross: Arun Valley, eastern Nepal (Sugita et al. 1994).

The elevational variations in indices representing diversity of trees taller than 1.3 m are shown in Figs. 8 and 9. Above 2700 m asl, Fisher's index represented a negative correlation with elevation (r = -0.663, p = 0.028, Spearman's rank correlation) and indicated comparable values to the Arun Valley (Sugita et al. 1994), although below that elevation the value for P13 was lower. In contrast, the Shannon-Wiever index showed no correlation with elevation and was significantly lower than those from the Arun Valley (p = 0.0007, Mann-Whitney test). The Fisher's index for Types c–f did not differ significantly from Types a–b (p = 0.11), whereas the Shannon-Wiever index was significantly lower for Types c–f than for Types a–b (p = 0.025, Mann-Whitney test).

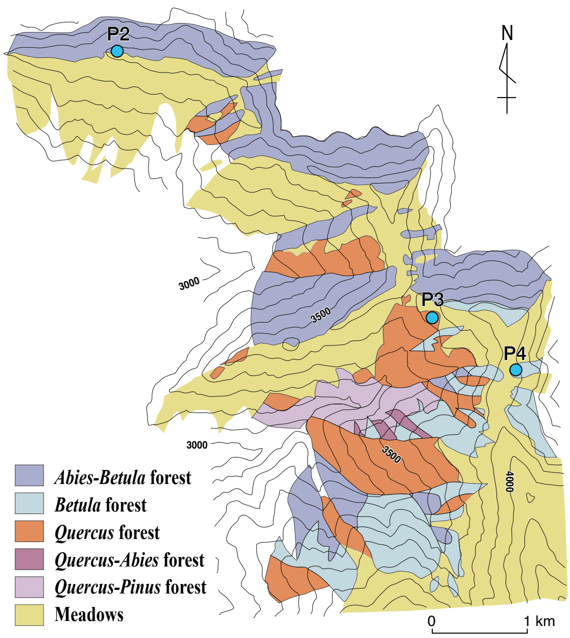

Fig. 10. Vegetation map of a part of subalpine zone in the Jumla-south mountain area. *Abies: A. spectabilis, Betula: B. utilis, Quercus: Q. semecarpifolia, Pinus: P. wallichiana.*

Spatial patterns of vegetation types across slope aspects

The vegetation map of a part of the Jumla-south mountain area, the distributions of vegetation types across elevation and slope aspect,

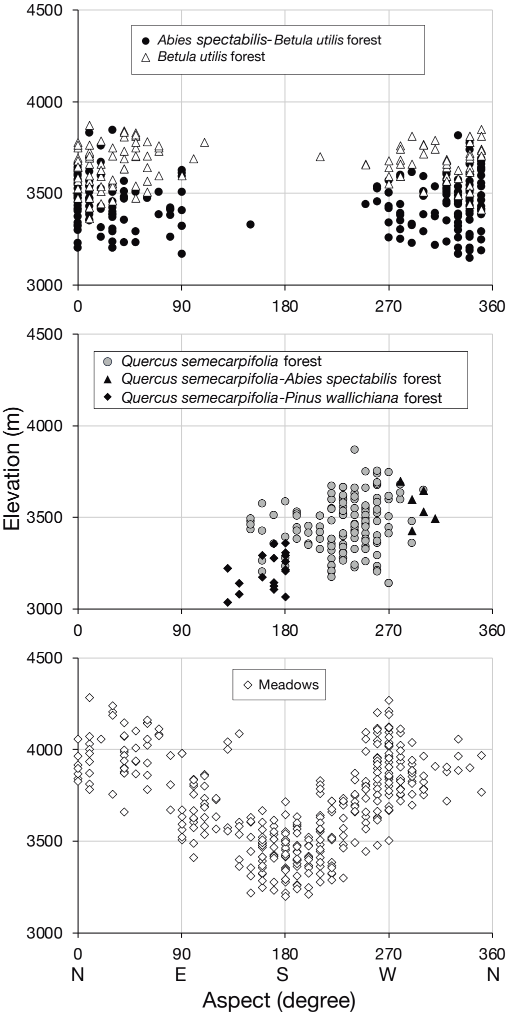

Fig. 11. Distribution of vegetation types across elevation and aspect.

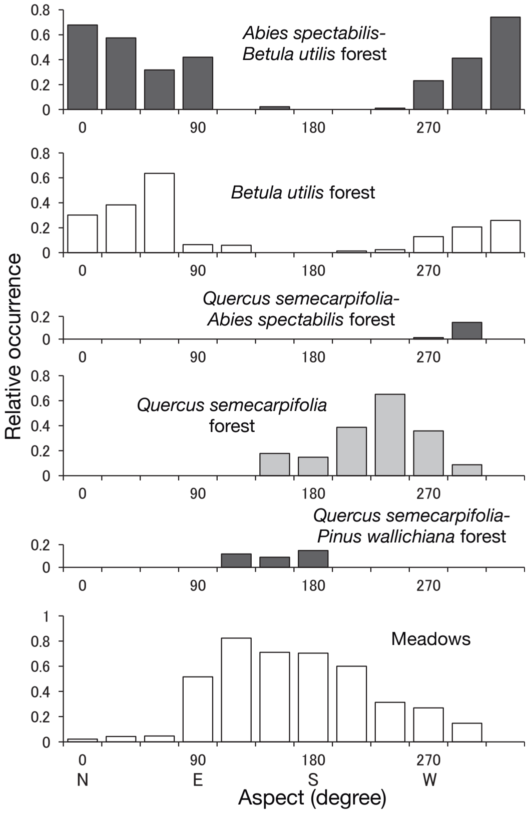

Fig. 12. Relative occurrences of vegetation types for slope aspect within the elevational range of 3000–3800 m.

and the relative frequencies of vegetation types for each slope aspect are shown in Figs. 10–12. Six vegetation types were recognized. *Abies spectabilis-Betula utilis* forest and *B. utilis* forest occurred mainly on north-facing slopes and were scarcely found on south-facing slopes, with the latter forest type occurring at higher elevations than the former. In contrast, *Quercus semecarpifolia* forest occurred on south- to west-facing slopes and was rarely found on north-facing slopes. *Quercus semecarpifolia-Pinus wallichiana* forest occurred on south- to east-facing slopes, and *Q. semecarpifolia-A. spectabilis* forest occurred on west- or northwest-facing slopes. Meadows dominated by *Iris* sp., *Selinum tenuifolium*, *Dipsacus inermis*, *Potentilla griffithii*, *Artemisia* sp., etc. occurred mainly on south-facing slopes and were scarcely found on north-facing slopes below 3800 m asl. The forest limit was at 3800 m, above which only meadows occurred, appearing broadly regardless of slope aspect (although no south-facing slopes existed within this elevational range).

Discussion

Comparison of vegetation between eastern and western Nepal

The South Asian summer monsoon, blowing northwestward from the Bay of Bengal, encounters the Himalayas in eastern Nepal, where moist air is forced upward along their southern slopes, resulting in heavy rainfall. After releasing much of its moisture in eastern Nepal, the monsoon air mass becomes progressively drier as it moves westward, resulting in less rainfall in western Nepal (Nayava 1980; Kansakar et al. 2004). The annual precipitation in the surveyed region (less than 1000 mm) is far lower than that in eastern Nepal (e.g., 2500–3500 mm at Num, Arun Valley, 1730 m asl).

Five forest zones with principal tree species are recognized in eastern Nepal (Ohsawa 1983; Ohsawa et al. 1986; Carpenter and Zomer 1996): subtropical zone (–1000 m, *Shorea robusta*), warm temperate zone (1000–2000 m, *Schima wallichii, Castanopsis tribuloides*), temperate zone (2000–2500 m, *Quercus lamellosa, Q. lineata*, etc.), cool temperate zone (2500–3000 m, *Acer campbellii, Magnolia campbellii*), and subalpine zone (3000–3800 m, *Abies spectabilis*, *Betula utilis*). Among the principal species of the forest zones in eastern Nepal, only subalpine *Abies spectabilis* and *Betula utilis* were commonly found and characterized forest zones in the Jumla-Dolpa region. Instead, species rare or absent in eastern Nepal, such as *Quercus semecarpifolia*, *Pinus wallichiana*, *Picea smithiana*, *Cedrus deodara*, *Cupressus torulosa*, *Juniperus indica*, *Pinus roxburghii*, etc., commonly grew in this region (Table 4, Fig. 5), indicating principal species differences between eastern and western Nepal.

Ohsawa et al. (1986) pointed out that *Pinus roxburghii*, *P. wallichiana*, and *Quercus semecarpifolia* occur as relict patches on locally dry habitats such as south-facing convex slopes or as pioneer species in disturbed sites in the eastern Himalayas, whereas they appear as climax species in the western Himalayas. Regeneration traits of tree species are reflected in DBH frequency distributions, in which unimodal patterns indicate cohort regeneration following large-scale disturbances, while inverse-J patterns indicate continuous regeneration under small-scale disturbances (Oliver & Larson 1996). An inverse-J DBH distribution has been reported for *Pinus wallichiana* from a trans-Himalayan dry valley in north-central Nepal (Ghimire et al. 2010). In our results (Fig. 5), *Pinus wallichiana*, together with *Quercus semecarpifolia*, showed both unimodal and inverse-J distributions, suggesting that the species can adopt either regeneration mode depending on environmental conditions and disturbance regimes. *Cupressus torulosa* and *Juniperus indica* also exhibited inverse-J distributions, indicating their potential to regenerate continuously as late successional species, although species such as *Pinus roxburghii* and *Cedrus deodara* showed unimodal patterns reflecting pioneer-type regeneration traits. These various size structures support Ohsawa's assertion that the dry-wet climatic gradient across the Himalayas induces shifts in successional status.

Although some studies reported an increase in basal area with an increase of precipitation (Khaine et al. 2017), the total basal areas in the Jumla-Dolpa region showed not significant differences from those in Arun Valley, eastern Nepal (Fig. 6), indicating equivalent or even higher values despite the dry climate.

Variation in vegetation within the Jumla-Dolpa region along wet-dry gradient

After releasing much of its moisture on the windward side of the Himalaya, the air descends on the northwestern and trans-Himalayan sides. Descending air warms adiabatically, reducing relative humidity and suppressing cloud formation. This creates a deep rain-shadow zone, especially pronounced in western and northwestern Nepal, where the Himalayas block moist monsoon air masses. The Dolpa region located to the northwest of the Dhaulagiri Himal is one of the driest regions of Nepal due to this rain-shadow effect. In our survey region, Jumla is relatively humid (annual precipitation: 803 mm), southern Dolpa around Dunai is drier (less than 500 mm), and northern Dolpa around Phoksundo Lake is even drier (300–400 mm). Such a clear wet-dry gradient likely influences vegetation in the region.

In the NMDS diagram, vector *EAST* was parallel to axis NMDS1 (Fig. 2), suggesting that the west-east position probably reflecting climatic dryness is the principal factor determining vegetation. Type A (or a) dominated by *Abies spectabilis* or *Betula utilis* and Type B (or b) dominated by *Picea smithiana* or *Quercus semecarpifolia* occurred in the relatively wet western part of the region, with Type A at higher elevations than Type B. Meanwhile, Types C–E (or c–f) dominated by *Pinus wallichiana*, *Juniperus indica*, *Cedrus deodara*, or *Pinus roxburghii* occurred in the drier western part (Fig. 3). In the driest Phoksundo area, forests were fragmented, and scrubs dominated by *Caragana gerardiana*, etc. (P11) were widely observed. Further analyses of climate-vegetation relationships will require additional vegetation surveys and meteorological data.

Species richness and diversity along wet-dry and elevational gradient

Many studies have mentioned that climate variables, mainly precipitation and temperature, and their interactions are the main driver determining plant species richness (Hawkins et al. 2003), and that precipitation seasonality, especially, is the foremost predictor of species richnes (Cheng et al. 2026). Higher species richness and diversity have been reported in wetter regions than in drier regions (Kushwaha & Nandy 2012; Khaine et al. 2017). Species richness of the Himalayas declines remarkably from the east to the northwest (Rana et al. 2019). However, the relationship between species richness and precipitation is often ambiguous, and even opposite patterns have been reported in the dry regions of north-central Nepal (Bhatta et al. 2021). In our results, both Gleason's and Fisher's indices showed no remarkable differences between the Jumla-Dolpa region and the Arun Valley (Figs. 7, 8), indicating comparable species richness despite contrasting moisture conditions. Meanwhile, the Shannon-Wiever index was lower in the Jumla-Dolpa region than in the Arun Valley (Fig. 9), suggesting reduced diversity caused by lower evenness among the canopy species under the influences of dry climate.

Comparable trends were also observed along the wet-dry gradient within the Jumla-Dolpa region. Types c–f that occur in the drier areas were almost composed of a single species (Table 4), and their Shannon-Weaver indices were significantly lower than those of Types a–b (Fig. 9). This suggests that dry climate strongly reduces the diversity of canopy species. Meanwhile, Fisher's diversity and the Gleason indices showed similar values between the two groups (Figs. 7, 8). The Shannon-Weaver index reflects the diversity of large canopy trees, because it is calculated based on basal areas, whereas Fisher's index calculated using the number of individuals reflects the diversity of small-diameter trees in the understory. These results suggest that the effects of the dry climate on species diversity and species richness act more strongly on canopy trees than on herbaceous and woody plants in the understory.

Patterns of species richness along the elevational gradient have been examined in many mountainous regions, and various patterns such as monotonic, unimodal, and multimodal patterns have been demonstrated. A monotonous decline pattern is not usual, but a unimodal hump-shaped pattern (maximum diversity at middle elevation) is most commonly observed (Rahbek 1995; Dani et al. 2023). The elevations of peak diversity for vascular plants are reported variously, depending on the geographical ranges of the Himalayas, 650–2950 m in Sikkim (Sharma et al. 2019), 1400–1500 m in eastern Nepal (Carpenter 2005), around 2500 m (Subedi et al. 2020) or around 3500 m (Bhattarai et al. 2014) in western Nepal, and around 2800 m in the Indian western Himalayas (Rawat et al. 2021), and seem higher in the western Himalayas than in the eastern Himalayas. In our results, the elevation of peak diversity was ca. 3000 m (Fig. 7), equivalent to those reported in the western Himalayas. Grazing pressure and other anthropogenic disturbances are likely to reduce species richness, particularly at lower elevations than the peak diversity elevation (Ghimire et al. 2010; Bhatta et al. 2021).

Vegetation patterns in relation to slope aspects

The vegetation map of the subalpine zone in the Jumla-south mountain area (Fig. 10) showed strikingly contrasting spatial pattern between north- and south-facing slopes: *Abies spectabilis* and *Betula utilis* forest dominated on north-facing slopes and *Quercus semecarpifplia* forest and meadows dominated on south-facing slopes (Figs. 11, 12). Such aspect-related vegetation patterns are widely reported, especially in mid-latitude regions (Singh 2018). In the Himalayas, many studies have documented vegetation differences between contrasting aspects. In eastern Nepal, *Pinus roxburghii*, *P. wallichiana*, and *Quercus semecarpifolia* occur sporadically in small stands exclusively on south-facing convex slopes or ridges (Ohsawa et al. 1986; Zomer et al. 2001). In the alpine zone, south-facing slopes are covered by *Kobresia* grassland, whereas north-facing slopes are covered by dwarf scrubs of *Rhododendron, Salix*, etc. (Kikuchi & Ohba 1988; Carpenter & Zomer 1996; Kikuchi et al. 1999). Aspect-related patterns in vegetation are, however, less distinct in the eastern part of the Himalayas and are very pronounced in Karnali Province of western Nepal: *Quercus semecarpifolia* and *Pinus wallichiana* on sunny, south-facing slopes, and *Abies spectabilis* on wetter north-facing slopes (Stainton 1972; Acharya & Paudel 2020). In Manang Valley, a rain-shadow region north of the Annapurna range with less than 400 mm of annual precipitation, *Pinus wallichiana* dominates on both aspects, followed by *Juniperus indica* on south-facing slopes, whereas *Abies spectabilis* and *Betula utilis* occur only in small numbers on north-facing slopes (Panthi et al. 2007; Ghimire et al. 2010; Paudel & Vetaas 2014; Måren et al. 2015). In Himachal Pradesh, northern India, located further west in the northwestern Himalayas, drought-adapted species, such as *Acacia catechu, Bauhinia variegata,* and *Bombax ceiba,* dominate on south-facing slopes, and moisture-adapted species, such as *Cedrus deodara* and *Quercus leucotrichophora,* on north-facing slopes, and *Pinus roxburghii* on both slope aspects (Bhardwaj et al. 2021). Among these cases, the aspect-related differences in the Jumla-south mountain area are outstandingly distinctive, although the climate of this area is relatively moderate. Måren et al. (2015) noted that extremely arid climates tend to reduce aspect-related differences compared with moderately moist climates.

In the northern hemisphere, south-facing slopes receive more direct sunlight and less snowmelt water than north-facing slopes. High evapotranspiration on south-facing slopes reduces soil moisture (Sharma et al. 2010), causing drought stress during the growing season. As a result, drought-tolerant species dominate on south-facing slopes, whereas moisture-demanding species dominate on north-facing slopes. Because south-facing slopes are warmer, have drier soils that make burning easier, and are thus more suitable for pastures, they may have been more strongly affected by historical anthropogenic activities such as grazing and burning (Aase et al. 2010; Paudel & Vetaas 2014). The fact that meadows extend down to 3000 m on south-facing slopes, although *Abies* and *Betula* forests extend up to 3800 m on north-facing slopes and *Quercus* forest also up to 3800 m on south-facing slopes (Fig. 11) suggests that the grazing pressure has lowered the forest limit below the climatic limit on south-facing slopes.

Acknowledgements

The authors are greatly indebted to the staff of the Department of Forestry and Plant Research and the National Council of Science and Technology, H.M.G. Nepal, for their support in conducting the field survey. We thank the late Dr. Mutsuhiko Minaki, the leader of the research team, for his leadership in the expedition, and other team members, Drs. Hiroshi Yagi, Yuichi Kadota, Akira Takahashi, and K. K. Joshi, for co-operation during the expedition. We are also grateful to Drs. Hideaki Ohba, Mitsuo Suzuki, and the late Takao Kikuchi for their valuable suggestions, Dr. Shuichi Noshiro for valuable comments on the draft of this manuscript, and Drs, Keshab R. Rajbhandari, the late Takashi Yamazaki, Kouji Yonekura, Makoto Amano, Naohiro Naruhashi, Yu Iokawa, Nobuko Yamamoto, Hidehisa Koba, Chika Mouri, Hirokazu Tsukaya, Nobuhira Kurosaki, Takahide Kurosawa, Shinobu Akiyama, Futoshi Miyamoto, Michio Wakabayashi, Naoko Fushimi, and the Society of Himalayan Botany, Tokyo, for their plant specimen identification, Dawa Thundup Sherpa, Pemba Sherpa, Nima Gyalzen Sherpa, Antare Tamang, Zitbahadur Tamang, and Bagbir Tamang, for their supports during the field works. This study was supported in part by a Grant-in-Aid for Scientific Research (Overseas Scientific Survey) from the Ministry of Education, Science and Culture, Japan (Project No. 02041088).

References

Aase, T. H., Chaudhary, R. P. & Vetaas, O. R. 2010. Farming flexibility and food security under climatic uncertainty: Manang, Nepal Himalaya. *Area* **42**: 228–238.

Acharya, K. P. & Paudel, P. K. 2020. *Biodiversity in Karnali Province: Current status and conservation*. Ministry of Industry, Tourism, Forest and Environment, Karnali Province Government, Surkhet, Nepal. 177 pp.

Barnekow Lillesø, J.-P., Shrestha, T. B., Dhakal, L. P., Nayaju, R. P. & Shrestha, R. 2005. *The Map of Potential Vegetation of Nepal: A forestry/agro-ecological/biodiversity classification system*. Center for Skov, Landskab og Planlægning/Københavns Universitet. Development and Environment No. 2/2005.

Bhardwaj, D. R., Tahiry, H., Sharma, P., Pala, N. A., Kumar, D. & Kumar, A. 2021. Influence of aspect and elevational gradient on vegetation pattern, tree characteristics and ecosystem carbon density in Northwestern Himalayas. *Land* **10**(11): 1109.

Bhatta, K. P., Aryal, A., Baral, H., Khanal, S., Acharya, A. K., Phomphakdy, C. & Dorji, R. 2021. Forest structure and composition under contrasting precipitation regimes in the high mountains, western Nepal. *Sustainability* **13**: 7510.

Bhattarai, P., Bhatta, K. P., Chhetri, R. & Chaudhary, R. P. 2014. Vascular plant species richness along elevation gradient of the Karnali River valley, Nepal Himalaya. *International Journal of Plant, Animal and Environmental Sciences* **4**: 114–126.

Carpenter, C. 2005. The environmental control of plant species density on a Himalayan elevation gradient. *Journal of Biogeography* **32**: 999–1018.

Carpenter, C. & Zomer, R. 1996. Forest ecology of the Makalu-Barun National Park and conservation area, Nepal. *Mountain Research and Development* **16**: 135–148.

Cheng, C., Zhou, G., Tang, X., Wang, S., Su, Y., Wu, J., Xu, X., Xu, W., Lin, F., Zhou, Y., Wang, G., Yan, J., Ma, K., Du,S., Li, S., Han, S., Ma, Y., Liu,J. & Wu, D. 2026. Spatial patterns and future potential of tree species richness and structural diversity in China's forests. *Nature Ecology & Evolution* **10**: 70–82.

Dani, R. S., Divakar, P. K. & Baniya, C. B. 2023. Diversity and composition of plants species along elevational gradient: Research trends. *Biodiversity and Conservation* **32**: 2961–2980.

DHM. 2024. *Nepal Climate Summary 2023.* https://dhm.gov.np/uploads/dhm/climateService/Annual_Summary_20232.pdf

DNPWC. 2007. *The Management Plan of Shey-Phoksundo National Park (SPNP) and its Buffer Zone*. Department of National Parks and Wildlife Conservation, Kathmandu.

Ghimire, B., Mainali, K. P., Lekhak, H. D., Chaudhary, R. P. & Ghimeray, A. K. 2010. Regeneration of *Pinus wallichiana* AB Jackson in a trans-Himalayan dry valley of north-central Nepal. *Himalayan Journal of Sciences* **6**: 19–26.

Ghimire, S. K., Mckey, D. & Aumeeruddy-Thomas, Y. 2006. Himalayan medicinal plant diversity in an ecologically complex high altitude anthropogenic landscape, Dolpo, Nepal. *Environmental Conservation* **33**: 128–140.

Hawkins, B. A., Field, R., Cornell, H. V., Currie, D. J., Guégan, J.-F., Kaufman, D. M., Kerr, J. T., Mittelbach, G. G., Oberdorff, T., O'Brien, E. M., Porter, E. E. & Turner, J. R. G. 2003. Energy, water, and broad-scale geographic patterns of species richness. *Ecology* **84:** 3105–3117.

Hill, M. O. 1979. TWINSPAN—A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of the individuals and attributes. Cornell University, Ithaca, New York.

ICIMOD. 2010. *Land Use Map of Nepal, 2010*. Kathmandu, Nepal.

Kansakar, S. R., Hannah, D. M., Gerrard, J., & Rees, G. 2004. Spatial pattern in the precipitation regime of Nepal. *International Journal of Climatology* **24**: 1645–1659.

Khaine, I., Woo, S. Y., Kang, H., Kwak, M., Je, S. M., You, H., Lee, T., Jang, J., Lee, H., Lee, E., Yang, L., Kim, H., Lee, J. & Kim, J. 2017. Species diversity, stand structure, and species distribution across a precipitation gradient in tropical forests in Myanmar. *Forests* **8**(8): 282.

Khatiwada, K. R., Panthi, J., Shrestha, M. L. & Nepal, S. 2016. Hydro-climatic variability in the Karnali River basin of Nepal Himalaya. *Climate* **4**(2): 17.

Kikuchi, T. & Ohba, H. 1988. Preliminary study of alpine vegetation of the Himalayas, with special reference to small scale distribution patterns of plant communities. *In*: H. Ohba & S. B. Malla, eds., *The Himalayan Plants*, vol. 1, 47–70. University of Tokyo Press, Tokyo.

Kikuchi, T., Subedi, M. N. & Ohba, H. 1999. Alpine vegetation and its pattern on Jaljale Himal, eastern Nepal. *In*: H. Ohba, ed., *The Himalayan Plants*, vol. 3, pp. 1–21. University of Tokyo Press, Tokyo.

Kushwaha, S. P. S. & Nandy, S. 2012. Species diversity and community structure in sal (*Shorea robusta*) forests of two different rainfall regimes in West Bengal, India. *Biodiversity and Conservation* **21**: 1215–1228.

Måren, I. E., Karki, S., Prajapati, C., Yadav, R. K. & Shrestha, B. B. 2015. Facing north or south: Does slope aspect impact forest stand characteristics and soil properties in a semiarid trans-Himalayan valley? *Journal of Arid Environments* **121**: 112–123.

Minaki, M. 1992. Botanical survey in Jumla-Dolpa district in west Nepal. *Newsletter of Himalayan Botany* No. 11: 1–5.

Nayava, J. L. 1980. Rainfall in Nepal. *Himalayan Review* **12:** 1–18.

Ohsawa, M. 1983. Distribution, structure and regeneration of forest communities in eastern Nepal. *In:* M. Numata, ed., *Structure and Dynamics of Vegetation in Eastern Nepal*, 89–120. Chiba University, Chiba.

Ohsawa, M., Shakya, P. R. & Numata, M. 1986. Distribution and succession of west Himalayan forest types in the eastern part of the Nepal Himalaya. *Mountain Research and Development* **6**: 143–157.

Oliver, C. D. & Larson, B. C. 1996. *Forest Stand Dynamics* (update edition). John Wiley, New York.

Panthi, M. P., Chaudhary, R. P. & Vetaas, O. R. 2007. Plant species richness and composition in a trans-Himalayan inner valley of Manang district, central Nepal. *Himalayan Journal of Sciences* **4**: 57–64.

Paudel, S. & Vetaas, O. R. 2014. Effects of topography and land use on woody plant species composition and beta diversity in an arid Trans-Himalayan landscape, Nepal. *Journal of Mountain Science* **11**: 1112–1122.

R Core Team. 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rahbek, C. 1995. The elevational gradient of species richness: a uniform pattern? *Ecography* **18**: 200–205.

Rana, S. K., Price, T. D. & Qian, H. 2019. Plant species richness across the Himalaya driven by evolutionary history and current climate. *Ecosphere* **10**(11), e02945.

Rawat, B., Gaira, K. S., Gairola, S., Tewari, L. M.& Rawal, R. S. 2021. Spatial prediction of plant species richness and density in high-altitude forests of Indian west Himalaya. *Trees, Forests and People* **6**, 100132.

Sharma, C. M., Baduni, N. P. , Gairola, S., Ghildiyal, S. K. & Suyal, S. 2010. The effect of slope aspects on the forest composition, community structure and soil nutrient status of some major natural temperate forest types of Garhwal Himalayan. *Journal of Forestry Research* **21**: 331–337.

Sharma, N., Behera, M. D., Das, A. P. & Panda, R. M. 2019. Plant richness pattern in an elevation gradient in the eastern Himalaya. *Biodiversity and Conservation* **28**: 2085–2104.

Sharma, S., Khadka, N., Hamal, K., Baniya, B., Luintel, N. & Joshi, B. B. 2020. Spatial and temporal analysis of precipitation and its extremities in seven provinces of Nepal (2001–2016). *Applied Ecology and Environmental Sciences* **8**: 64–73.

Sharma, S., Khadka, N., Nepal, B., Ghimire, S. K., Luintel, N. & Hamal, K. 2021. Elevation dependency of precipitation over southern slope of central Himalaya. *JALAWAAYU* **1**: 1–14.

Shrestha, M. R., Rokaya, M. B., & Ghimire, S. K. 2005. Vegetation pattern of trans-Himalayan zone in the North-West Nepal. *Nepal Journal of Plant Sciences* **1:** 129–135.

Shrestha, T. B. 1982. *Ecology and Vegetation of North-west Nepal (Karnali Region)*. Royal Nepal Academy, Kathmandu, Nepal. pp 121.

Singh, S. 2018. Understanding the role of slope aspect in shaping the vegetation attributes and soil properties in Montane ecosystems. *Tropical Ecology* **59**: 417–430.

Stainton, J. 1972. *Forest of Nepal*. John Murray and Co, London.

Subedi, C. K., Rokaya, M. B., Münzbergová, Z., Timsina, B., Gurung, J., Chettri, N., Baniya, C. B., Ghimire, S. K. & Chaudhary, R. P. 2020. Vascular plant diversity along an elevational gradient in the Central Himalayas, western Nepal. *Folia Geobotanica* **55**: 127–140.

Sugita, H., Subedi, M. N., Yonebayashi, C., Takayama, H. & Minaki, M. 1994. Floristic composition and structures of forests in the Arun Valley, eastern Nepal. *Ecological Review* **23**: 17–42.

Zomer, R. J., Carpenter, C., Ustin, S. L. & Ives, J. D. 2001. Structure, composition and community ordination of tropical monsoon forest within the Makalu Barun Conservation Area of eastern Nepal. *Phytocoenologia* **31**: 161–184.