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CONTENTS

Surendra P. Singh – Research on Indian Himalayan Treeline Ecotone: an overview 163

Avantika Latwal, Priyanka Sah & Subrat Sharma – A cartographic representation of a timberline, treeline and woody vegetation around a Central Himalayan summit using remote sensing method 177

Priyanka Sah & Subrat Sharma – Topographical characterisation of high altitude timberline in the Indian Central Himalayan region 187

Rajesh Joshi, Kumar Sambhav & Surender Pratap Singh – Near surface temperature lapse rate for treeline environment in western Himalaya and possible impacts on ecotone vegetation 197

Subzar Ahmad Nanda, Zafar A. Reshi, Manzoor-Ul-Haq, Bilal Ahmad Lone & Shakoor Ahmad Mir – Taxonomic and functional plant diversity patterns along an elevational gradient through treeline ecotone in Kashmir 211

Ranbeer S. Rawal, Renu Rawal, Balwant Rawat, Vikram S. Negi & Ravi Pathak – Plant species diversity and rarity patterns along altitude range covering treeline ecotone in Uttarakhand: conservation implications 225

P. K. Dutta & R. C. Sundriyal – The easternmost timberline of the Indian Himalayan region: A socio-ecological assessment 241

Aseesh Pandey, Sandhya Rai & Devendra Kumar – Changes in vegetation attributes along an elevation gradient towards timberline in Khangchendzonga National Park, Sikkim 259

Achyut Tiwari, Pramod Kumar Jha – An overview of treeline response to environmental changes in Nepal Himalaya 273

Pradeep Singh, Vijay Arya, G. C. S. Negi & S. P. Singh – Expansion of *Rhododendron campanulatum* krummholz in the treeline ecotone in Tungnath, Garhwal Himalaya 287

Pradeep Singh & G. C. S. Negi – Treeline species phenology: shoot growth, leaf characteristics and *nutrient* dynamics 297

Ashish Tewari, Shruti Shah, Nandan Singh & Amit Mittal – Treeline species in Western Himalaya are not water stressed: a comparison with low elevation species 313

Ripu Daman Singh, Pankaj Tewari, Pratap Dhaila & Krishna Kumar Tamta – Diversifying livelihood options of timberline resource dependent communities in Uttarakhand Himalayas: Conservation and development implications 327

Ipsita Roy, Parminder S. Ranhotra, Mayank Shekhar, A. Bhattacharyya, Ashish K. Pal, Y. K. Sharma, S. P. Singh & Utsa Singh – Over-representation of some taxa in surface pollen analysis misleads the interpretation of fossil pollen spectra in terms of extant vegetation 339

Utsa Singh, Mohit Phulara, Bency David, Parminder S. Ranhotra, Mayank Shekhar, A. Bhattacharyya, Rupesh Dhyani, Rajesh Joshi & Ashish K. Pal – Static tree line of Himalayan silver fir since last several decades at Tungnath, western Himalaya 351

Bhupendra S. Adhikari, Rahul Kumar & Surendra P. Singh – Early snowmelt impact on herb species composition, diversity and phenology in a western Himalayan treeline ecotone 365

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Research on Indian Himalayan Treeline Ecotone: an overview

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Abstract: In spite of being the highest in the Northern Hemisphere (up to 4900 m), treelines in Himalayas are among the least investigated systems. This paper (i) sheds light on treeline distribution along Himalayan Arc; (ii) discusses factors affecting treeline elevation in a warming world; (iii) reports initial findings of a multi-site and multi-partner research project on Himalayan treelines; and (iv) analyses future research needs. The Himalayan treeline elevation increases from the north-west to south-east along the Arc, and is higher on south aspect than north aspect and in inner ranges than outer ranges. Apart from heat deficiency, several factors such as mass elevation effect and height of the nearest mountains and changes in grazing pressure influence treeline elevation in Himalayas. The principal treeline ecotone genera are *Betula*, *Abies*, *Rhododendron* and *Juniperus*. The treeline maps developed with remote sensing techniques at a regional level show that the elevations of the nearest mountain summit influence treeline elevations to an extent. Temperature Lapse Rate (~0.53 °C/100 m) estimated from observed data, is found lower than generally used in literature, and differs seasonally and across aspects. Our tree water relation study suggests that water is not a limiting factor in treeline ecotone, however, data on tree ring width chronology emphasize the significance of pre-monsoon drought in treeline dynamics. Tree species richness increases from west to east, but the same way not apply to other growth forms. *Rhododendron campanulatum* seems to move up rapidly, and thus, has potential to influence the ecology of alpine meadows. Treeline and livelihood issues need to be managed to conserve treeline ecotones. Long term treeline studies are required to make generalizations in the context of climate change.

Key words: Birch (*Betula utilis*), climate change, *Rhododendron campanulatum*, treeline ecotone and elevation, tree growth forms, tree water relation.

Introduction

Beyond a certain elevation in high mountains, trees fail to grow largely because of heat deficiency, resulting in a "physiognomic discontinuum", characterized by the separation of forests from treeless alpine meadows. Called as alpine treeline, this conspicuous margin between tree-covered and tree-less areas represents an ecotone of vast bio-geographic importance with a wide ecological, climatic and socio-economic relevance (Collaghan *et al.* 2002). This transition zone between the biomes of two distinct physiognomies (forests and alpine grasslands) is rich in endemic species (Dhar 2000), and sensitive to climate change. Often occurring around summits, treelines are part of the mountain habitats where accelerated increase in plant species richness is taking place in a warming world (Steinbauer *et al.* 2018).

As for elevational position of treeline, it is largely controlled by heat deficiency but several local factors both ecological and social influence its position (Körner 2012). Climate warming, by promoting tree growth and increasing tree cover and treeline elevations may affect snow cover, and resultant albedo, and ecosystem carbon storage (Wielgolaski *et al.* 2017).

Somehow, the term treeline has remained

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missing in forest literature of the Himalayas, until recently (Singh & Rawal 2017). One of the reasons for the lack of studies on treeline could be its remoteness; the Himalayan treelines are often above 4000 m elevation, compared to as low as 500–800 m around 50° N latitude (Körner 2007). However, the lack of appreciation of its significance is also apparent.

It is the rapid warming in Himalayas (Ren & Shrestha 2017; Shrestha *et al.* 1999), which drew attention of researchers and general public (Yao *et al.* 2012) to high mountain ranges, however, much of that has been on the status of glaciers and their impact on river discharge, and treeline studies have remained peripheral. Schickhoff's (2005) analysis of patterns in treeline elevation and species distribution based on past studies has been a notable contribution, generating interest of researchers in Himalayan timberline. One of the major observations of the analysis was that most of timberlines in the Himalayas occupy elevations lower than that they could have occupied had climate been their only determinant. Most treelines in Himalayas are affected by grazing and tree cutting (Schickhoff 2005).

In recent years, a few studies have been carried out on tree ring width chronology in relation to climatic parameters (e.g., Gaire *et al.* 2014; Suwal *et al.* 2016), however, they are too few to capture the high heterogeneity in Himalayan conditions that prevail from the east to west Arc. To address this knowledge gap, we conducted a coordinated multi-site and multi-partner study on treelines of Indian Himalayas that considered several aspects of Himalayan treelines: elevational distribution of treeline, species richness pattern, tree ring width chronology, phenology, tree water relations, plant growth in relation to snow melt, surface temperature lapse rate and local livelihood connections to treelines. While so doing, we followed a team research approach, built around periodical workshops and continuous exchange of ideas and opinions to develop work plans, methods (it resulted in a manual, Singh & Rawal 2017), collect data and discuss research findings.

In this introductory article of this issue of *Tropical Ecology*, I (i) briefly introduce treeline ecotones, and discuss patterns in treeline elevation and species along the Himalayan east-to-west Arc; (ii) summarise features emerging from the multi-site and multi-partner research, the papers of which mainly constitute of this issue of *Tropical Ecology*, and (iii) refer to future research needs in Himalayan treelines. One of the major proposed outputs of this on-going exercise is to establish Himalayan treeline as a major research system in relation to climate change, and its recognition as an important conservation entity.

Himalayan region and study sites

Extending from Afghanistan in the northwest (ca. 26°N and 70°E) to Yunnan in the southeast (ca. 26° N and 100°E), the Himalayas are highly heterogeneous, encompassing the Tibetan Plateau in the north, all the 14 world's mountain peaks above 8000 m, and the foothills along the boundary of the Indo-Gangetic plains in the south. As the rule of thumb, 1° increase in latitude leads to 0.55 °C decrease in temperature, so, on an average the extreme northwest should be 5.5 °C cooler than the extreme southeast. However, because of continentality summer temperatures are higher in northwest Himalayan region. While annual precipitation above 3000 mm is common in the outer ranges receiving direct thrust of monsoon air masses, areas in the north of the main Himalayan ranges have some of the largest rain shadows with annual precipitation even less than 300 mm. In general, moisture decreases from east to west and from south to north (i.e., from low to high elevations; Singh *et al.* 2017), but in the absence of meteorological stations, the elevations above which precipitation drops sharply cannot be generalized. Our one year precipitation data of a Uttarakhand treeline site indicates that annual precipitation may remain high (2500–3300 mm) even above 3000 m (Joshi *et al.* 2018, this issue).

Areas shielded from monsoon by high ranges not only receive much less precipitation, generally well below 1000 mm, but there the seasonal distribution of precipitation also gets modified. While in monsoon rainfall pattern, 70–80% of annual precipitation occurs during monsoon months, generally June to September, in areas with non-monsoonal rainfall pattern there are more winter and pre-monsoon (March–May) precipitations (Fig. 1). These differences in precipitation regime influence treeline elevation and species composition (Schickhoff 2015).

Broadly speaking, the mean annual temperature declines from 22–24 °C in foothills to 18–20 °C at 1000 m, 10–15 °C at 2000 m, 7–10 °C at 3000 m and less than 7 °C in Alpine zone. However, temperature and elevation-relationship is not strait forward. For example, the elevated heating surface of large Tibetan Plateau raises temperature by its mass elevation effect (Zhang & Yao 2016). This is

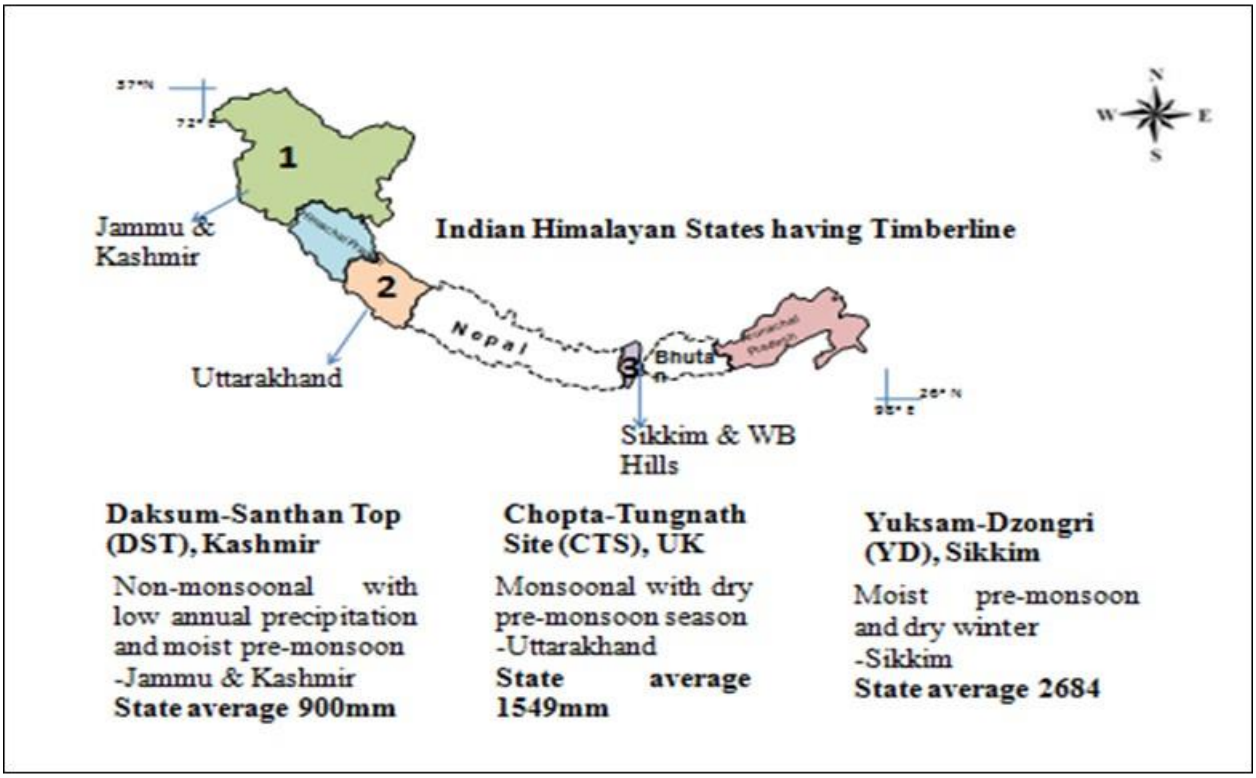

Fig. 1. Three study sites for detailed treeline/timberline study. The study sites cover much of the range of variation across the Himalayan Arc, and represent three precipitation regimes (Courtesy: Subrat Sharma, GBPNIHESD, Almora).

one of reasons for the occurrence of the highest treeline in Tibet.

In the western Himalaya, from lower to higher elevation, forest vegetation varies from tropical sal (*Shorea robusta*) forest in foothills to sub-tropical chir pine (*Pinus roxburghii*) and chir pine-broadleaved forest between 1000–2000 m, and evergreen temperate broadleaved forests (*Quercus leucotrichophora*, *Q. floribunda*), and conifer forests (*Abies pindrow*, *Abies spectabilis*, *Pinus wallichiana*, *Cupressus torulosa*, *Cedrus deodara*, *Picea smithiana*) between 2000 and 3000 m. The subalpine forests (>3000 m) which follow, generally consists of fir (*Abies pindrow* or *A. spectabilis*) and birch (*Betula utilis*) forest. Most of the region is under evergreen forests, with occasional patches of deciduous species along water courses (e.g., *Acer* spp., and *Aesculus indica*). The Alpine zone, generally above 4000 m, includes alpine meadows and alpine scrubs. In the eastern Himalayas there are more of broadleaved species, such as oaks (e.g., *Quercus lamellosa*, and *Q. oxyodon*) and laurels (*Litsea*, *Machilus*, *Neolitsea*, *Lindera* and *Symplocos*) between 1800 and 2550 m, and species of *Schima* and *Castanopsis* between 1000–2000 m. Conifers generally dominate only in subalpine belt.

Sheep and goats which are integral part of summer time grazing in alpine areas of Kashmir, Himachal Pradesh and Uttarakhand are largely absent in Sikkim and Arunachal Pradesh (Singh & Thadani 2015). However, even in western Himalayan states and Nepal now livestock density is on decline, hence giving an opportunity to trees to move upslope in some areas (Suwal *et al.* 2016). In all these Himalayan regions glaciers are shrinking (Singh *et al.* 2011; Yao *et al.* 2012).

As indicated in Fig. 1, the study sites of the coordinated treeline research project are located in Kashmir valley, Uttarakhand and Sikkim which broadly cover the range of variation that occurs along the Himalayan Arc. While, Kashmir is relatively dry (600 mm annual precipitation) and non-monsoonal, with monsoon months (June to September) accounting for only 28.9% annual precipitation), Sikkim is wet and monsoonal, Uttarakhand is strongly monsoonal in precipitation trend, with about 80% annual precipitation occurring from June to September, but moderately moist (Fig. 1).

In many regions of Himalayan warming is 2 to

3 times more than that of global average rate (Singh *et al.* 2011).

Treeline patterns along the Himalayan Arc

Treeline ecotone represents a transition characterized by decreasing tree cover and tree height from upper limit of closed forests to the treeless vegetation, often referred to as alpine meadows. Generally, the upper limit of continuous forest (forest with at least 30% crown density) is called timberline. Above it, trees become sparse and forests increasingly open, eventually grading into isolated and scattered trees with large gaps. The line (theoretical or imaginary line) which connects highest elevation trees is called alpine treeline (Fig. 2). By definition, here a tree is single-stemmed and 2 m or more in height. There is another term in the context of treeline ecotone, called tree species line, which consists of individuals of tree species which are shorter than 2 m or/ and multi-stemmed, often crippled because of damages caused by extreme weather events such as storms, and snowfall (Fig. 2). Mention may be made of 'krummholz', which consists of dwarfed and crooked trees with deformed physiognomies. They can be genetically as well as environmentally controlled. In Himalayas, *Rhododendron campanulatum* is a characteristic krummholz forming species. However, krummholz can also be of the forest species, such as fir or birch (Holtmeier & Broll 2017). It may be pointed out that above definitions often vary in literature (Holtmeier 2009; Holtmeier & Broll 2017; Körner 2012). For example, Holmeier and Broll (2017) use timberline and treeline interchangeably.

Treeline form varies depending up on abiotic and biotic factors and historical background. Generally, treeline is diffuse type, with tree individuals getting gradually sparser and shorter above timberline (Fig. 3). Some species, like *Quercus semecarpifolia* in western Himalayas form natural abrupt treeline (Fig. 3), which might reflect self control through shelter effects on seedlings (Körner 2012). In the southern Hemisphere, *Nothofagus* genus is known to form such a sharp treeline (Wardle 2008).

On mountain slopes, with alternating concave (furrows) and convex (ridges) surfaces, a finger like treeline is formed because in concave portion snow accumulation restricts the tree formation, so trees are confined to convex surface (Fig. 3). Formation of island type treeline can also be seen in Himalayas. In this, patches or islands of trees are surrounded by treeless vegetation in high elevations.

Should *R. campanulatum* be included in treeline? Generally, it is included in treeline (Schickhoff 2005) though the nature of its growth form is unclear. It is a 'sub-tree' with a short stem, copiously almost from ground, and the branches are deformed, crippled and gnarled. Is it not a tree which becomes shrubby under unfavourable condition. Perhaps, it can be called conveniently a sub-tree, and its dynamics could be considered separately from treeline dynamics. Individuals of *R. campanulatum* are distributed amongst scattered and isolated trees of treeline, as well as in open areas below timberline. Seeing that *R. campanulatum* has responded to climate change by moving upslope, that its effect on alpine meadows is likely to be considerable in terms of ecosystem properties, and that its quite common along the Himalayan Arc, its dynamics deserves a separate treatment in its own. The krummholz patches could be considered part of ecotone along with juniper mats which are common in Kashmir (Fig. 2).

There is no authentic compilation of Himalayan treeline species. A collection of information from treeline (Singh, Sharma & Dhyani Unpubl.) indicates that treelines in Himalayas have 10 genera and 58 species, which are quite high given that globally about 18 genera and 122 treeline species have been described (Holtmeier 2009, Körner 2012). Globally, Pinaceae and Betulaceae are most common families in treelines. In Himalayas, common treeline genera are *Juniperus* (juniper), *Abies* (fir), *Betula* (birch) and *Rhododendron*, however, *Picea*, *Pinus* (*P. wallichiana*), *Larix* (larch) and *Tsuga* may also reach treelines. While birch, junipers and *Rhododendron campanulatum* are largely treeline ecotone species, fir, spruce, pine and oak are subalpine forest species which may go up to treeline ecotone.

As for the highest treeline record of the Northern Hemisphere, it is held by a juniper (*Junieperus tibetica*) forming treeline up to 4900 m in Tibet (Bosheng 1993, Miehe *et al.* 2003, 2007). *Polylepis tarpacana* (Rosaceae) holds record for the Southern Hemisphere. It forms a 3.5 m tall (and 30 cm diameter) tree at 4810 m in the Bolivian Andes (Hoch & Körner 2005).

The treeline elevation in the Himalayas increases from NW to SE along the Himalayan Arc (Fig. 4), despite eastward increase in mesic condition in which treeline gets suppressed (Körner 2012). It is largely because of decrease in latitude from NW to SE (range being about 10° N lat.). Globally, treelines are lower in a wet condition

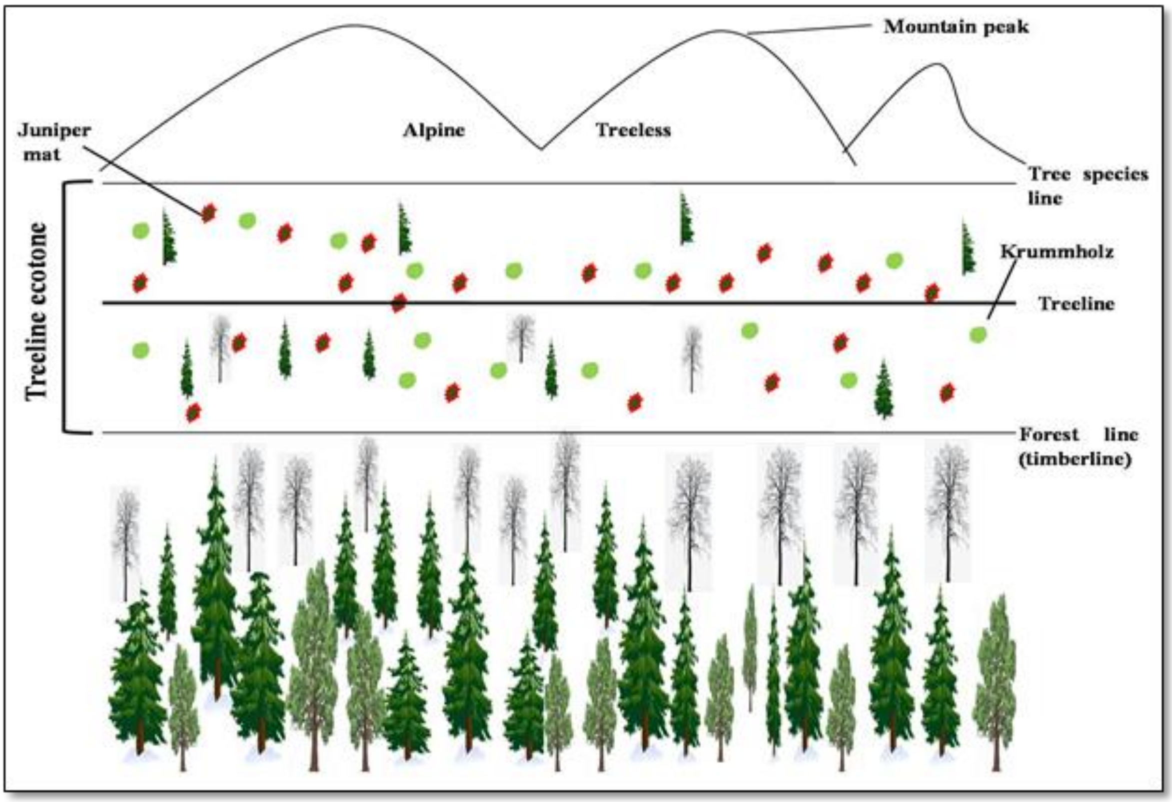

Fig. 2. A representation of treeline ecotone in Himalayas, indicating timberline, treeline and tree species line. Amongst scattered tree individuals, patches of krummholz and mats are shown. Juniper mats are common in Kashmir (developed with the help of Surabhi Gumber and Ripu Daman Singh).

(Körner 2012) presumably because of the longer stay of snow which limits the tree recruitment. However, in SE Himalayas growth period is quite long, > 200 days (between May and October) because of warm and moist conditions. Moreover, the heavy rainfall of this region does not allow snow to stay for long. In a monsoonal regime, much of the snowmelt occurs during initial monsoon months (Yao *et al.* 2012). Generally, in a warm temperate zone (28°–42°N lat) growth period in treeline is 140–150 days (see in Körner 2012), which are distinctly shorter than growth period in Himalayan treeline ecotones (roughly 200 days or more). From the stand pint of growth period, the Himalayan treelines are closer to subtropical zone (19°N–19°S) with growth of 200–265 days (Körner 2012).

Factors affecting tree growth and treeline elevation in a changing climate

Temperature is the principal determiner of treeline elevation, however, precipitation can modify it. On average across all bioclimatic regions of the world the root zone soil temperature (at 10 cm depth) is 6.4±0.7 °C as growth season mean, and 7.8±1.1 °C as the warmest month mean (Table 1.). The minimum growing period required for tree growth is 94 days (Körner 2012), compared to this, it exceeds even 200 days in some areas of Himalayas. Water is generally not a limiting factor in treeline areas, as low temperatures of treelines keep evapo-transpiration loss low (Körner 2012). Among the abiotic factors other than temperature, elevation mass effect, latitude, geographical location, aspect, nature of slope, wind speed, height of nearest mountains, pre-monsoon (March to May) drought, snow cover, moisture influence treeline elevation (Fig. 5). Latitude and mountain height together account for 89% of the variation in timberline formed by *Betula pubescens* in Scandinarian mountains (Odland 2015). So the absence of high mountain areas above timberlines would restrict its upliftment in a warming world (Odland 2010). That pre-monsoon (March to May) warming without additional precipitation adversely affects tree ring

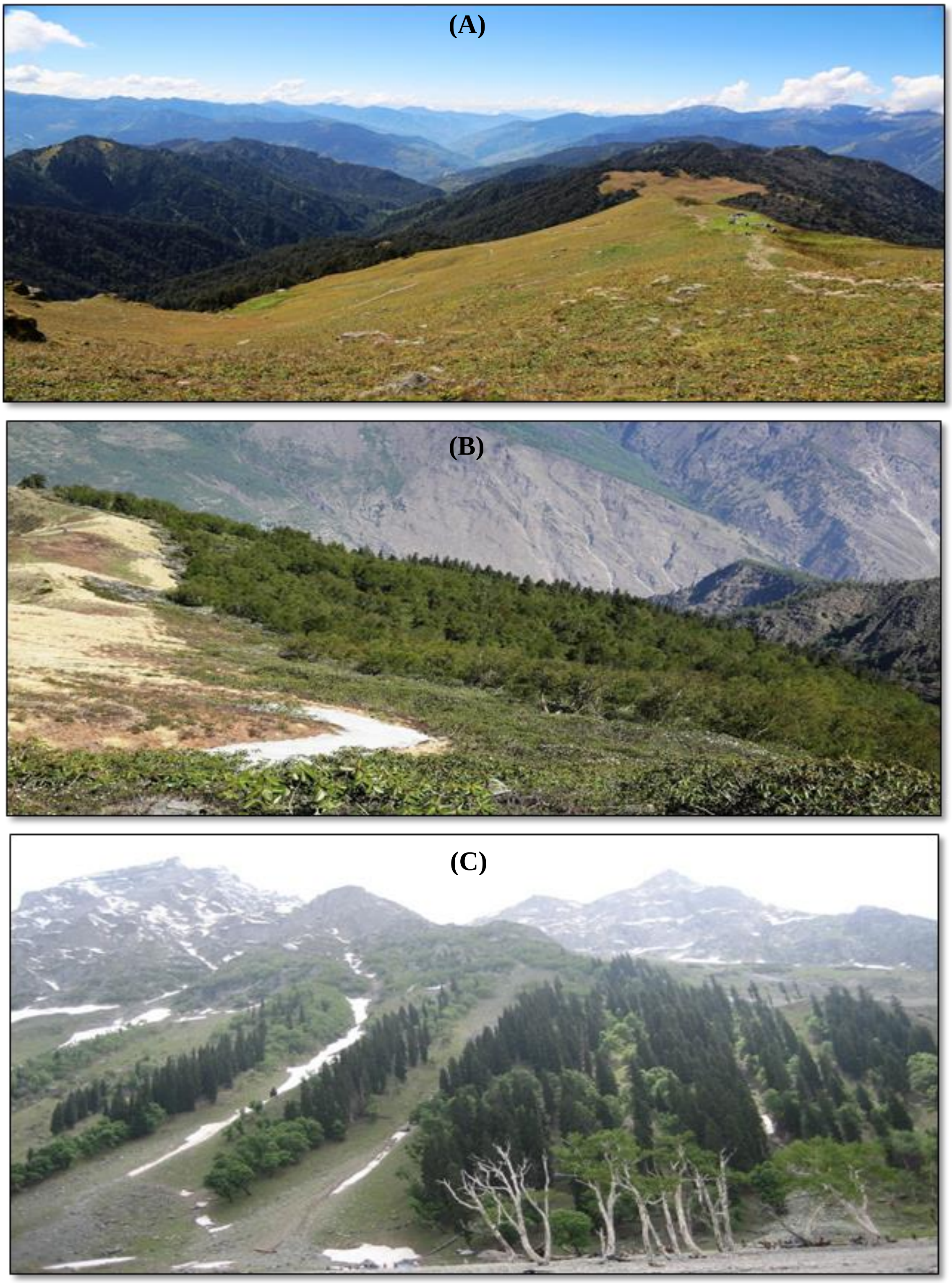

Fig. 3. Various forms of treeline: (A) Abrupt treeline- *Quercus semecarpifolia* forming abrupt timberline in Chaudas valley 3800 m (Courtesy: Dr. Vikram Negi, GBPNIHESD); (B) Diffuse treeline- *Betula utilis* and *Rhododendron campanulatum* forming treeline at Lata-Khark Nanda Devi Biosphere Reserve 4000 m (Courtesy: Dr. Vikram Negi, GBPNIHESD); and (C) Finger like treeline- *Betula utilis* and *Abies pindrow* froming fingerlike treeline (Courtesy: Prof. Zafar Reshi, Kashmir University).

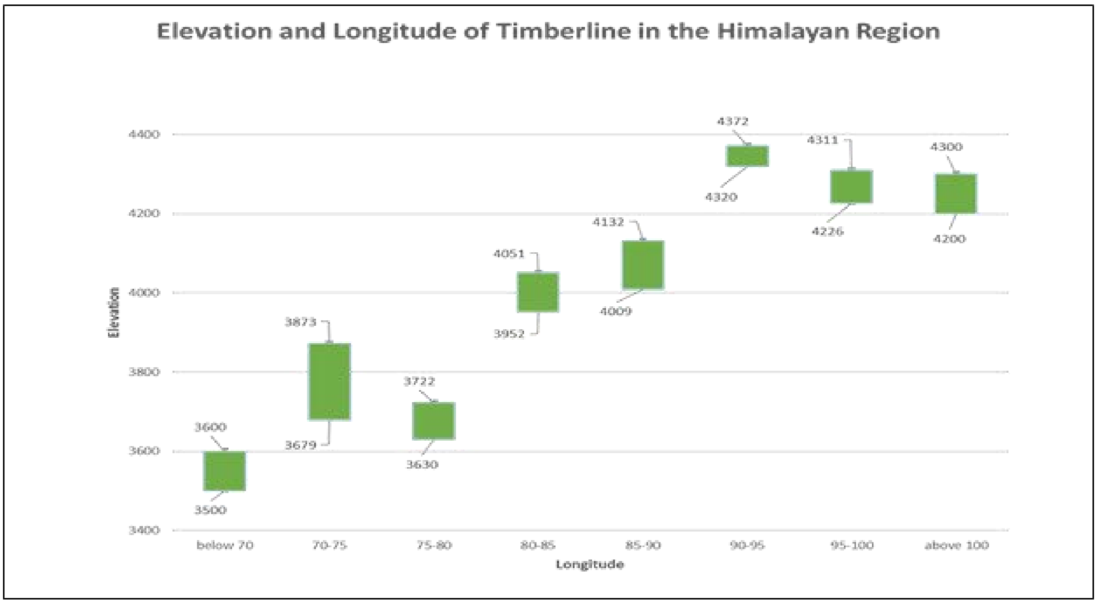

Fig. 4. Lowest and highest limit of treeline (average of pooled samples) in different longitudinal bands along the arc (west to east). Number in parenthesis indicates *n*. (Source-Drawn by Dr. Subrat Sharma, GBPNIHESD). Pattern of change in treeline elevation from west to east of the Himalayan Arc (data are based on secondary sources, particularly Schickhoff 2005).

growth is apparent from studies on several treeline, such as *Abies spectabilis*, *A. pindrow*, *Picea smithiana*, *Juniperus sp.* and *Betula utilis* and others (Table 2). In monsoon climate, pre-monsoon is a dry and warm period, global warming by increasing evapotranspiration loss seems to make conditions further drier. In contrast, warming in winters can favour growth by improving soil water supply because of more snow melt (Gaire *et al.* 2014).

Treeline elevation is affected by mass elevation effect and height of nearest mountains (Odland 2015). A mountain with large mass varies more from the free atmosphere than a mountain with smaller mass. Zhang & Yao (2016) suggest that treelines would not rise above 3500–3700 m elevations in Himalayas, without the mass elevation effect. Furthermore, for tree species to move up, several hundred meters of mountain terrains above the timberline are required for the development of treeline (Körner 2012).

It may be pointed out that, in much of the western Himalayas treelines are generally not climatic treelines because of age old pastoralism (Fig. 5). Since pastoralism was far less extensive in the eastern part (Singh & Thadani 2015), there the treeline elevation could be closer to climatic treeline elevation, and this may be another reason for the higher treeline elevations in SE Himalayan part than in the NW part. Now, pastoralism is on decline in many areas, resulting in the upslope movement of treelines (Chhetri *et al.* 2016). The effect of increased tourism and *Cordyceps* collection from high mountain areas is likely to be just opposite (Fig. 5). Several millions of collectors stay in Alpine meadows and treeline areas of Uttarakhand, Nepal and Tibet each summer, digging soil to collect *Cordyceps* from plant roots. They not only trample ground vegetation, but also collect firewood from treeline areas. Summer temperatures are higher in dry inner Himalayas, that is why treeline elevations are higher there than in outer Himalayas under the direct influence of monsoon (Schickhoff 2005; Subrat Sharma unpubl.). Between south and north aspects, treeline is higher on the former because of warmer conditions (Schickhoff 2005; Reshi unpubl.). However, in Himalayas the treelines in the southern aspect are deformed because of greater anthropogenic pressure. Aspect also affects treeline's species composition. As discussed in the article on vegetation analysis of this issue, in Kashmir on the warmer South aspect *Pinus wallichiana* forms treelines, while on the cooler North aspect, fir (*Abies pindrow*) and birch (*Betula utilis*) occupy treelines.

Findings from site-specific research

Our research approach was three-pronged. Firstly, we tried to cover the east-to-west Arc of Indian Himalayan region by sampling at three sites,

Table 1. Summary of root-zone soil temperature (°C; mean ± S.E.) of treeline from various bioclimatic zones (extracted from Körner 2012). Though the latitudes of Tungnath, Uttarakhand falls within warm temperate category, its growing period is longer, closer to that of subtropical zone.

Bioclimatic zone with latitudes	Seasonal mean	Warmest month	Season length (days)
Subarctic-boreal (45°–68°N)	6.2±0.7	78±1.1	104±7
Cool temperate (45°–47°N)	6.8±0.3	9.0±0.4	145±21
Warm-temperate (28°–42°N)	7.4±0.4	8.9±0.9	140±1.1
Subtropical (19°N–19°S)	5.5±0.7	6.7±0.7	257±73
Equatorial tropical (6°N–3°S)	6.1±1.5	6.8±0.4	338±28
Mean of the above 5 zones	6.4±0.7	7.8±1.1	197±98

representing western part (Kashmir) central part (Uttarakhand) and eastern part (Sikkim) (Fig. 1). Secondly, at each of the three regional sites, a set of studies, which we thought would throw light on understanding the treeline ecotone, were carried out. They dealt with timberline mapping, tree species composition and pattern of species diversity along an elevation transect leading to treeline, tree ring chronology, and temperature lapse rate analysis based on observed temperature data. Thirdly, we carried out additional studies on one site (Uttarakhand) to further deepen our understanding of processes involved in the functioning of treeline communities and ecosystems. They pertained to treeline species shift, phenology with focus on leaf and nutrient dynamics, tree water relations, and livelihood issues. Given the constraints of working in remote treelines of Himalayas, it was not feasible to include all sites for these detailed studies. As for mapping of treeline using remote sensing method, it is being done for all the Indian Himalayan states where timberline occurs. So far as we know, such an attempt has not been carried out before.

Data collected for Uttarakhand timberline using remote sensing technique indicated that 57% of total timberline length (about 2750 km) was between 3400 and 3800 m, but isolated and small timberlines were distributed over a wide elevation range, about 2000 m (Table 2). As discussed earlier and shown in Fig. 5, several local factors affect timberline position. It is apparent that uppermost timberline of a region cannot be known by sampling one or two sites in field. Range of timberline elevations, and frequencies by range classes are required to capture the regional variabilities. This exercise will also enable us to compare temporal changes in timberline position under the climate change impact. However, remote sensing would require ground truthing to identify species of treeline individuals which may warrant enormous physical efforts.

As for the species of timberline and treeline ecotones, fir, birch and *Rhododendron campanulatum* are common species. The presence of tall fir trees (*Abies pindrow*, *A. spectabilis* and *A. densa*) is a constant feature of treeline areas of the three study sites. Wherever birch is present, it exceeds the elevational levels of all other tree species, and forms treeline. Treelines are generally diffuse type, but *Quercus semecarpifolia* often forms an abrupt treeline/timberline. To what extent, an abrupt treeline is a species character needs to be explored. In Uttarakhand, while moist areas have *Abies* spp., *Q. semecarpifolia* and *Betula utilis*, the drier areas have *Juniperus semiglobosa* and *Pinus wallichiana* in treeline.

Along the elevation gradient in Uttarakhand (based on 3 monsoonal and 2 non-monsoonal sites) tree species richness peaks around 2500 m, and between 2000–3500 m elevations 54 tree species occur (across 5 transects, Pindari, 2000–3300 m, Tungnath, 2100-3300 m and Bhagirathi, 1000–3000 m, which are monsoonal and Byans, 2000–4000 m and Nelang, 3100–3800 m, which are non-monsoonal). Using various sources we are planning to prepare a treeline database.

As for species richness, there is a tendency for increase in tree species richness from west to east, but the same may not be apparent for other growth forms. Along the entire elevational transect (data based on point sampling in each 100 m band) there occur approximately 55–60 tree species in Kashmir, 75–80 in Uttarakhand, and 175-180 in Sikkim (on estimates based various transect studies).

We are estimating temperature lapse rate (TLR) with elevation on the basis of observed data (possibly the first study in Indian Himalayas). The preliminary analysis indicates that the mean annual

Table 2. A summary of the findings of the multi-site and multi-partner treeline research project in Indian Himalayan region. The three study sites were located in Kashmir, Uttarakhand and Sikkim.

Studies	Findings	Remarks
Treeline mapping with remote sensing technique-Uttarakhand study; others under investigation	Elevations of timberlines varies by 2000 m, going up to 4366 m, indicating that high timberlines can occur also in regions other than Tibet; however, about 57% of 2750 km long timberline in Uttarakhand occurs between 3400 and 3800 m; unbroken timberline accounts for 86.5% of total timberline, the remaining occur as island like pieces	Possibly, it is first estimate of timberline length elevational variation at state/region level
Treeline species in Kashmir, Uttarakhand and Sikkim		
Kashmir Daksum-Sinthan site Timberline Latitude-33°36′43″N/ Longitude-75°26′6″E (District Anantnag, Kashmir)	On moist slopes *Abies pindrow* (fir) dominates up to 3200 m, forming close canopied forests, whereafter its importance decreases with a concomitant increase of *Betula utilis* (birch), which is a typical treeline species (3200–3700 m); *Rhododendron campanulatum* is its common associate, but it can also occur beyond treeline, whereafter alpine meadows occur. Birch generally occurs within a thin belt of open type forest within treeline ecotone. On drier southern aspect, *Pinus wallichiana* (blue pine), goes up to treeline. Juniper mats and krummholz, seem to facilitate growth of blue pine. Plant growth forms vary in beta diversity: almost same species of lichens occur throughout the elevation gradient, while herbs change rapidly, hence could be a better indicator to climate change.	This is the first sample based study to compare the treeline vegetation of the Himalayan Arc. Comparisons are being analysed, it seems that birch declines eastward.
Uttarakhand Tungnath site Latitude- 30°27′04″ to 30° 28′58″N/ Longitude- 79°28′58″ to 79°12′53″E, (District, Chamoli Uttarakhand)	Species composition is diverse; *Quercus semecarpifolia* (kharsu oak), fir spp. and birch occur in monsoonal sites, while on drier aspects and in non-monsoonal sites birch, fir (*A. spectabilis*), blue pine (*Pinus wallichiana*) and *Juniperus semiglobosa* are common. Within an elevation range of 2000–3500 m, 1493 plant species, with 106 trees, 241 shrubs and 1146 herbs occur; elevation range 2000–2500 m accounts for 819 species (55%) and 3000–3500 m for 626 species (42%). Along the elevational gradient (2000–3000 m) tree species declined from 87.7% of total species to 14.2%, and shrubs from 67.4% to 15.4%, while herbs were rather invariant (46.2–49.5%). Treeline is at 3500–3700 m	
Sikkim Yuksam-Dzongri transect, West Sikkim Latitude- 27°29′04.79″N/ Longitude-88°08′58.69″E	*Abies densa* is the main treeline and subalpine forest species. At some sites *Tsuga dumosa* reaches close to timberline. Between 3000-4000 m plant species richness peaked at 3100 m, and then declined. Stem density is higher than in the other two sites.	
Correlation between tree ring width and climate	Only warmer condition of autumn months had positive effects on the growth of *Abies pindrow* (at Tungnath).	In drier areas studied elsewhere, pre-monsoon drought which is intensified by warming limits growth of birch; here too, even in fir only, autumn temperature had positively effect.

Contd…

Table 2. Continued.

Studies	Findings	Remarks
Surface Temperature Lapse Rate (TLR)	TLR is lower (~0.50 °C per 100 m elevation) than the rate applied earlier (~0.6 °C per 100 m elevation); seasonal variations are wide, and bimodal (low during winter and monsoon, and high during pre-monsoon and autumn), TLR also varies across aspects and between minimum and maximum temperatures. Growing period, determined as period between the date of bud swelling and the date when shoot growth stops is >200 days, clearly longer than generally found for mid latitudinal (20°–40°N lat.) mountains(about 145 days).	The first estimate of TLR based on observed data of along a transect.
Tree water relations	Treeline trees are less water stressed than mid elevation trees; treeline trees employ a characteristic winter adaptation mechanisms.	Possibly, it is the first water relations study on Himalayan treeline.
Phenology at Tungnath sites- upward movement of *Rhododendron campanulatum*	*Rhododendron campanulatum* has been moving up at the rate of 3.4 m/yr during last two to three decades. Because of this krummholz species, the treeline ecotone is getting densified. Because of summer season water availability, treeline species do not wait for monsoon arrival to initiate growth. Nitrogen resorption from senescing leaves ranged from about 44% in fir to 76% in *R. campanulatum* Soil organic carbon concentration decreased with elevation, soil N showed just an opposite pattern.	More long term study based on permanent plots are required.
Snow impact on plant growth at Tungnath site	Seasonal pattern of snowfall has changed drastically, adversely affecting the early growing species, like *Gentiana argentea*. In the meadow, herbs vary in physiognomic structure, while *Danthonia* forms more than 150 g m^{-2} biomass, *Trachydium* seldom exceeds 30 g m^{-2}, *Danthonia* occupies snow-free microsites and *Trachydium* those where snow stays for long.	Poor access to the site due to snow limits research activity during winter months.
Exploring livelihood options	All households practice agriculture, but also earn from religious tourism. Dependence on forest biomass for firewood, fodder and litter collection is still high. Project interventions include mushroom cultivation improved-composting, water storage, floriculture, etc.	Development activities take 8–10 years to yield results.

TLR is relatively lower (0.50 °C/100 m elevation) than generally used (>0.6 °C/100 m elevation) (Table 2). It means temperature at a given elevation in high Himalayas is warmer than assumed. It is quite likely that TLR is declining because of global climate change, as the degree of warming increases with elevation, thus reducing the difference in temperature with elevation. TLR varies with aspect and among seasons. It is lower during monsoon months when much of the seasonal biomass accumulation takes place. This might have contributed to higher treeline elevation in Himalayas. The aspect (exposure of slope) factor of the rate of warming partly accounts for difference in treeline elevation across aspects.

Study on tree ring chronology indicated that tree ring width was positively correlated only with temperature of autumn months, whereas summer time temperatures (March to September) were negatively correlated. During pre-monsoon, the rise in temperature is likely to increase evapo-transpiration loss, which, in turn may result in an

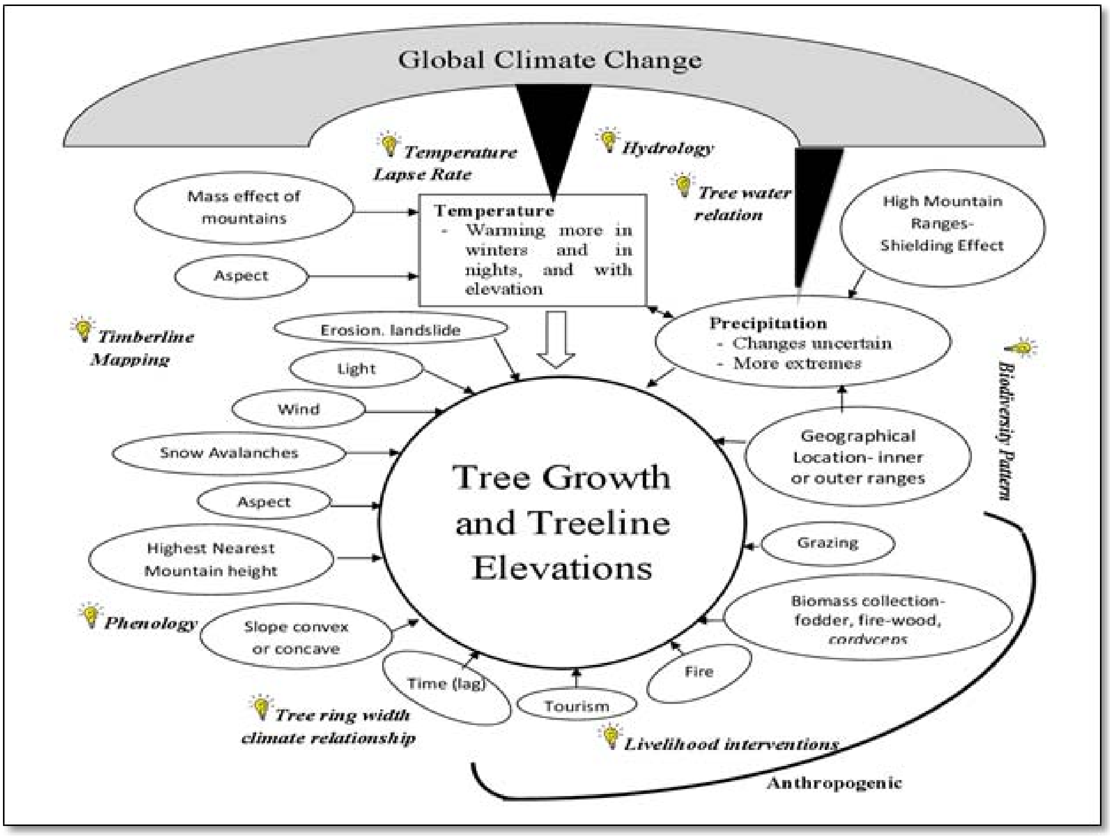

Fig. 5. A schematic representation of factors affecting tree growth and treeline elevations in Himalayas, both climatic and anthropogenic ones. Temperature is the major climatic factor to affect treeline, but role of precipitation can also be substantial. Both are being affected by global climate change. Research studies being carried out to understand various aspects of treeline ecotone are indicated in bold italics along with light bulbs.

intensification of drought and suppression of tree growth (Gaire *et al.* 2014).

Contrary to the opinion of suppression of tree growth due to drought, the tree water relation data of Tungnath indicate the absence of water stress in treeline ecotone. This could be partly because Tungnath is a relatively wet site and the study year was unusually wet. The lack of water stress (predawn tree water potential was always above –1MPa) is consistent with general observation for treeline areas of mountains (Körner 2012). Even in an extremely dry condition in Southern Alps shoot water potential is reported to remain between –1.5 and –1.9 MPa at mid-day (Anfodillo *et al.* 1998).

R. campanulatum, the sub-tree rhododendron has been moving upslope at the rate of 3.4 m/year for last 2–3 decades at Tungnath site (see Negi *et al.* in this issues). Studies on tree species movement in Himalayas has been uncertain. For example, in Nepal white *A. spectabilis* showed an upward shift at the rate of 5-26 m decade^{-1}, *Betula utilis* remained static because of moisture stress (Gaire *et al.* 2014). Climate change seems to be affecting timing of bud-break, leaf expansion, leaf senescence and resorption of nutrients (see Negi et al., in this issues). Data are being analyzed to find out generalizations of patterns. In treeline ecotone not only growth period is shorter than that of mid-elevation sites, the time of highest temperature is shifted from June (in mid elevation) to August (treeline sites).

Within the ecotone, soil organic carbon increased with elevation and soil N decreased. On average treeline ecotone species had lower leaf nitrogen concentration than mid-elevation species. Slow decomposition of litter under low temperature indicates low mineralization rate.

Much of treeline sites remained snow covered during winters (up to March, at least), however, snow-free areas are likely to have increased in recent years, resulting in decreased albedo and more absorption of sun, and hence increased warming. Early snow melt adversely affected early growing species, such as *Gentiana argentea* because the fresh snow fall may damage growing tissues more than old and dormant ones (Adhikari *et al.* in this issue). Species of Alpine meadows differ considerably in their biomass and this is partly related to the snow cover duration. Snow removal experiment has been set up and data are being collected. Several changes are taking place in treeline ecotone, which need to be detected. Accumulation of species near summits, spread of invasive alien species, and species range shifts are some examples (Fig. 5).

Villages near timberlines in Himalayas extract a considerable amount of biomass from natural forests, largely for firewood, fodder and litter collections. People follow traditional form of agriculture in which 8–10 energy unit are derived from forests to realize 1 energy unit of agriculture production. Several livelihood options are being applied and results have begun to occur. Villagers have begun to cultivate mushrooms and flowering plants inside polyhouses. To establish business activities in such a remote areas warrants long term interventions and diverse approaches.

Way forward

The present study, firstly provides several starting points for making comparisons about situations changing rapidly under the influence of climate change and local anthropogenic activities, and secondly, it generates some research questions. The timberline mapping will provide baseline for the entire Indian Himalayan region to make comparisons for determining future changes. It can be used to address several research questions with regard to: the changes in timberline due to climate change, densification of vegetation in treeline ecotone, and impact of upward movement of woody species on alpine meadows, in terms of species composition, and carbon storage in treeline zone and other landscape level characters. However, baseline data need to be collected immediately at several representative treeline ecotone sites. There is a need to carry out a multi-site research on carbon considering all important components, namely biomass, organic soil layer and mineral soil layer along an elevation gradient to understand changes that treeline movement can bring about in regional carbon status (Speed *et al.* 2014). Related to this is the role of soil properties in affecting alpine treeline (Müller *et al.* 2018).

It appears that climate warming is favouring *R. campanulatum*. How the rapid spread of this species is likely to impact treeline ecotone and adjoining grasslands in terms of resource values and ecosystem services? Permanent plot based long term studies could prove to be quite rewarding in this regard. Our this study could be used to find out acceleration in species upward movement under the climate change influence.

There is a need to analyse vegetation changes in response to climate change at a micro-scale with focus on non-woody species like angiosperm herbs, bryophytes and ferns. The traditional profile diagram of vegetation at micro-scale can be quite handy to monitor changes. We have learned from this study that lichens are rather tardy in their response to climate change because of their tolerance to wider temperature ranges.

A GLORIA like study design is required to monitor treeline ecotone changes under the influence of climatic change. The permanent plots established should represent diverse physiognomic types (trees, krummholz, mats and diverse meadow forms) that occupy a treeline ecotone. A profile diagram of ecotone could be quite hardy in detecting changes both spatially and temporally.

Why a species forms an abrupt type of treeline, or to what extent a sharp treeline is a species character? This question has hardly been addressed. Would an abrupt treeline less responsive to climate warming in terms of upward species shift than diffuse treeline?

Related to this is finding out the changes that occur in dry matter allocation to different tree components, such as root and leaf mass fractions, litter fall and litter decomposition and nutrient cycling as we move towards treeline. Our this study gives an idea of leaf nitrogen concentration and its resorption from senescing leaves. How these processes are going to be affected by climate change, and what will be its consequences at community or ecosystem level are worth knowing to manage treeline ecotones. In some of these patterns and processes, the role of mycorrhizal association could be critical.

Our this study on surface temperature lapse rate indicates that the relationships between elevation and temperature are far more complex than generally perceived, they are of critical importance in understanding high elevation patterns both abiotic and biotic. This research is required to be carried out for another 5–10 years to capture temporal trends. Moreover, several more transects are required to be considered, both in outer and inner Himalayan regions, characterized by moist and dry climate, respectively.

Tree provenance study could be used to find out the populations which could perform better in a changing world. For this, populations of species that occupy distinct elevations, geographical locations, such as western and eastern Himalayas, and precipitation regimes, such as areas exposed to and away from monsoon impact could be investigated.

The environment of treeline ecotone is under a severe stress, so there the facilitative role is likely to be of critical importance for regeneration of some species. In view of this, the facilitative role of juniper mats and rhododendron krummholz needs to be detected.

Water was found to be a non-limiting factor in the study of Tungnath, but it may restrict plant establishment in inner regions, where annual precipitation is not only small, but also differs in season. So focus in future should be places like Kinnaur and Kashmir. How, seedlings manage their water status in areas above treeline in varied habitat needs to be investigated.

Conclusions

Himalayas are among the most data-deficient regions of the world, which is a matter of great concern because the region is warming very rapidly and is inherently vulnerable to such severe changes. Among various regions in Himalayas, treeline is the least investigated, and appreciated as a conservation entity. Because treelines in Himalayas are among the highest in the world, they are remote, hence difficult to study. The present study indicates that treeline elevations in a region vary far more than generally perceived, thus further complicating the task of their management. Whatever little data that we have collected in relation to surface temperature lapse rate (TLR), they indicate that TLRs vary considerably with season and aspect. They need to be thoroughly investigated as dependence on one standard value may lead to wrong projections. One of the serious research problems in Himalayas has been making predictions based on data which are inadequate, poorly represent study systems, short-lived and collected using a mixture of methods. Though treeline is solely determined by temperature, patterns and processes of communities and ecosystem considerably vary across various Himalayan regions. The study has thrown light on tree ring width and climate relationships, tree growth in relation to snow cover, but the temporal and spatial scales need to be increased far more, to address question effectively. Our research provides a baseline for future comparisons and generate several new questions of academic and management importance.

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A cartographic representation of a timberline, treeline and woody vegetation around a Central Himalayan summit using remote sensing method

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Abstract: Using remote sensing techniques, here we have characterized spatial features of Himalayan treeline ecotone in a watershed (Tungnath, Garhwal in the Indian Central Himalaya), considering timberline, treeline, woody patches, and isolated trees. For the first time, timberline and treeline positions have been drawn and remote-sensing based methodological protocol demonstrated. Satellite image of LISS IV and Digital Globe were used to map Tungnath watershed. Forests occupied 80% of the watershed, leaving a small area (3.7%) for alpine meadows. Total length of timberline in the watershed was 7.91 km with elevation range of 3065–3460 m (average being 3277 m). Timberline length distribution by 50 m elevation band indicated that the highest portion (~41%) of timberline occurred between 3250 m and 3300 m. Timberline elevation decreased from moist to dry slope exposure. In the watershed, elevation of treeline ranged from 3280 to 3510 m which was generally 15 m to 170 m below the upper boundary of watershed but at few locations scattered trees reached at the upper watershed boundary. Beyond timberline in higher areas we recorded 124 woody patches and 50 scattered individuals of *Rhododendron campanulatum* and 47 solitary trees of eight species (*Abies, Betula,* etc.). Distance of woody patches from timberline varied from its edge (zero distance) to above 600 m. These details would help in detecting changes due to climatic warming and other factors, and in developing landscape-level understanding on facilitation/expansion of tree species towards high altitude.

Key words: Himalaya, satellite image, timberline, treeline, watershed, woody patch.

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Introduction

High elevation limit of forests, called as timberline or forest line, represents one of the most conspicuous vegetation boundaries in mountains (Daubenmire 1954; Holtmeier 2009; Körner 1998). Heat deficiency and reduced length of growing season are regarded as the principal causes of timberline and treeline formation (Schickhoff 2005). Considered to be among the most prominent vegetation zones in high mountains, the timberline ecotone is often characterized by a steep environmental gradient, increasing fragmentation of vegetation and stuntedness of trees (Shi & Wu 2013). While timberline is the upper limit of continuous forests, treeline represents the highest elevation trees. In a way, it is an imaginary line that connects the elevations of uppermost trees, often growing as isolated individuals or in small patches (Singh & Rawal 2017). Positions of uppermost outposts of individuals/woody patches are considered an important ecological indicator of climate change (Fissore *et al.* 2015). Beside steering range expansion, these isolated trees provide habitat for several organisms like spider (Frick *et al.* 2007).

Locations of timberline have been documented

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Fig. 1. Location of Tungnath watershed in the Indian Central Himalaya.

by various workers using sources like historical maps and satellite images (Bharti *et al.* 2012; Weisberg *et al.* 2013) and aerial photographs (Danby & Hik 2007). With enhanced resolution it is possible to map individual trees using GPS (Piermattei *et al.* 2012). Such information about timberlines of Himalayas is rather scanty. In recent years mapping of timberline in Himalaya has drawn attention due to its sensitivity to changing climate and its potential use as indicator of climate change in the Himalayas (Bharti *et al.* 2011, 2012; Singh *et al.* 2012) and other mountains (Barry 1994; Kanka *et al.* 2005). To the best of knowledge of authors, high resolution mapping of timberline, treeline and woody vegetation above sub-alpine forests in Himalayas has not been attempted in the past. The spatial distribution patterns of trees in relation to other landscape features of treeline areas are hardly known.

However, some important studies about the factors affecting treeline elevations have been carried out in the European mountains, known to have a long history of treeline studies. For example, a positive relationship has been observed between the elevation of nearest mountain summit and elevation of *Betula* timberline (Odland 2015). There is a need to develop a methodological protocol to understand relationship between timberline and controlling topography of the Himalayan mountains.

Using high resolution satellite images in a watershed in this study we have (i) developed a synoptic view of timberline ecotone, (ii) characterized its various spatial attributes, and (iii) identified locations of individual trees of treeline ecotone in relation to topographical features. The detailed dataset could be bench-marked for long term monitoring of climate change impact and developing relationship between climatic parameters and vegetation. The specific objectives of the study are to (i) prepare a detailed map depicting locations of uppermost edge of forest (timberline), individual trees and woody patches above timberline, and treeline (highest elevation of tree occurrence), (ii) understand relationship between local topographical features (altitude, aspect, watershed boundary, area available above timberline) and timberline and treeline, and (iii) provide a baseline to assess changes for occurring due to climate change.

This mapping of treeline ecotone at a micro-level would provide template for long term monitoring using high resolution satellite images. Spatial attributes of treeline and timberline will provide more synoptic details on treeline expansion than the estimates derived from locations based ground observation. By periodical sampling one could learn about the role and fate of isolated trees and woody patches in driving future development of vegetation and its significance as habitat for wildlife in a warming world.

Study area

Tungnath watershed (between 30.47–30.51° N latitude and 79.15–79.22° E longitude) has an area of 24 km^2 in Mandakini River catchment of Uttarakhand state (Fig. 1). Part of the watershed falls in Kedarnath Wildlife Sanctuary. A Hindu shrine, Tungnath temple, which is visited by pilgrims in thousands during summer, is also located in the alpine area of the watershed. Tungnath is also a destination for trackers, nature lovers, and bird watchers in different seasons. Small seasonal and perennial streams are common. Altitude in the watershed varies between 1630 m and 3625 m asl, however much of the area (82%) falls between 2400 m and 3200 m asl, and little is left above 3200 m (8%) and below 2400 m (9%).

Methods

For a fine resolution mapping of watershed, two different high resolution satellite images were used and the steps given below were followed:

(i) Landuse/landcover mapping of Tungnath watershed was done through multispectral data of LISS IV (spatial resolution of 5.8 m). The acquired snow-free image of year 2015 (21 December) was used to distinguish evergreen and deciduous forests, and to separate treeless alpine areas from the forested areas. For landuse/landcover analysis, layer stacking was done using ERDAS IMAGINE 2016 to develop False Color Composite (Band 2, Band 3, and Band 4). Supervised classification was done to obtain following classes - (1) mixed evergreen and deciduous forests, (2) alpine meadows, (3) low altitude grasslands, (4) woody patches above timberline, (5) forest blanks, (6) cultivated land, (7) rocks and boulders, (8) barren, (9) water bodies, (10) settlement, and (11) road. The validation was carried out using natural colour high resolution image (0.5–2 m) of different seasons from Digital Globe at GoogleEarth™ Pro.

(ii) Timberline and trees were mapped using natural colour and high spatial resolution image (0.5–2 m) of Digital Globe for (a) continuous close canopy towards high altitude limits of forests, i.e., timberline (termination of the continuum of forests extending from lower region to higher region), (b) patches of woody vegetation (*Rhododendron campanulatum* thickets) beyond timberline, i.e., outside forests, and (c) isolated standing individual trees in the alpine meadows, i.e., outside the forests and woody patches.

Visual interpretation technique was employed to separate and map these three features of woody vegetation, and to mark iso-heights as a line in the study area (*timberline* - connecting the highest edge of continuous forest; *treeline*- outposts of individual trees). ArcGIS was used for various analysis and extraction of spatial attributes of vegetation. Treeline, joining top most trees located above timberline, is an imaginary and broken (at several places) line. Distance from watershed boundary was measured as crow fly line between points of maximum elevation of treeline at a location to the nearest point of upper watershed boundary. Distance of individual trees from the nearest timberline point was measured as a positive indicator of advancement in tree establishment beyond timberline. In case of woody patches this distance was measured from lowest elevation at boundary of a patch. Mean elevation of a woody patch was determined by i.e., centroide function.

(iii) Topographical (altitude, slope, aspects) and geographical features (timberline elevation, height of summit, watershed boundary, elevation of individual trees, and others) were obtained from Aster Digital Elevation Model (resolution of 30 m), and relationship was developed between spatial patterns of timberline and topographical features of watershed. DEM of GoogleEarth™ Pro was used to develop relationships of treeline, woody patches and individual trees with topographical features by importing shape files to GoogleEarth™ Pro. Effect of mountain height on the timberline was determined following Odland (2015), and relationship between timberline elevation and mountain heights (summits and watershed boundary) was analyzed by linear regression.

(iv) Extensive ground truthing was done for locations of trees (species at timberline and beyond) to map occurrence at highest elevations. Locations were captured using GPS (Garmin Oregon 550) having capability to capture Photo with GPS tagging but comments can not be icorporated. One mobile Application (named HIMA) was developed for Android Phone to use multiple functions (camera, clock, and GPS) in an integrated manner so notes may also be taken in the phone itself. GPS and HIMA app on Android phone (ASUS ZOOLD) were used in ground truthing. On availability of internet connectivity HIMA app automatically uploads the data to the server where it can be visualized on internet (*himalayancitizen.co.in*). This mobile app can be downloaded from Google Play and from the web page of visualization. Above timberline, trees of different species, and individuals of *R. campanulatum* (above 1 m in height) were mapped.

Results

Landuse/landcover

Of the total area of Tungnath Watershed (Fig. 2) about 80% was under forests (Table 1), with 78.5% under mixed evergreen forests, divisible into mixed *kharsu* oak (*Quercus semecarpifolia*) - fir

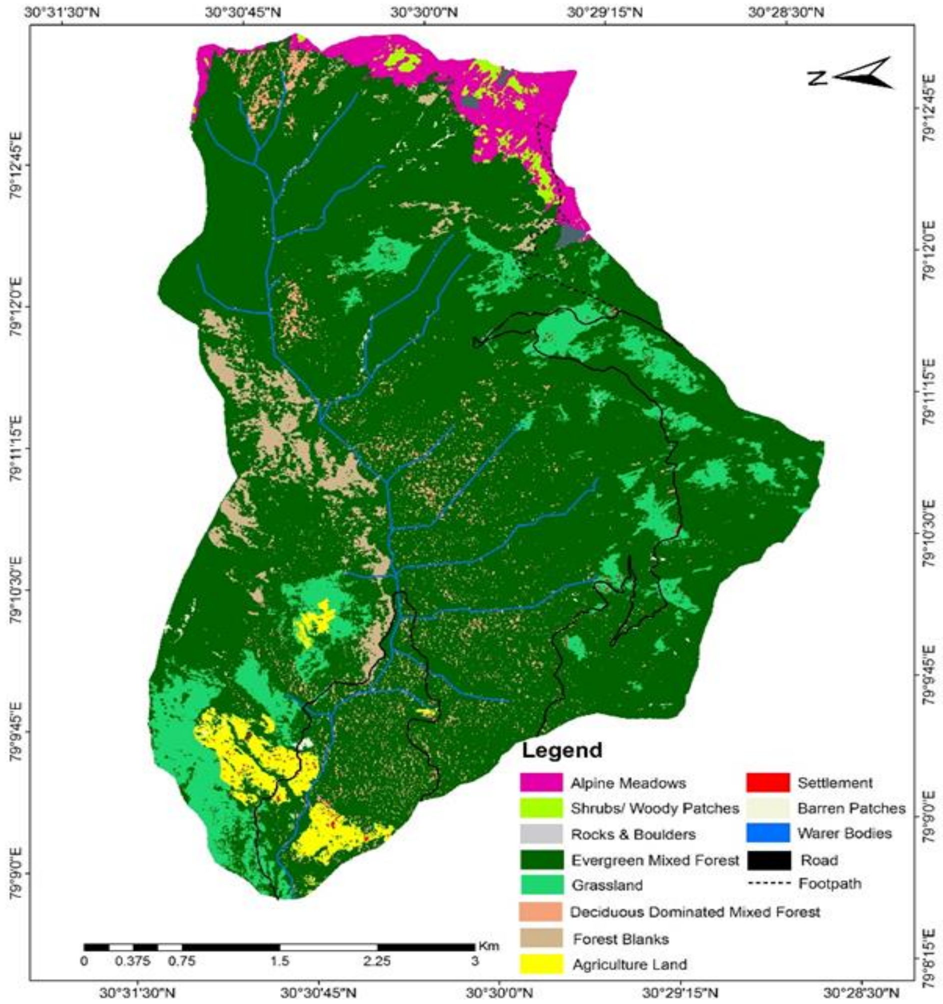

Fig. 2. Landuse/landcover of Tungnath watershed (derived from LISS-IV image).

Table 1. Landuse/landcover of Tungnath watershed (derived from LISS-IV).

Classes	Area (ha)	Area (%)
Evergreen mixed forest	1877.9	78.2
Deciduous dominated mixed forest	49.8	2.1
Alpine meadows	88.3	3.7
Low altitude grassland	198.8	8.3
Shrubs/woody patches	17.4	0.7
Forest blanks	80.9	3.4
Agriculture land	56.0	2.3
Rocks and boulders	4.9	0.2
Barren patches	6.2	0.3
Water bodies	10.4	0.4
Settlements	2.8	0.1
Roads	7.1	0.3

Table 2. Distribution of woody patches of *R. campanulatum* by different size classes.

Area (ha)	Number	Percent
< 0.05	73	58.9
0.05–0.1	14	11.3
0.1–0.5	26	21.0
0.5–1	7	5.6
>1	4	3.2

(*Abies pindrow* and *Abies spectabilis*) type towards higher altitudes, and (ii) mixed moru oak (*Q. floribunda*) and banj oak (*Q. leucotricophora*) type towards lower altitudes. At few places deciduous mixed forest (2% of the total watershed) occurred, generally along streams. Woody patches above timberline occupied 17.4 ha area.

Of the total watershed area, grasslands below 3000m asl altitude occupied 8.3%, and alpine meadows, above 3000 m asl, 3.7% (80 ha). Before

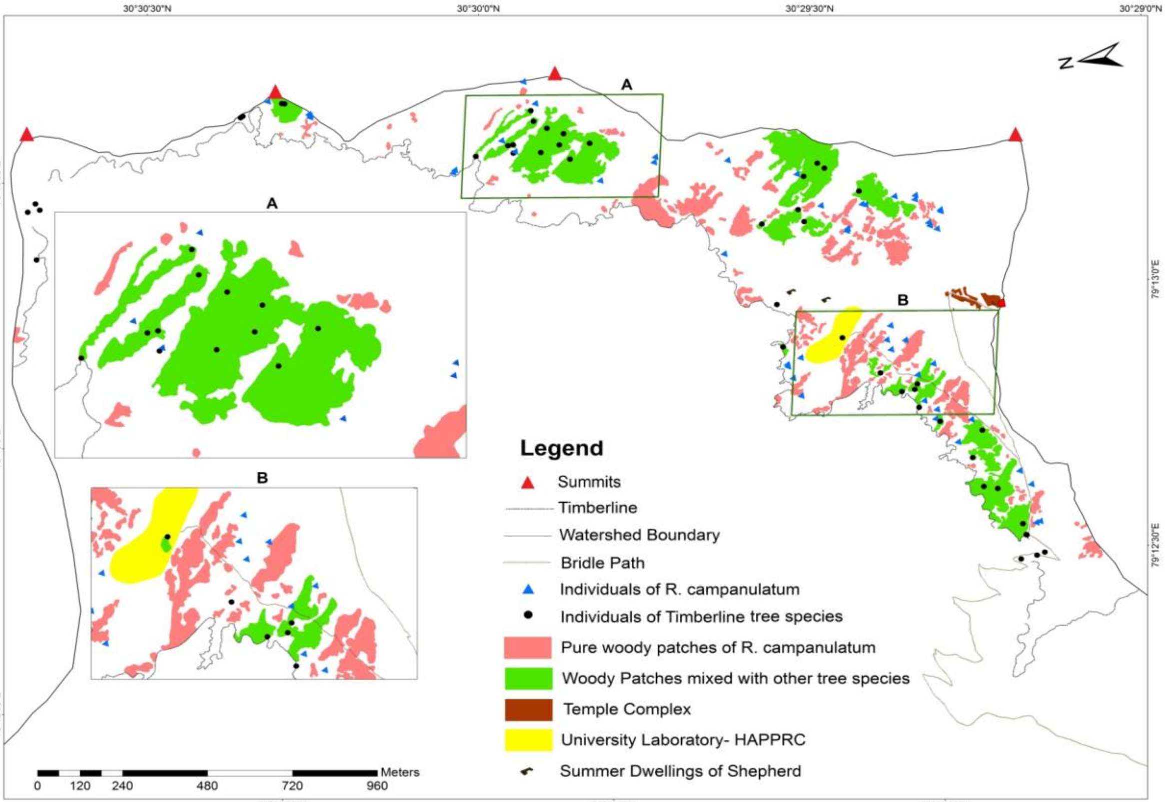

Fig. 3. Details of timberline and woody vegetation (patches and individual trees) above timberline in Tungnath.

inclusion in the Kedarnath Wildlife Sanctuary, this watershed was a grazing ground for sheep and goats, brought from faraway places by nomads, and livestock from nearby villages. Agriculture remains confined to the lower elevation in an area of 56 ha (2.3% of the total watershed).

Spatial features of timberline and treeline

The 7.91 km long timberline took a zig-zag course between 3070 m asl and 3460 m asl (Fig. 3). Of this about 55% was within a hundred meter range between 3200 m and 3300 m asl (Fig. 4A). Field observations from other locations of Uttarakhand also indicate similar altitudinal range for timberlines. Running continuity of timberline in the watershed was broken (7 fragments) by natural (streams, rocks, etc.) and man-made barriers (concrete path made for tourists). The dominant tree species at timberline were *A. spectabilis, B. utilis,* and *Q. semecarpifolia* but their dominance kept in changing along the timberline courses (Fig. 3). The *Betula* timberline was relatively higher, the mean elevations being above 3300 m. The mean timberline elevation dominated by *Abies* was 3250 m and that of *Quercus* was 3200 m.

As for timberline distribution in relation to slope exposure, it was largely divided between NW aspect (~50% of timberline) and W aspect (~31%). The proportion of timberline tended to decrease from moist to dry aspects (Fig. 4B).

Scattered and isolated trees of *A. spectabilis, B. utilis*, *Sorbus foliolosa, Prunus cornota,* and *Acer pictum* were present above timberline. The line connecting uppermost trees (treeline) ranged from 3280 m (minimum) to 3510 m (maximum). Treeline elevation was 15 m to 170 m below the upper boundary of watershed but at few locations scattered saplings of tree species occurred at the upper watershed boundary. Evidently, at these locations trees cannot move up under the influence of climate warming, they could only increase in density.

Among the different tree species forming treelines, the highest advancement (tree-species line) was observed for *Betula utilis* (237 ± 153 m

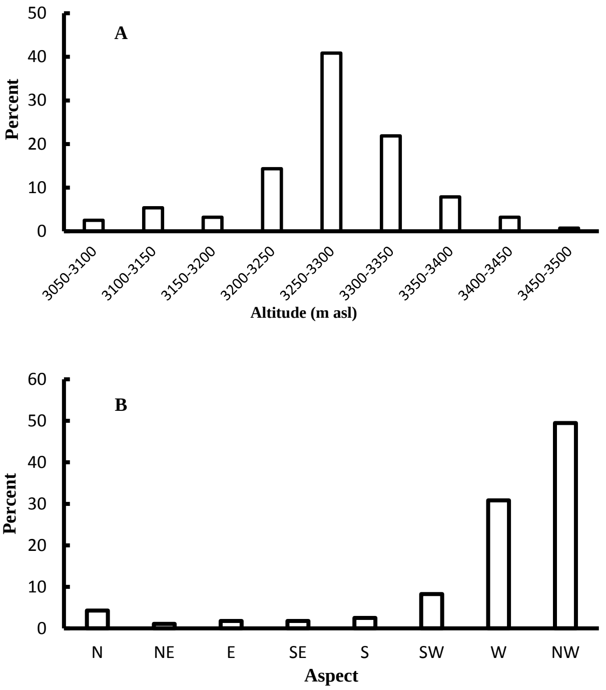

Fig. 4. Timberline distribution (as percentage of the total timberline length) in relation to elevation (A), and aspects (B).

Table 3. Distribution of woody patches and individual trees of *R. campanulatum* by 50 m elevation bands ranging from 3200 m to 3550 m asl.

Altitude (m asl)	Woody Patches		Individual Trees	
	Number	Percent	Number	Percent
3200–3250	2	1.6	-	-
3250–3300	16	12.9	8	16.0
3300–3350	56	45.1	15	30.0
3350–3400	19	15.3	11	22.0
3400–3450	13	10.5	2	4.0
3450–3500	13	10.5	6	12.0
3500–3550	5	4.0	8	16.0

average distance from timberline), followed by *S. foliolosa* (218 ± 157 m). Average advancement of tree-species line from timberline for other species (*A. spectabilis, A. pictum, Q. semecarpifolia, R. arboreum, P. cornota, Viburnum grandiflorum*) ranged from < 10 to 94 m.

Spatial characteristics of Rhododendron campanulatum *above timberline*

Above timberline, *R. campanulatum* extended into alpine meadows. This species forms extensive patches of woody vegetation as well as occurred as solitary individuals. The advancement of *R. campanulatum* krummholz seems to be a common feature of treeline ecotone in this part of Himalayas.

Woody patches

Above timberline, 124 woody patches of different sizes were formed by *Rhododendron campanulatum* (Fig. 3). These patches were either exclusively of *R. campanulatum* (85% of the total woody patches) or *R. campanulatum* mixed with a few individuals of *Abies, Betula*, and *Sorbus* (15% of the total patches of *R. campanulatum*). Among timberline species, *Sorbus foliolosa* (a small tree) was most commonly occurring tree species in these woody patches.

The total area under woody patches of *R. campanulatum* was 22.6 ha, which accounted for about 17% of the total area above timberline. The area of individual woody patches ranged widely from 72 m^2 to 36,704 m^2, and with increasing patch size, the number of patches decreased, almost 59% of patches being smaller than 500 m^2 (Table 2). Woody patches having the other tree species were bigger in size (7000 ± 9500 m^2 average size) than the pure patches of *R. campanulatum* (900 ± 1600 m^2).

Distribution of woody patches (elevation at central point of the patch) by 50 m elevation bands along altitudinal gradient indicates that the highest number of woody patches (56) occurred between 3300 m and 3350 m asl (Table 3). In general, individual patches had a narrow range of elevational width (lowest and highest point of a patch). In few patches such a spread was observed for 75 m or more. Further investigations are required for micro-habitat characterization of such patches.

Some woody patches occurred next to timberline, but there were many several hundred meters upslope (up to 750 m). More than half of patches (59%) occurred within the 100 m distance from timberline, thereafter the number kept on decreasing leaving only 3 patches above 500 m distance from timberline (Fig. 5).

Like timberline, a few woody patches (6 in number) occurred at the locations on the watershed boundary, while farthest was located at a distance of 925 m from the watershed boundary. 43.5% of the woody patches were located at a distance of < 200 m from nearest watershed boundary.

Individual trees

Outside the woody patches, a total 50 solitary individuals of *R. campanulatum* were also identified

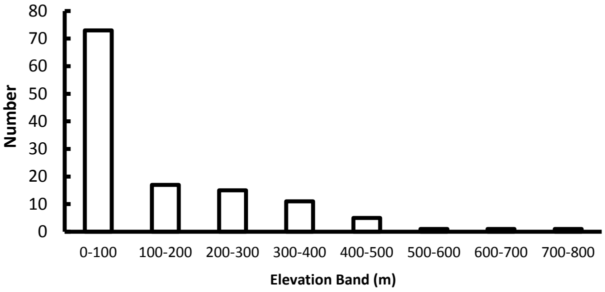

Fig. 5. Frequency distribution of woody patches above timberline in relation to distances (100 m band) from timberline.

Table 4. Distribution of scttered solitary individual trees by distance band of 100 m from the nearest edge of timberline.

Distance Range	Scattered Individual			
	R. campanulatum		Timberline Tree Species	
(m)	Number	Percent	Number	Percent
0–100	23	46.0	27	57.4
100–200	10	20.0	4	8.5
200–300	1	2.0	9	19.1
300–400	7	14.0	4	8.5
400–500	2	4.0	3	6.4
500–600	3	6.0	-	-
600–700	4	8.0	-	-

above timberline between 3250 m and 3550 m asl on the image, and were mapped (Fig. 3). The highest number of individuals (30% of total) occurred in the same altitudinal range (3300–3350 m) where woody patches occurred most (Table 3). About 66% of the individuals were located within 200 m from the timberline (Table 4). With increase in distance number of individuals was decreasing.

Spatial characteristics of individual trees above Timberline - Timberline tree species

A total 47 solitary individuals of 8 species were identified at treeline (presence of a tree at the highest elevation); 62% of such treeline individuals were of *Abies* (32% of the total individuals at treeline) and *Sorbus* (30%). *B. utilis* and *R. arboreum* contributed equally (13% each). Four species (*Acer, Viburnum, Prunus* and *Quercus*) were represented by one or two individuals at different locations of treeline.

Timberline is not a straight line; hence distance of individual tree to nearest timberline point (crow fly distance) was measured to realize advancement in tree establishment. Some trees were just adjacent to timberline <10 m, whereas the farthest was at 470 m (*Sorbus*) from timberline (~3510 m asl, Fig. 6). Among these eight species, *Q. semecarpifolia* was slow moving species (all individuals were <10 m from timberline) which could be due to viviparous nature of seeds. In contrast, *Betula,* having wind dispersed seeds, was growing from 50 m (3320 m asl) to 460 m (3500 m asl) above timberline. This range for *Abies* was from <10 m (3320 m asl) to 230 m (3360 m asl).

More than half of the individual trees of all species were located within 100 m from the timberline (57%, Table 4). A greater scatter of tree individuals within 100 m distance band indicates that individuals can establish as high as up to 3400 m and more, if the distance is below 100 m from timberline (Fig. 6). It shows that distance is more limiting than elevation under a certain limit.

Space above timberline/treeline and summit syndrome

Due to local topographical variations, elevation ranges of treeline and timberline coincided at a few points in the watershed. Elevations of timberline (n = 23) and treeline (n = 14) were positively related with mountain heights (in this case, summits and nearest point of watershed boundary) of the Tungnath watershed. It was observed that an increase in mountain height will lead to an increase in timberline (P = 0.01) and treeline (P = 0.04) elevation. Between the two, the upper elevation of timberline was more influenced by availability of space towards higher elevation. It shows that the presence of low height mountains may lower the local timberline elevation in the Himalayas.

Discussion

This study has shows that the use of remote sensing techniques can give several useful cartographic information about treeline ecotone which are not possible by manual sampling (Fig. 3). The remote sensing techniques enabled us to give a detailed spatial distribution of timberline, treeline, woody patches, and isolated individual trees above timberline. Treeline and timberline elevations are known to be affected by several factors, apart from heat deficiency. Grazing pressure (Piermattei *et al.* 2012), the lack of substrate or habitat for seedling establishment (Germino *et al.* 2002), and abiotic

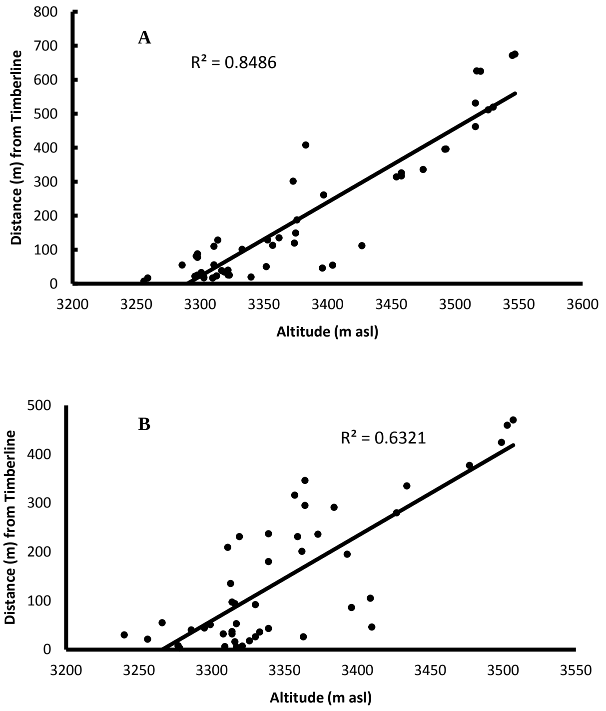

Fig. 6. Distribution of solitary individual trees along altitude (above timberline) and distance from timberline - (A) *R. campanulatum*, and (B) Tree species of timberline.

factors (solar irradiance and nighttime temperature) in photosynthetic carbon acquisition by seedlings, (Johnson *et al.* 2004), and soil moisture (Hughes *et al.* 2009) are some of factors often suggested to limit the upslope shift of trees. Using remotely sensed data we found that there is significant positive correlation between timberline/ treeline elevations and height of nearest mountain ranges or summits in the watershed.

The scattered individual trees and woody patches are not only structural features of treeline ecotone, but also facilitators of further growth of vegetation in a warming world. In other words, the isolated individual trees and woody patches may provide nuclei- for the growth of vegetation. Facilitative effects of woody patches are known for tree species recruitment in harsh alpine environment. For example, *Rhodeodendron* thickets provide microsite habitat for seedling establishment of *Betula* species in Europe (Akhalkatsi *et al.* 2006). In Andes, above-timberline small forest patches had similar patterns of seed dispersal as the timberline but minimal (< 1%) seeds were dispersed up to 10m into the grasslands of high altitudes (locally known as *Puna*). At edge of a patch/forest timberline, seedling abundances were lower in the grasslands relative to the adjacent forest and forest–*puna* ecotone (Rehm & Feeley 2013). This indicates that patches above the timberline may act as source for further forest expansion into the higher reaches, however competition with alpine communities and with *Rhododendron* patches may also limit it. In Australia, it has been observed that tussock grasses may physically protect as well as compete with the tree seedlings of *Eucalyptus pauciflora* growing near treeline (Noble 1980).

In addition to biological attributes of a tree species and impacts of climate change, cultural influences are critical for understanding the response of timberline. Alpine zone of the Tungnath watershed is affected by livestock grazing and tourism. Such activities may influence perceived shifts of timberline (upward movement) due to climate change. The presence of large herbivores and their activities in alpine landscape may either strengthen or nullify the impacts of a changed climate (Cairns & Moen 2004; Hofgaard *et al.* 2009). The recent expansion of black pine (*Pinus nigra*) trees in the central Apennines of Italy was attributed to reduced livestock grazing as well as to climate change (Piermattei *et al.* 2012). At Tungnath site, while grazing pressure is on decline, tourism and hiking activities have increased. Improved road network has increased human pressure and disturbances.

Conclusion and future research

Remote sensing techniques can help in capturing several spatial characters of treeline ecotone at micro-watershed level by providing spatial distribution of timberline, treeline, woody patches, and isolated trees above timberline. This study for the first time shows the precise position of treeline and timberline in a Himalayan watershed. This is the first remote sensing based attempt which contributes to methodological protocol to develop insight into the characteristics of Himalayan treeline ecotone. Such details are required to detect changes due to climate change and other factors. Further research is required (i) to know and quantify species association/vegetation assemblages of woody patches, and (ii) in association with present data set to develop landscape level understanding on facilitation/ expansion of tree species towards high altitude.

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Topographical characterisation of high altitude timberline in the Indian Central Himalayan region

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Abstract: This study explores spatial patterns of timberline in the Indian Central Himalayan region (Uttarakhand State) to determine timberline elevations and its distribution across 22 watersheds. Characterization of spatial attributes of timberline based on topographical features was carried on. This study shows that remote sensing technique can be quite rewarding for capturing regional scenario on spatial distribution of timberlines. We could provide several new information on the spatial patterns of Indian Central Himalayan timberline. Firstly, the length of timberline is far longer than generally indicated by field sampling approach alone. In Uttarakhand it was 2750 km long within a crow flight distance of about one hundred km. Secondly, the segmentation of timberline due to immature topography and high tectonic activities is quite common. Thirdly, small timberlines enclosing small summits covered with alpine meadows are common feature in this part of Himalayas where forests grow up to considerably high elevations. In such cases climate warming is expected to drive the accumulation of species around the summits under the influence of global warming. Fourthly, it is long continuous timberline where much of the upward movement of plants would take place because of the availability of land areas between snowline and timberline. Such information about regional timberline will improve our understanding about influence of regional peculiarities on current positions and provide benchmark for assessing future shifts due to climatic changes and anthropogenic activities.

Key words: Central Himalaya, climate change, forest, mountain summit, timberline, topography.

Guest editor: S.P. Singh

Introduction

The intensity of climate change is likely to be more severe towards higher latitudes and altitudes (McNeely 1990), where timberlines occur; hence they are among the most vulnerable systems to global climate change. Climatic timberline (based on local maximum elevation of existing forest stands; Körner & Paulsen 2004) is one of the fundamental ecological boundaries (Schickhoff 2005). The high altitude limits of forests are synonymously referred as treeline or timberline by various workers but are different. The treeline represents an ecological transition zone between fundamentally different low land and high altitude ecosystems (Mani 1978) which is a boundary or transition zone. Viewing from a distance, the ecotonal transition looks quite abrupt and is customarily regarded as a line (Shi & Wu 2013). Using satellite images or other remote sensing techniques certain canopy coverages can be mapped as treeline, and with GPS as treeline ecotone (Danzeglocke 2005; Singh *et al.* 2012).

Through satellite remote sensing effective monitoring (Baker *et al.* 1995) is possible for timberline resources and impacts of climate change

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**Corresponding Author*; e-mail: subrats@rediffmail.com on them. There is a need for satellite based mapping in the Himalaya because of their remoteness and difficult terrain. The highest treeline of the Northern Hemisphere occurs in Himalayan (Miehe *et al.* 2007). Field samples limited to a few places may not represent regional position of timberlines. Thus, sky-based measurements are necessary to detect the responses of timberline ecotone to the climate change at a regional level.

To find out advancement of timberline in the Himalayan region, use of remote sensing is a better choice over field based study (Bharti *et al.* 2012; Juntunen *et al.* 2002; Panigrahy *et al.* 2010a, b; Singh *et al.* 2012) but actual shift of timberline remains debatable (Bharti *et al.* 2011). Accurate determinations of timberline elevations (Beaman 1962) are desirable not only to know current position, but also for other reasons too- understanding of ecology of a species (distribution, tolerance range, comparative studies, etc.) and influence of geography (position and magnitude of controlling factors, and fluctuations therein).

Globally, timberline elevation decreases with latitude (Berdanier 2010) but latitudinal decrease of timberline elevation is not consistent as in mountain several other factors also influence it (Daubenmire 1954). In Europe, a study on Fennoscandian timberline indicates that factors other than climate such as "mountain mass elevation" and “summit syndrome” also affect timberline elevation (Odland 2015). This study explores spatial patterns of timberline in the Indian Central Himalaya to (i) determine timberline elevational range (lowest and highest) in relation to latitude, (ii) characterize the spatial attributes of timberline based on topographical features, and (iii) to find out distributional pattern of timberline in different watersheds, with and without permanent snow cover. An accurate estimation of regional timberline will improve our understanding about the influence of regional peculiarities on current positions and provide benchmark for assessing future shifts due to climatic changes and anthropogenic activities.

Study area

Indian Central Himalayan region (Uttarakhand State) occupies 53,483 km^2 geographical area between 28°43′N latitude and 31°28′N and 77°34′E and 81°03′E longitude. About 67% of the geographical area of the state is below 2500 m asl (Sharma & Phartiyal 2014), and forests occupy about 45% of the total area (FSI 2015). Altitudinal zonation of the state between 2500 m (lower limit of occurrence of high altitude forest types) and 4500 m asl (upper limit of forests) indicates that only 17% area of the state is available for forest types occurring in high elevations (Fig. 1), and 16.2% of the area in the state is above 4500 m asl which is occupied largely by permanent snow, glaciers, rocks, and moraines. From south to north mountain ranges can be classified as: (i) *Inner Himalaya* - permanent snow cover and adjacent high elevations of largely geological belts of 'Greater Himalaya' and in some part 'Trans Himalaya', (ii) *Outer Himalaya* - ranges, towards south, far away from Inner Himalaya having low or moderate elevations of Siwaliks and some part of Lesser Himalayan belt, and (iii) *Middle Himalaya* - in between Inner and Outer Himalaya moderate elevational ranges of largely Lesser Himalayan belt having abrupt high rising summits at few locations due to local geological faults. The drainage system is part of the *Ganga* river system to which various rivers and tributaries (snowfed and rainfed) originating from different watersheds contribute. The common timberline tree species are *Betula utilis, Abies pindrow, Quercus semicarpifolia*, etc (Rawal *et al.* 2018 in this issue).

Methods

Spatial data on timberline of entire Indian Central Himalaya was generated from maps developed using satellite images, and was subject to various statistical treatments.

Digital Data and Image Interpretation: Satellite images of Landsat 8 (multi-spectral, spatial resolution of 30 m) were used to generate a regional scale timberline (highest edge of the forest) mapping. Images were downloaded from United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/) for the year 2015. Total five satellite scenes (georeferenced and orthorectified - UTM WGS 1984, zone 44) covered the entire region (Table 1). Satellite data were subject to layer stacking (Band 2, Band 3, Band 4, Band 5, Band 6 and Band 7) to develop False Colour Composite, and image enhancement techniques were applied to improve the interpretability of image. Various spatial tools of ERDAS IMAGINE 2016 were used for this purpose. The satellite images were then subjected to knowledge based interpretation technique and timberline was delineated by visual interpretation method. This method is more appropriate in mountainous conditions (rugged terrain of the Himalaya) where complex topography challenges auto extraction. An isoline connecting the highest edge of forests was

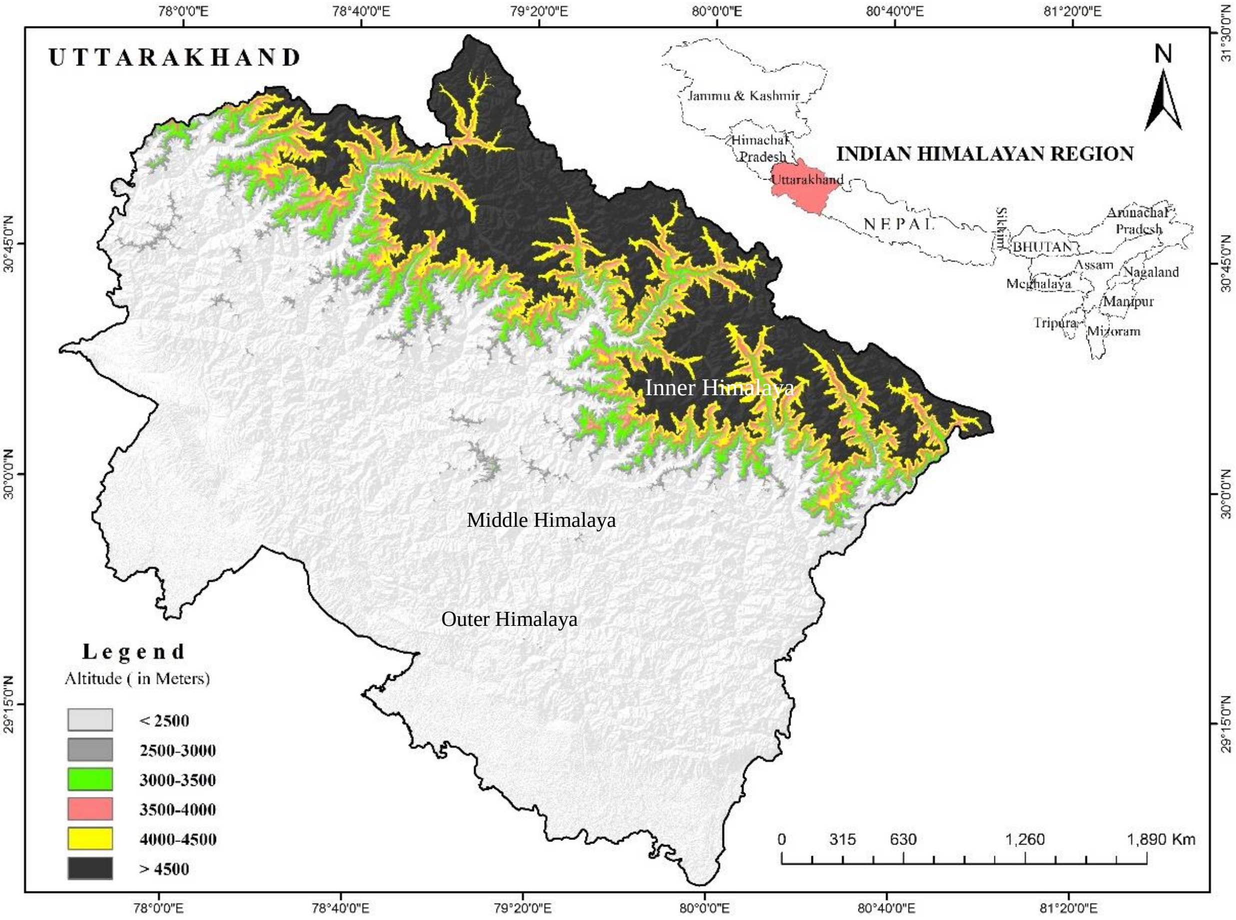

Fig. 1. Location map of Indian Central Himalaya (Uttarakhand) showing areas under different elevational bands above 2500 m.

Table 1. Landsat images used to determine the timberline of Indian Central Himalaya.

Date	WRS Path	WRS Row
2015/12/15	144	039
2015/11/20	145	039
2015/12/22	145	040
2015/12/29	146	038
2015/12/29	146	039

created as “timberline”. This line breaks at various places due to natural factors (landslide, rocks, etc.). High resolution Google Earth™ images were used for the validation of inaccessible sites.

Spatial attributes and relationship with topography: Topography (elevation and aspects) influences the presence and distribution of vegetation in an area. Generation of various spatial statistics and development of relationships with topography were done on GIS platform using Digital Elevation Model (DEM) of the earth surface. DEM of ASTER having same spatial resolution as of satellite data, was obtained from United States Geological Survey (USGS) portal (https://earthexplorer.usgs.gov/). This DEM was used to develop relationship between spatial characteristics of timberline with topographical features namely altitude, slope, and aspect. DEM was used to delineate watersheds using GeoMedia Desktop 2016. Arc GIS was used for various spatial analyses and extraction of attribute data of timberline.

Results

Types of timberline and their spatial attributes

Watersheds in high altitude areas of this study generally consisted of forest, alpine meadows and permanent snow cover from lower to higher elevations. By definition, a timberline is upper edge of a forest with at least 30% crown density. A timberline generally took a course of line of many

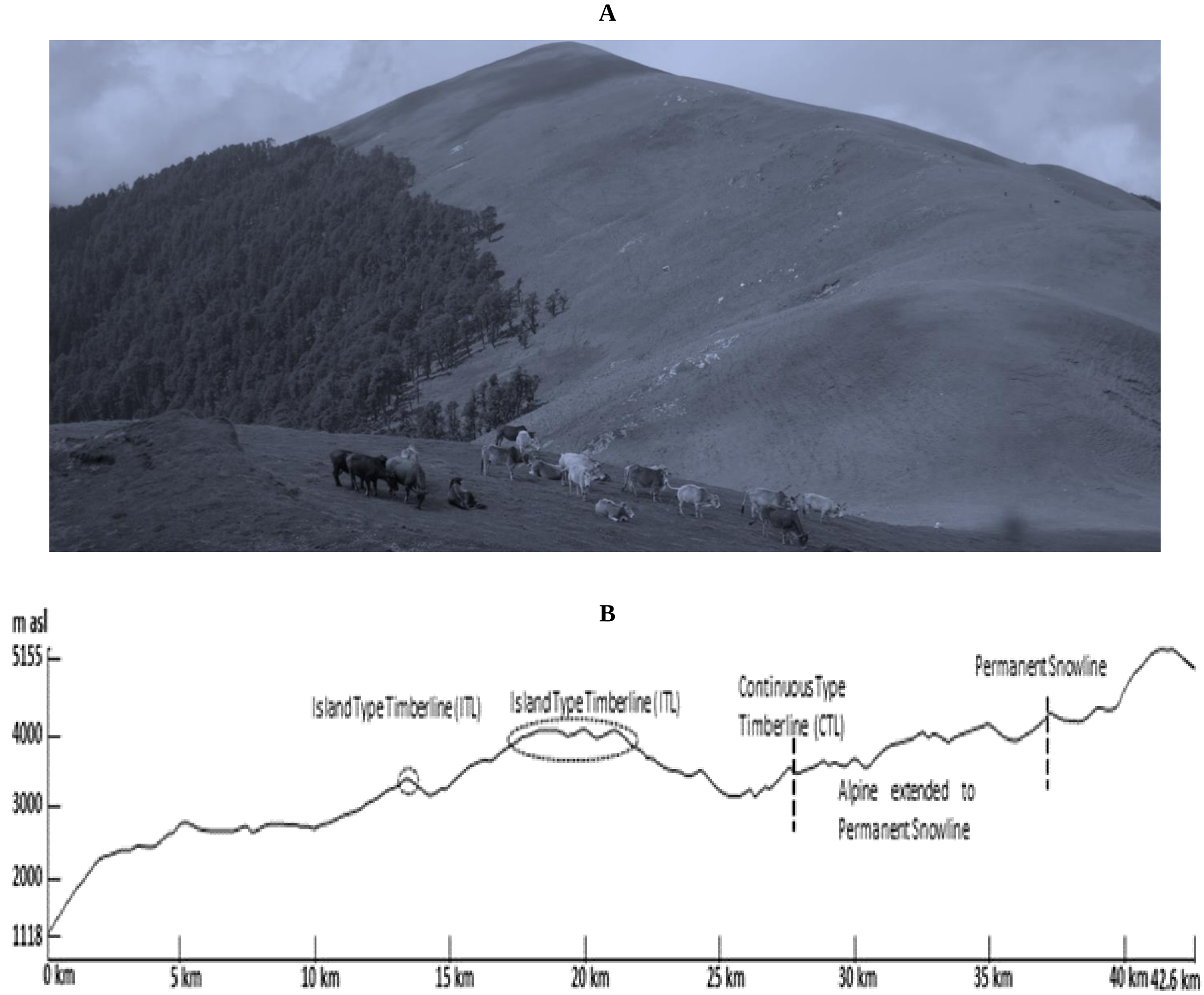

Fig. 2. **(A)** An isolated summit with an abrupt type timberline is made of *Quercus semecarpifolia*. The upper part is under alpine meadows, in lower part grazing livestock could be seen. **(B)** Sectional profile of a ridge running from river bed (1182 m) to altitude above 5000 m asl. Locations of two types of timberline (island and continuous), and permanent snowline are given.

miles in length parallel to permanent snowline, however, some timberlines encircled or enclosed small islands of alpine meadows near the summits in a relatively low elevation areas (Fig. 2A). In such cases summits are part of the alpine meadows. Here the first one is being referred to as continuous timberline (CT) and second one as summit enclosing timberline (SET) (Fig. 2B).

It may be pointed out that both timberlines were broken into several segments due to topographical barriers, but the segments of CT were long, often of tens and hundreds in kilometres. SETs were relatively shorter. Total length of timberline (sum of all pieces of the CT and SET types) in Uttarakhand was 2,750 km, of which CT type accounted for about 90%, and SET type, the rest. SET type occurred as isolated small circular and semi-circular fragments. The continuous type of timberline was like a long line broken only occasionally; the entire length of this was 2485 km, and it was broken into 91 segments, giving an average length of 27.3 km per segment.

The CT type timberlines traversed landscapes like a wave, moving up and down by several hundred meters within a few kilometres. Because it travelled along a zig-zag course, its total length was 7–8 times of the crow flight distance across the region, it occupied.

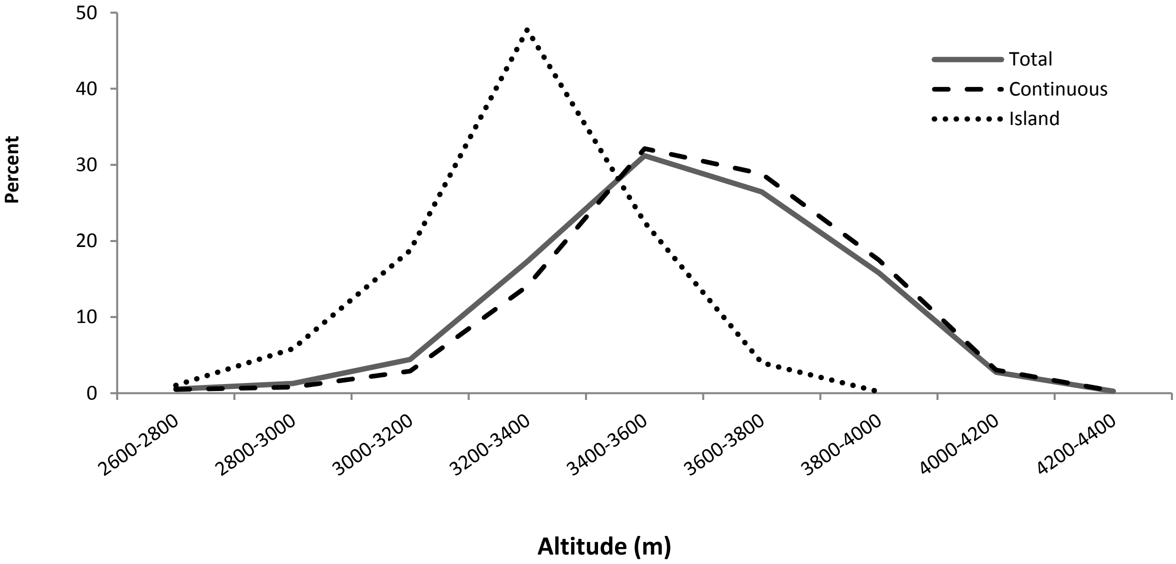

Fig. 3. Proportional distribution of timberline length along an elevation gradient. Percentage by elevational band of 200 m.

Distribution of total timberline length along the elevational gradient of about 1600 m (from 2600–2800 m elevation band to 4200–4400 m elevation band) showed a bell shaped pattern with peak (accounting for over one-third of the length) at 3600–3800 m (Fig. 3). The 3400–3800 m elevation range accounted for 57.6% of total timberline length of CT type. The peak distribution of SET type timberline was at a bit lower elevation band than continuous timberline type. Of the total length of SET type, about 61% occurred between 3400–3800 m.

The length of a continuous type timberline (CT) segment varied widely from 0.43 km to 388 km, and timberline became increasingly segmented towards higher side of elevation range because of increased topographical barriers and complexities.

In CT type the mean timberline elevation of segments (elevation of a segment varied along its length, hence a mean) ranged from 3215 m to 4020 m asl (Fig. 4). Distribution of timberline segments (as mean elevation timberline of segment) was as following- segment below 3500 m, 19%; between 3500 and 3600 m, 22%; between 3600 and 3700 m, 14%; 3700 and 3800 m, 22%; and above 3800 m asl, 23%.

Total length of SET, occurring at 32 different locations, was 265 km (Fig. 5). None of this type of timberline occurred above 4000m elevation. About 48% of 265 km occurred between 3200 m and 3400 m asl, and about 70% between 3200 and 3600 m, whereafter it sharply declined (Fig. 3). The length of SET at different locations ranged considerably from 0.55 km to ~60 km.

Distribution of timberline in relation to aspect and slope angle

Distribution of entire timberline with respect to aspect indicated that more of the timberline occurred on warmer aspects (SW = 14.3%, SE = 14%, W = 13.4%, E = 13.1%, & S = 12.6%; total 68%) than cooler aspects (N = 10.5%, NE = 10.9%, & NW = 11.2%; total 32%). The mean timberline elevations were generally higher on cooler aspects than the warmer aspects.

High Himalayan topography is very rugged and constituted by peaks and walls of watersheds, and valley floor. High altitude forests either creep into a valley floor or climbs to upslope on watershed boundary. Distribution of timberline in different slope categories indicates that trees have capability to grow on steep slopes, exceeding even 40°. Slope-wise distribution was as following: 17.7% of total timberline on gentle to moderate slopes (<20^{o}), and 27.7% on moderately steep slopes (20–30°), 27.7% on steep (30°–40°), and 26.9% on very steep slopes (> 40).

Spatial attributes of timberline in different watersheds

We delineated 22 watersheds from DEM within the region, of which in 15 watersheds timberline was

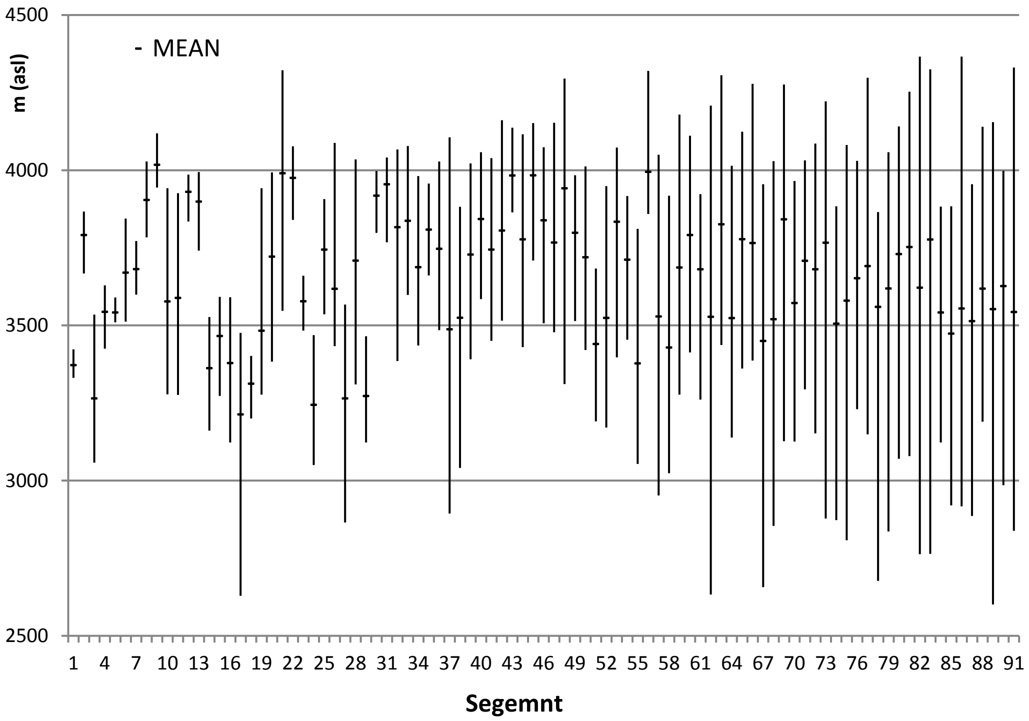

Fig. 4. Elevation range of a segment of continuous type timberline. Segments are arranged according to increasing length.

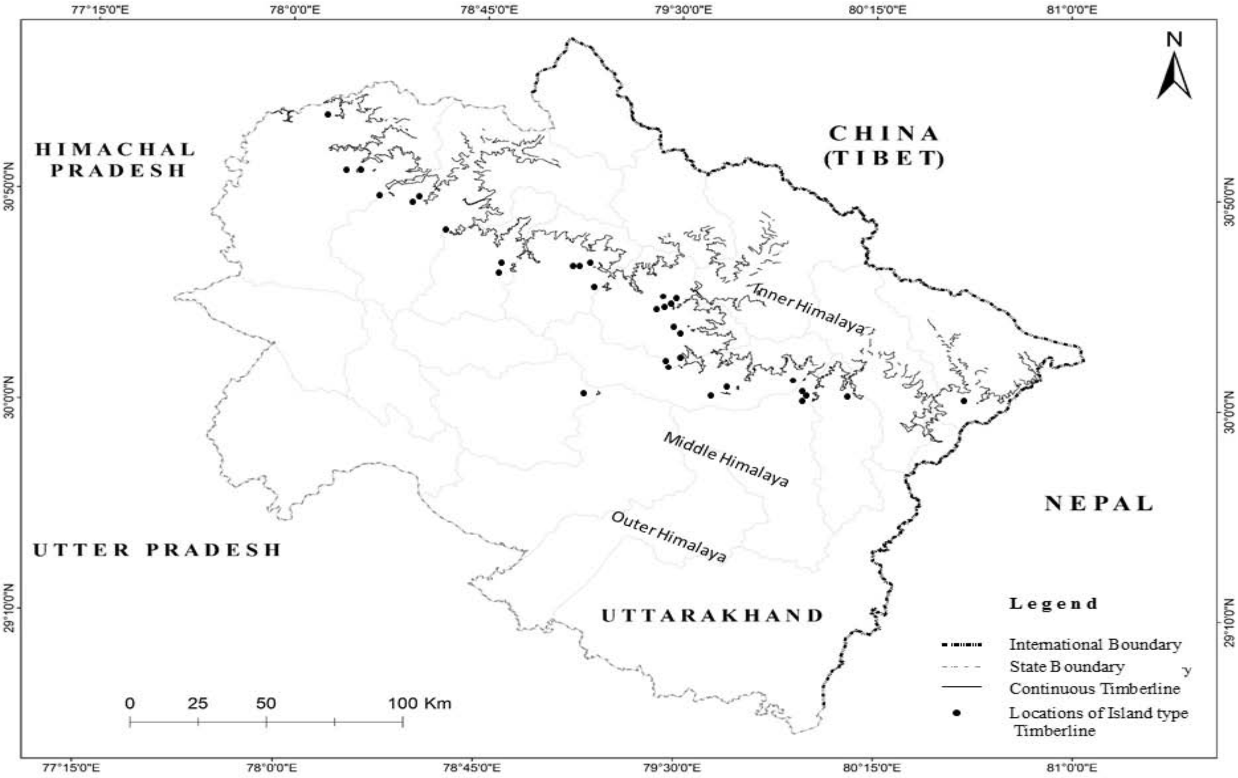

Fig. 5. Distribution of continuous and islands type (isolated pieces/dots) timberline in the Indian Central Himalaya. The island type timberline occupies relatively lower elevations.

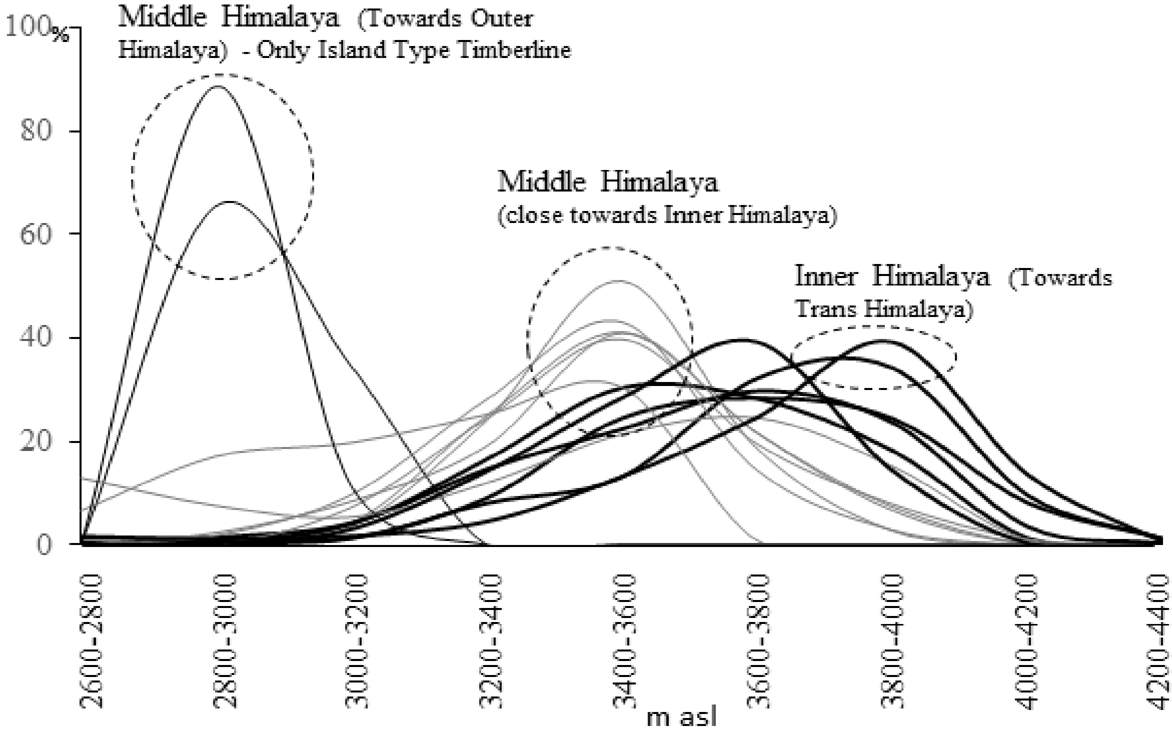

Fig. 6. Proportional distribution of timberline length by elevation bands (200 m) in study watersheds.

present (either one type or both types). Out of the 15 watersheds, four were without the permanent snowline, thus were largely rainfed. In two of such rainfed watersheds, CT was present which was running from the adjacent watershed (having permanent snow cover).

We infer from our timberline maps that the formation of CT type timberline requires the continuity of suitably high elevation over a fairly long stretch in a watershed. CT was present in that rainfed watershed which was adjacent to the snowfed watershed, but it was absent in that rainfed watershed which was adjacent to another rainfed watershed. In such rainfed watersheds only SET type was present. It is difficult to know whether the high elevation of watersheds with permanent snow cover simply provided suitable timberline elevation or its snow melt also facilitated tree growth.

Topography influenced the range of timberline elevation (TLE) in watersheds. Among the various watersheds, the minimum TLE ranged from ~2600 m to 3040 m while maximum TLE was between 3045 m and 4365 m. Among the different watersheds, mean TLE (mean of the watershed) ranged from 2930 m to 3755 m.

The elevation bands in which timberline occurred most varied across the study watersheds (Fig. 6). It was 2800–3000 m in two watersheds (I), 3400–3600 m in seven watersheds (II), 3600–3800 m in four watersheds (III) and 3800–4000 m in two watersheds (IV). These can be referred to as elevation centres of timberline. The timberline was centred in the lowest elevation band (I) in rainfed watershed of outer and Middle Himalayan ranges (see Fig. 5). In contrast, the highest timberlines were centred in snow-fed watersheds of inner Himalayan ranges (see Fig. 5).

Difference between lowest and highest timberline elevation within a watershed was between 145 m and 215 m in rainfed watersheds having only SET type timberline, while this difference in other watersheds ranged from 890 m to 1700 m.

SET was absent in three watersheds, and two (Sarswati and Dhauliganga) of these were located in the Inner Himalayan ranges where timberline elevation was the highest. The third watershed, Kaliganga (without SET), was a large watershed distributed both in Indian and Nepal, but the Indian portion (falling in the study area) was only 223 km^2 in Area.

It was observed that watersheds having more geological faults had more number of SET type timberline and higher segmentation in CT. In these high ranges geological disturbances account for the segmentation and isolated timberlines. These observations indicate that geological factors have a considerable role in giving shape to high elevation forests and timberline.

Discussion

This study shows that remote sensing technique can be quite rewarding for capturing regional scenario of timberlines. Unlike mountain timberlines of Europe and other such regions, in Himalayas they are high, remote and difficult to access. We could provide several new pieces of information on the spatial patterns of Indian Central Himalayan timberline. Firstly, the length of timberline is far longer than generally indicated by manual sampling. It is a major phyto-geographical feature, running across the region along a zig-zag course for 2750 km within a crow fly distance of a few hundred kilometres. Secondly, the segmentation of timberline due to immature topography and high tectonic activities is quite common. Thirdly, the presence of small timberlines enclosing small summits covered with alpine meadows is a common feature in this part of Himalayas where forests grow up to considerably high elevations. In such cases climate warming is expected to drive the accumulation of species around the summits under the influence of global warming. Fourthly, it is long continuous timberline where much of the upward movement of plants would take place because of the availability of land areas between snowline and timberline. Fifth, the elevational range of timberline even in a small geographical area can be clearly more than 1000 m. It would be interesting to know the patterns of timberline species distribution along such a length sunning across several watersheds.

More than half of the timberline length occurred between 3200 and 3600 m. This elevation band can be considered as ‘timberline centre’ for the Indian Central Himalaya, however TLE range was much wider. Two watersheds (Ganga and Yamuna) of the river Ganga contribute nearly 30% of the total timberline length of Uttarakhand, though they occupy only 16% of the total area of the state.

Apart from long continuous timberline, we identified an *island type timberline* (SET) around summits. SET was more in the Garhwal region of the state (27 locations) than Kumaun, indicating its more rugged and geologically broken terrain than the Kumaun region. Complexities of topographic features such as suitable elevation and availability of space (Latwal *et al.* 2018 in this issue), abrupt summits, steep slopes, and geographical placement (present study) influence the distribution of timberline in the region. Due to such spatial diversity, timberline species of the region may react in different ways to the changes due to climate and anthropogenic factors.

Aspect may influence species composition and structure of timberline (Danby & Hik 2007). An influence of topography and geology of the region is apparent on timberline elevation and location based shapes. Due to availability of suitable elevation, *Abies pindrow* forms timberline around two summits located within rainfed watersheds. These summits are located in the southernmost Himalayan ranges, and isolated like dots. Tree populations of these island type habitats are more vulnerable to impacts of climate change coupled with anthropogenic activities. Influence of human activities cannot be ignored, which lead to uncertainties in determining anthropogenic and climatic timberlines. This study along with observations of anthropogenic activities can be used as bench mark for such locations to detect any shift (in timberline elevations) in future.

Conclusion

Use of satellite images is promising technology to identify spatial attributes of timberline at a regional scale. This is the first study which describes spatial attributes and characterizes the Himalayan timberline on that basis. A comparison of the information generated with remote sensing method in this study with those derived from field sampling in mountains emphasizes that the latter gives not only a very incomplete picture of treeline, but also a distorted one. It seems that timberline elevation can exceed 4000 m in many parts of Himalayas, but they may be only exceptions. Our remote-sensed cartography shows that timberlines in Central Himalayas are centered between 3200–3600 m. Changes in the timberline centers would be more meaningful in the context of a region to document climate change impact than changes in one or two outliers. This study has created a framework to determine the impact of climate change in relation to the form of timberline, its elevation length and extent of isolation.

Island type of timberlines (SET) is important to monitor climate change impact, as they might be more sensitive in terms of changes in cover. They might act as nuclei around which future build up of vegetation may occur when heat deficiency is removed due to climate change. The study offers a method which could be used to analyze the pan-Himalayan distribution of timberline, and compare their sensitivities to climate change.

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Near surface temperature lapse rate for treeline environment in western Himalaya and possible impacts on ecotone vegetation

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Abstract: This study presents the maiden results of near surface temperature lapse rate (TLR) for treeline environment in the western Himalaya in India based on ground observations along an elevation transect (1500–3680 m). Statistically significant correlation and linear regression model was used to calculate TLRs for different months. The mean annual TLR in western Himalaya is less steep (−0.53 °C/100 m) than the commonly used value (−0.65 °C/100 m). Notably, the lapse rates of temperature varied across different seasons and the two study aspects suggesting that TLR is governed by micro-climatic and physiographic features. The highest mean TLR (−0.64 °C/100 m on NW aspect and −0.60 °C/100 m on SE aspect) was observed for pre-monsoon season (March–May) whereas the lowest (0.42 °C/100 m on NW aspect and −0.39 °C/100 m on SE aspect) for the winter season (December–February). The annual cycle of TLR reveals a bi-modal pattern with two maxima in the pre-monsoon and post-monsoon seasons whereas two minima in winter and monsoon, respectively. The higher TLR in dry or warmer and lower in humid or cold atmospheric conditions suggest different controlling factors determine TLR in the individual seasons. There is a need to examine whether the low TLR of the present study transect (−0.53 °C/100 m) is because of elevation-dependent warming (being more in higher elevations) under the influence of global climate change. The observed shallower TLR, an indication of elevation-dependent warming, may have several implications on ecotone vegetation in Himalaya under changing climate scenarios.

Key words: Climate change, ecotone vegetation, elevation dependent warming, temperature lapse rate, treeline, Western Himalaya.

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Introduction

Alpine treeline ecotone, occurring between a subalpine forest and alpine meadow, is an extremely temperature-sensitive transition zone (Körner 1998). Sensitivity of plant species to change in temperature and other abiotic factors (e.g. radiation, moisture, wind, slope exposure, topography) is high across this ecotone (Holtmeier & Broll 2005; Körner & Paulsen 2004; Li *et al.* 2008; Wang *et al.* 2005). The alpine regions in Himalaya are considered climate hotspots and indicator zones of species geographic range shift induced by climate change and global warming (Grabherr *et al.* 1994; Körner 2003; Lesica & Steele 1996; Telwala *et al.* 2013; Walther *et al.* 2002). Over past few decades accelerated rates of warming are noticeable in most of the Himalayan regions (Bhutiyani *et al.* 2010; Gao *et al.* 2004; IPCC 2007; Joshi & Kumar 2013; Shrestha *et al.* 1999). A positive feedback effect, arising from decreasing albedo on account of decline in snow cover and change in land use-land cover, is one of the possible reasons for warming in high altitude mountainous regions (Pepin & Losleben

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2002; Rangwala & Miller 2012). The spatial patterns of warming have an unequivocal impact on ecological balance of mountain ecosystems which is largely influenced by local scale variations of climate parameters (Gerlitz *et al.* 2015). We hypothesize that elevation-dependent warming (Pepin *et al.* 2015) in mountain environments may alter the temperature lapse rate (TLR, defined as the rate of change in temperature with rise in elevation) of near surface temperature. The near surface TLR is a controlling factor of many environmental processes and hence the altitudinal dependence of temperature in mountainous region is important to study impacts of climate change on various processes (e.g. climate-vegetation interactions, glacier retreat and melt runoff, change in hydrological and moisture regimes, etc.).

Different values of environmental lapse rate (e.g. −0.55 °C/100 m, −0.60 °C/100 m, −0.65 °C/100 m) are often used to estimate air temperature at ungauged sites when low precision suffices (Rolland 2003). However, in complex Himalayan terrain, climate at regional and local scale is affected by topography, latitude, movement of air and vegetation patterns (Barry 1992). Because of these factors climatic parameters (e.g. temperature and precipitation) in this region vary remarkably even over a short geographic distance and hence the regional distribution of temperature and precipitation vary along altitudinal gradient. Lapse rates may vary with latitude, topographic slope, regions, and season (Bolstad *et al.* 1998; Dodson & Marks 1997; Immerzeel *et al.* 2014; Rolland 2003), hence cannot be treated as spatially and temporally constant. Therefore, simply adopting the general temperature-elevation (T - E) trends and the rough approximations or estimate may not effectively explain T - E trends at local level. Some studies across the globe have further confirmed that the temperature lapse rates and precipitation gradient are highly variable in space and time in mountain regions and its magnitude may vary in different location as a function of energy balance (Gardner *et al.* 2009; Gouvas *et al.* 2011; Kattel *et al.* 2012; Rolland 2003; Thayyen & Dimri 2014). Therefore, assumptions of persistent values of TLR in mountains is imprecise and may lead to erroneous results about change in elevation dependent warming rate and its impacts on different ecosystems along elevation gradient.

Several studies have been carried out in different mountain regions across the world (e.g. Washington Cascades Mountains, Northern Italy and Autrian Alps, Mt. Taibai, Colardo Rocky Mountains, and in the Northern Hemisphere) on variability of TLR and its controlling factors (Diaz & Bradley 1997; Minder *et al.* 2010; Pepin *et al.* 2015; Rolland 2003; Tang & Fang 2006). However studies on temperature gradient based on observed data are lacking for Himalayan regions which encompass very wide bioclimatic elevational gradients. This is mainly because of the fact that the ground based meteorological observations in Himalaya are very scanty and location specific long term precise climate records are limited, particularly for tree line environments and other high altitude ecosystems in Indian part of Himalaya (Friedland *et al.* 2003; Shrestha *et al.* 1999). Given this background, the key questions addressed in this paper are: (i) Does the near surface temperature lapse rate in tree line environment vary across the seasons?, (ii) Does the aspect play a role in distribution of the temperature and its elevation gradient in Himalaya?, and (iii) How does TLR for treeline environment in Himalaya differ from the global average? Apart from these, based on published literature, this study also highlights the possible impacts of observed TLRs on the treeline vegetation. As far as our knowledge goes, this is the first attempt to estimate temperature lapse rates for treeline environment in western Himalaya. In this study we hypothesize that (a) TLR should decrease because of elevation-dependent warming, which stresses more temperature rise in higher elevations than in lower elevation, (b) because of reduced snow cover and concomitance decrease in albedo, the elevation dependent warming could be higher in winters, (c) this difference could be reflected in lower TLR during winters, (d) in other words, climate change may alter TLR.

Study Site

The present study was carried out in and around treeline ecotone of Chopta-Tungnath transect in Indian Western Himalaya (30°30.76′–30°27.59′N; 79°05.54′–79°16.55′E) varies between 1600 and 3680 m and 1500 and 3680 m along South Eastern (SE) and North Western (NW) slopes, respectively (Fig.1a). The forests at the higher elevations of the study area fall under the subalpine zone, which gives way to alpine meadows beyond the timberline ecotone (Rai *et al.* 2012). In higher altitudes, above treeline (3400–3700 m) region of the study transect, the grasslands are dominated by herb species of *Anemone, Potentilla, Aster, Geranium, Meconopsis, Primula* and dotted pockets of shrubs of *Rhododendron anthopogon* and *Juniperus* species. Whereas, in sub-alpine region (i.e. between 2900–

(a) (b)

Fig. 1. (a) Location map of the installed loggers within the study area (Source: Google Earth), (b) Automatic Weather Station installed at a high altitude site (3360 m; 30^{0}29.57' N, 79^{0}12.95'E).

3400 m) mixed forests dominated by species like *Rhododendron arboreum, R. campanulatum* scattered with a few *Abies pindrow* and *Taxus baccata* trees are present. Below 2800 m, broad-leaved forests are dominated by *Quercus semecarpifolia*, *Betula utilis, Abies spectabilis, Acer caesium, Rhododendron arboreum* and *Sorbus foliolosa.* The climate of Tungnath region is characterized bylong wet summers and long and cold winters. Based on observed meteorological records obtained from an AWS installed within the study area at 3360 m asl (30°29.57′N, 79°12.95′E; Fig. 1a,b), the average precipitation and temperature for 2017 were found as 2941.59 mm and 6.03 °C respectively. The climate of the Chopta-Tungnath transect is dominated by monsoon circulation, with pre-dominant easterly winds in the summer and westerly winds from October to March.

Methods

Meteorological Setup and Data

To estimate the TLR and its spatial variations over the study area, 10 portable ONSET HOBO Pro-V2 microbloggers and 6 RG-200 tipping bucket rain gauges (Global Water make; 8" dia.) were installed along an elevation gradient from 1500 m to 3680 m at two different aspects (N-W & S-E). The temperature loggers were covered with radiation shields to protect the sensors from direct incoming shortwave radiation on exposed sunlight. On the N-W slope, a more advanced AWS was installed at an altitude of 3360 m asl which consists of a Campbell SR50A sonic ranging sensor, an ARG-100 tipping bucket with a simple HOBO event data logger, and a Campbell temperature probe (109-L), and other sensors for measurement of temperature, soil moisture, wind speed and direction, and net radiation. Station data from all the sensors installed at different locations were recorded at 15 minutes intervals and the data collected during one-year period (December 2016 to November 2017) were used for various analyses.

The data were analysed for the entire year (December 2016 to November 2017) and seperately for the four main climatic seasons, namely Winter (December-February), Pre-monsoon (March–May), Monsoon (June–September), Post-monsoon (October–November). These distinct seasons were identified based on analysis of the observed precipitation and temperature data from two high altitude station located at 3360 m asl and 3140 m asl on two different aspect within the study transect and also based on the literature (Immerzeal *et al.* 2014; Kattel *et al.* 2012) for comparison of results. Fig. 2 show variation in daily temperatre and precipitation at a high altitude station (3360 m asl) on NW slope where approximately 92% of the total auunal rainfall occured during monsoon and nearly 6% occured during post-mosoon season. Similar patterns of variation in temeprature and precipitation are

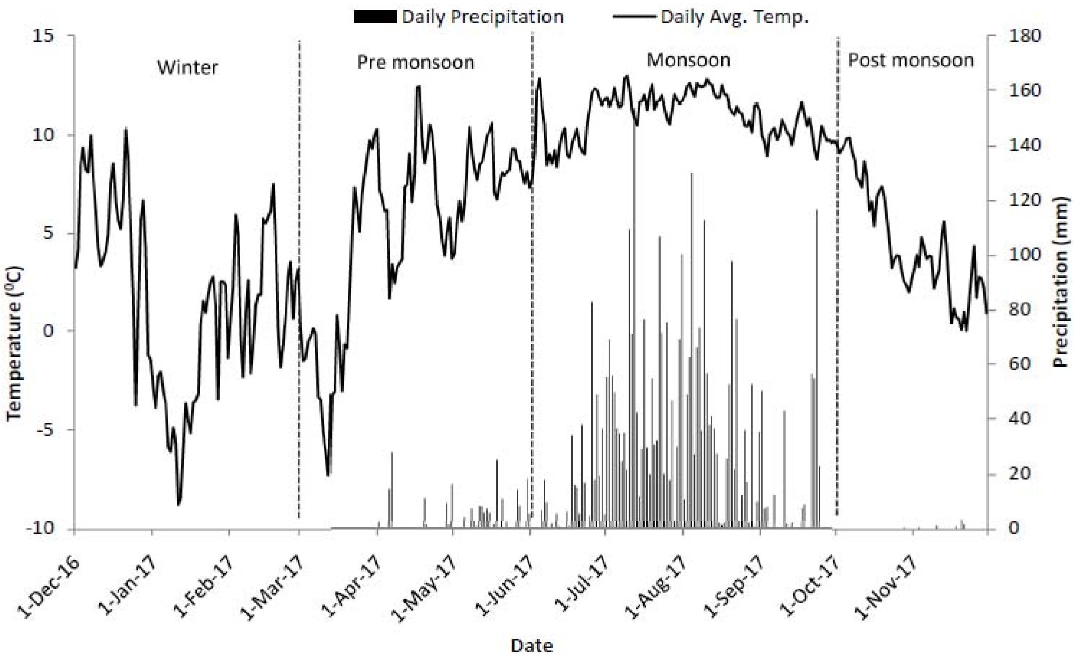

Fig. 2. Daily rainfall histogram and mean temperature at high altitude station (3360 m asl) on NW-aspect.

observed for SE slope; approximately 86% of the total aunnal rainfall occured during monsoon whereas nearly 12% occured during post-mosoon season. Within the study transect, the winter season at high altitudes is chareterized by the lowest temperatures and precipitation mostly in the form of snow. The pre-monsoon season is chareterized by relatively high temperatures gradually increasing till the onset of monsoon. During this period, high variability in diurnal temperature and small events of precipitation (average rainfall 315 mm) are obsrved. During the monsoon season heighest amount of rainfall (2120 mm) is received along with relatively high temperature, and charecteristically low diurnal varibility. A steady decrease in temperature alongwith a negligible amount of rainfall (average 7 mm) is the key feature of the post monsoon (autumn) season. Mean temeparture and precipitation records from two study aspects, north-west (WE) and south-east (SE) for the four seasons are summarized in tables 1 & 2.

Data analysis

The correlation coefficients between temperature and elevation of the station was calculated for the observed dataset. Monthly mean, maximum, and minimum temperatures were correlated to elevations, and the significant correlation coefficients were presented (Table 3). Correlation analysis was carried out to estimate the measure of the strength of the linear relationship between the two variables and test how strongly temperature is linearly controlled by elevation. The Pearson Correlation's Coefficient (*r*) between the two variables Temperature (*T*) and Elevation (*z*) can be expressed in the following forms:

$$r(T,Z) = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{T_i - \bar{T}}{S_T}\right)\left(\frac{z_i - \bar{z}}{S_z}\right)$$

Where and S_T, respectively, represents mean and standard deviation for temperature whereas and Z_T are the mean and standard deviation values for elevation. If the relationship between the variables is not linear, then the correlation coefficient does not adequately represent the strength of the relationship between the variable.

All temperature data were then aggregated to hourly values for various analyses. Generally, air temperature is assumed to decrease/increase linearly with elevation under well-mixed atmospheric boundary conditions (Lundquist *et al.* 2008). Temperature lapse rates were calculated by developing a regression equation using all point level observations of temperature and elevation. The developed regression determines nature of linear association between the two variables. TLRs (°C/100 m) were estimated using following regression equation:

$$LR = \frac{T_1 - T_2}{z_1 - z_2} = \frac{dT}{dz}$$

Table 1. An overview of the mean temperature (T in ^{0}C) and total rainfall (P in mm) for four seasons on North-West (NW) aspect.

Season	Station name (altitude in m asl)								
	Ukhimath (1500)**		Tala (1820)*	Dugalbhitha (2500)**		Chopta (2870)*	HAPPRC (3360)***		Chandrashila (3680)*
	T	P	T	T	P	T	T	P	T
Winter	12.61	---	9.69	5.57	---	3.27	1.72	---	2.48
Pre-monsoon	18.33	287.93	15.15	11.29	358.5	9.26	5.43	219.96	4.30
Monsoon	22.49	1425.49	19.48	16.07	2067.61	14.91	10.93	2721.62	10.19
Post-monsoon	17.07	0.5	14.30	9.88	5.31	8.19	4.56	10.41	6.57
Annual	17.6	1714.0	14.6	10.7	2431.4	8.9	5.6	2953.0	5.8

*Temperature logger, **Temperature logger & Raingauge, ***Automatic Weather Station.

Table 2. An overview of the mean temperature (T in ^{0}C) and total rainfall (P in mm) for four seasons on South-East (SE) aspect.

Season	Station name with altitude (in m asl)							
	Sirauli (1600)*	Mandal (2100)**		Kanchula Khark (2675)**		Saukhark (3100)**		Chandrashila (3680)*
	T	T	P	T	P	T	P	T
Winter	11.6	10.5	---	4.2	---	5.2	---	2.9
Pre-monsoon	18.1	15.6	280.47	9.8	379.8	7.7	371.1	4.3
Monsoon	22.4	20.1	1920.68	14.8	2208.8	12.7	2394.3	10.2
Post-monsoon	16.5	14.2	7.75	8.3	9.6	7.2	4.5	6.6
Annual	17.2	15.1	2209.0	9.3	2598.3	8.2	2770.0	6.0

*Temperature logger, **Temperature logger & Raingauge, ***Automatic Weather Station.

Table 3. Correlation between maximum, minimum, mean temperature and elevation

Months	Maximum temperature		Minimum temperature		Mean temperature	
	TLR (°C/100 m)	*r*	TLR (°C/100 m)	*r*	TLR (°C/100 m)	*R*
January	–0.67	–0.94*	–0.45	–0.94*	–0.53	–0.95*
February	–0.59	–0.93*	–0.42	–0.96*	–0.52	–0.97*
March	–0.82	–0.99*	–0.44	–0.95*	–0.61	–0.98*
April	–0.82	–0.97*	–0.51	–0.98*	–0.66	–0.99*
May	–0.84	–0.96*	–0.54	–0.99*	–0.67	–0.99*
June	–0.79	–0.97*	–0.51	–0.99*	–0.66	–0.99*
July	–0.62	–0.98*	–0.47	–0.99*	–0.54	–0.99*
August	–0.60	–0.98*	–0.44	–0.98*	–0.52	–0.98*
September	–0.63	–0.97*	–0.44	–0.98*	–0.55	–0.98*
October	–0.51	–0.95*	–0.47	–0.97*	–0.52	–0.97*
November	–0.30	–0.89*	–0.38	–0.94*	–0.36	–0.94*
December	–0.34	–0.75**	–0.18	–0.83**	–0.20	–0.83**

*Correlation values significant at $P < 0.01$; *correlation values significant at $P < 0.05$.

Where T_1 and T_2 are the air temperature of the highest and lowest points (in °C), and z_1 and z_2 are their respective elevations (m). The TLRs were calculated from regression of all values; this allows calculating the strength of the relationship between air temperature and elevation.

Considering the fact that temperature in mountains is regulated by topography, aspect and

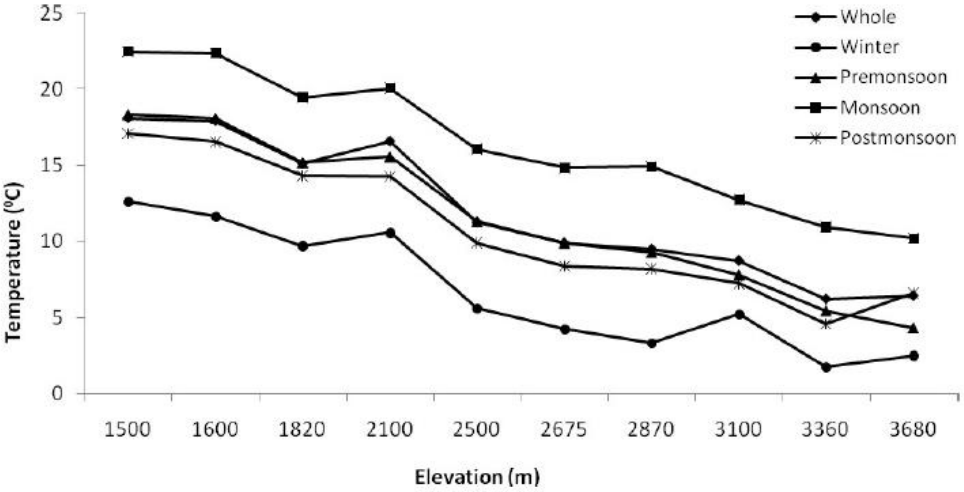

Fig. 3. Mean temperature versus elevation plot for entire transect for all four season and the whole year.

seasonal patterns of climate (Barry 1992), TLRs were calculated for the entire year as well as separately for each of four seasons; namely, pre-monsson (MAM)), monsoon (JJAS), post-monsoon (ON), and winter (DJF) for the study aspects seperately. Statistical analyses were performed to test the significance of results obtained. First, the significance of difference between the TLR for mean, maximum and minimum temperatures on two different aspects was tested using the independent samples t-test. An independent-sample *t*– test was performed to determine if the estimated TLR of each aspect was different from a general lapse rate value. Second, one-way analysis of variance (ANOVA) was used to compare the seasonal TLRs of one aspect to that of the other for the study transect, iteratively. The t-test and ANOVA were evaluated based on the significance alpha level ($\alpha = 5\%$ or 95% confidence interval) and p values ($P < 0.05$) using STATISTICA 8.0 statistical package.

Results

Correlation analysis between elevation and temperature

The correlation between monthly temperature and elevation was significantly negative at $P < 0.01$ and $P < 0.05$ for all months (Table 3). Among the seasons the lowest correlations(*r* varies between 0.75 to 0.95) were during winter months when temperatures were the lowest. Value of correlation coefficient increased from March and remained at the heighest level from May to September. Relatively lower correlation coefficients exists between maximum temperature during summer and elevation on account of the frequent terrain-dependent monsoon rainfall events (Kattel *et al.* 2012).

Temperature lapse rate variation in treeline line environment

Increase in temperature from winter to monsoon is obvious across the entire transect (Fig. 3). Significant correlations (at $P < 0.01$ and $P < 0.05$) indicate that the relationship between temperature and elevation is strong (Table 3); hence tempe-rature can be accurately predicted as a function of elevation. The TLRs for different months calculated from corresponding linear regression are presented graphically in Figs. 4 & 5.

Monthly variation in temperature lapse rate

Monthly variation in lapse rates for the two aspects (i. e. NW & SE) is shown in Figs. 4 & 5. Higher negative TLR values than seasonal mean are considered as the greater decline in temperature with increasing elevation whereas the less negative values of TLR are considered as the temperature inversion (Kattel *et al.* 2012). Along NW aspect, the mean TLR varied from −0.23 (± 0.55) °C/100 m in December to −0.69 (± 0.20) °C/100 m in May (Fig. 4). For maximum temperature, the highest lapse rate (−0.89 ± 0.77 °C/100 m) was observed in May and the lowest (−0.34 ± 0.01 °C/100 m) in November. TLR for minimum temperatures ranged from −0.18 (± 0.65) °C/100 m in January to −0.55 °C/100 m in May and June.

Along SE slope, the lowest TLR for mean temperature is observed in December (−0.18 ± 0.37

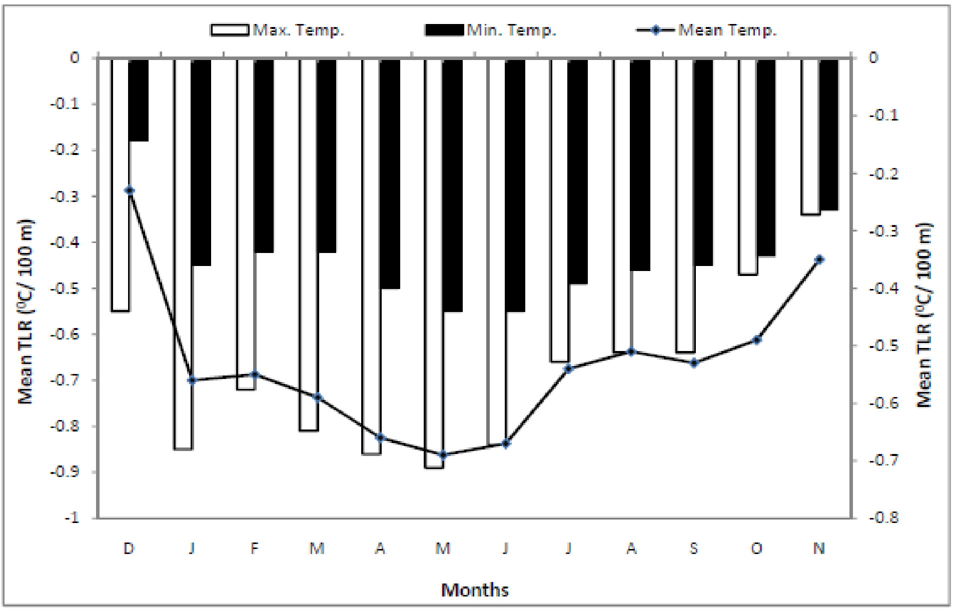

Fig 4. Variation in monthly temperature lapse rates along NW aspect of the study transect.

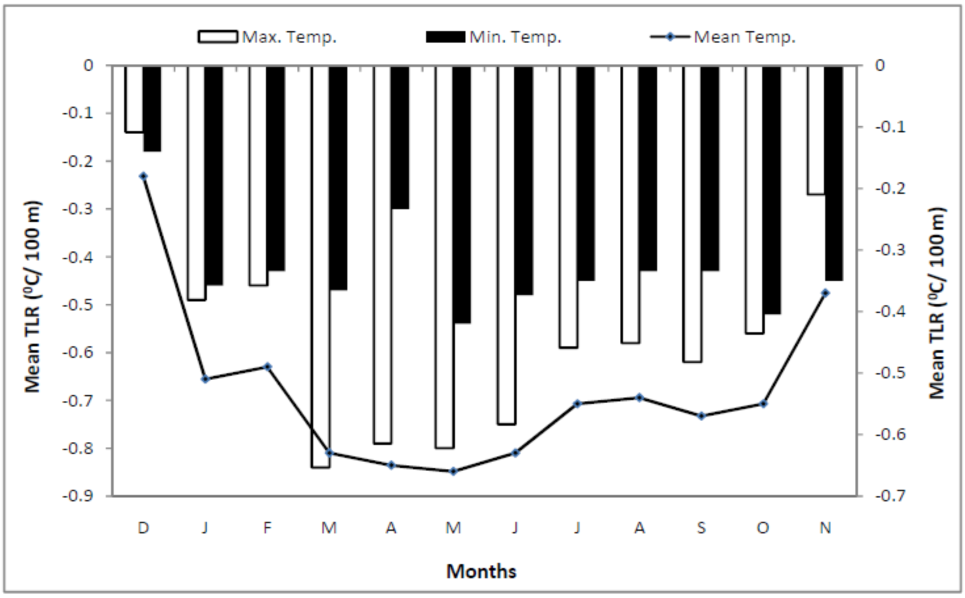

Fig. 5. Variation in monthly temperature lapse rates along SE aspect of the study transect.

°C/100 m) and highest in May (−0.66 ± 0.20 °C/100 m). For maximum temperatures, the TLRs were found to be varying between −0.14 ± 0.13 °C/100 m in December to −0.84 ± 0.42 °C/100 m in March. Whereas, for minimum temperatures, TLR varied between −0.18 ± 0.37 °C/100 m in December to −0.54 ± 0.02 °C/100 m in May (Fig. 5). Results show that TLR for maximum temperatures were significantly higher than that for minimum temperatures both for NW aspect (t = 6.553; $P = 0.00004$) and SE aspects (t = 2.725; $P = 0.019$).

Seasonal and Annual variation in TLRs and role of aspect

The highest TLR was observed for pre-monsoon season and the lowest during winter season for both mean and maximum temperatures. However, for

Table 4. TLR (in °C/100 m) for mean, minimum and maximum temperatures in relation to aspects and seasons.

Season	N-W Aspect			S-E Aspect		
	Mean TLR	Maximum TLR	Minimum TLR	Mean TLR	Maximum TLR	Minimum TLR
Winter (DJF)	–0.42	–0.71	–0.35	–0.39	–0.36	–0.35
Pre-monsoon (MAM)	–-0.64	–0.85	–0.49	–0.60	–0.81	–0.51
Monsoon (JJAS)	–-0.57	–0.67	–0.55	–0.55	–0.63	–0.57
Post-monsoon (ON)	–-0.44	–0.41	–0.38	–0.47	–0.42	–0.48

minimum temperatures, the highest TLR occurred during monsoon season on both the aspects (Table 4). Steepest average TLR is observed during pre-monsoon season (−0.64 °C/100 m on NW aspect and −0.60 °C/100 m on SE aspect) whereas lowest mean TLR was observed during winter season (−0.42 °C/100 m on NW aspect and −0.39 °C/100 m on SE aspect). Between the two aspects, TLR values were higher for NW aspect than for SE aspect. A significantly lower TLR was observed on SE aspect than on NW aspect for mean temperatures (t = 2.06; P = 0.035) and minimum temperatures (t = 2.1483; P = 0.04), but not in case of maximum temperatures (t = 1.44; P = 0.16). The two aspects also differed significantly ($P \leq 0.05$) in seasonal distribution of TLR (Table 4). On an annual scale, a higher value of mean TLR was observed for NW aspect (−0.46 °C/100 m) than the SE aspect (−0.36 °C/100 m). Based on the analysis carried out using One-Way ANOVA at 5% level of significance, it was found that the TLR varied significantly across all the seasons for the mean (F = 3.2175; P = 0.03), maximum (F = 3.675; P = 0.019), and minimum (F = 9.895; P = 0.0002) temperatures on both the aspects indicating that the seasons have strong influence in determining the TLR across the study transect and in general in the Himalaya. Our results show that high variability exists in temperature lapse rates for different months, seasons and aspects.

The analysis for annual cycle of TLR for maximum, minimum, and mean temperature for both the aspects shows that the seasonal variations of TLRs exhibit bi-modal patterns with peaks in pre-monsoon and post-monsoon periods and with two lowest values in the winter and monsoon seasons (Figs. 6 & 7).

Discussion

The mean TLR values (−0.53 °C/100 m) estimated in the present study based on observed data of an elevational transect is lower than the used in past literatures (−0.65 °C/100 m). It indicates that the temperature in higher ranges would be warmer than estimated on the basis of earlier used TLR.

Relatively lower winter time correlation coefficients may be related to temperature inversion effect that weakens the temperature-elevation relationship (Marshall *et al.* 2007). Opposite to the TLR, the inversion effect sets up when warmer air is displaced by the sinking cold air, particulary during night time (Rolland 2003). The higher LRs for maximum tempetaure than that for minimum temperature on both the aspepcts of the study transect may be due to the adiabatic mixing within the boundary layer during day time (Kattel *et al.* 2012).

The higher values of TLRs observed for NW aspect in comparison to SE aspect could be related to more rainfall on SE aspect than NW aspect; based on the data recorded from all the stations, the average rainfall for monsoon season was found as 2175 mm and 2070 mm on SE and NW aspects, respectively. Higher LR values in drier conditions than humid conditions have also been reported by Immerzeel *et al.* (2014), Kattel *et al.* (2015) and Tang & Fang (2006). The lapse rates observed in the present study support our hypothesis that the TLRs are controlled by both variation in topographic features (slope and aspect) and climatic conditions (relative humidity).

The highest mean TLR and the difference of lapse rate between maximum and minimum temperature were observed during pre-monsoon season on both the aspects (Table 4). Because of the absence of clouds and higher temperature during pre-monsoon, land surfaces receive more incoming solar radiation compared with outgoing radiation. This phenomenon results in a rise in daytime surface temperature and large sensible heat flux which can enhance strong dry convection in the day-time (Blandford *et al.* 2008). The pre-monsoon season also has the highest daytime saturation varour

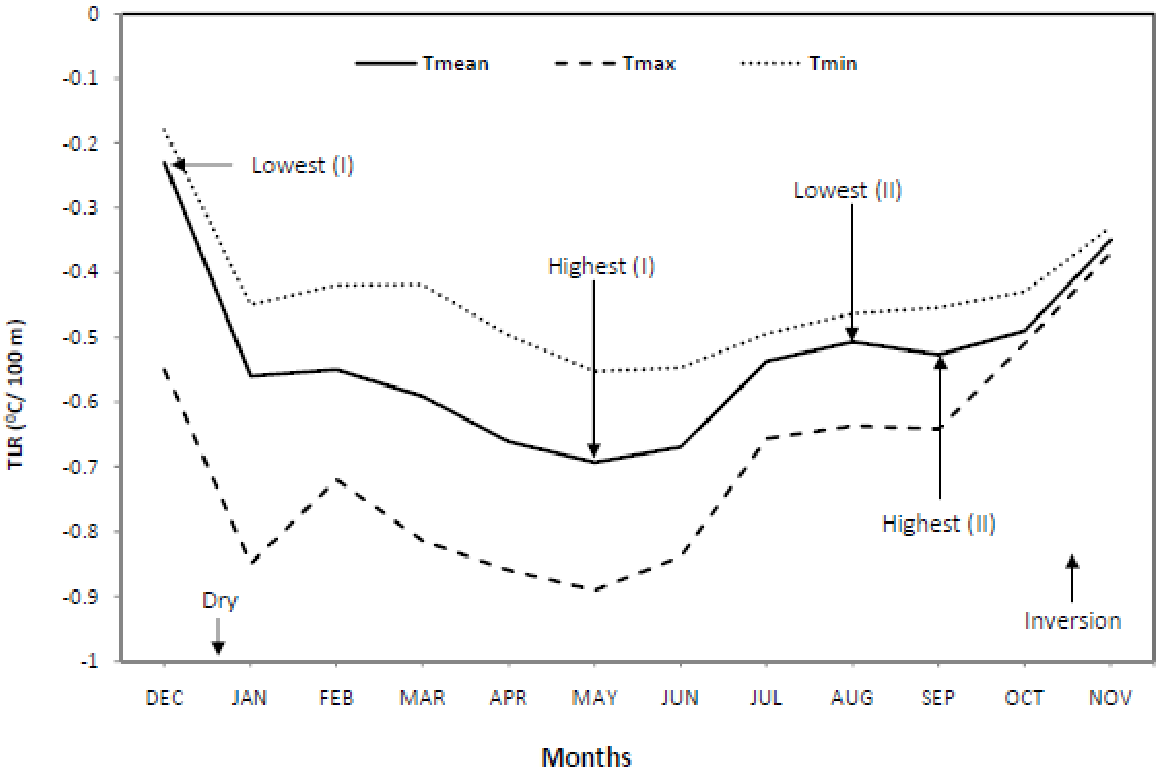

Fig. 6. Annual cycle of maximum, minimum, and mean TLR on NW aspect.

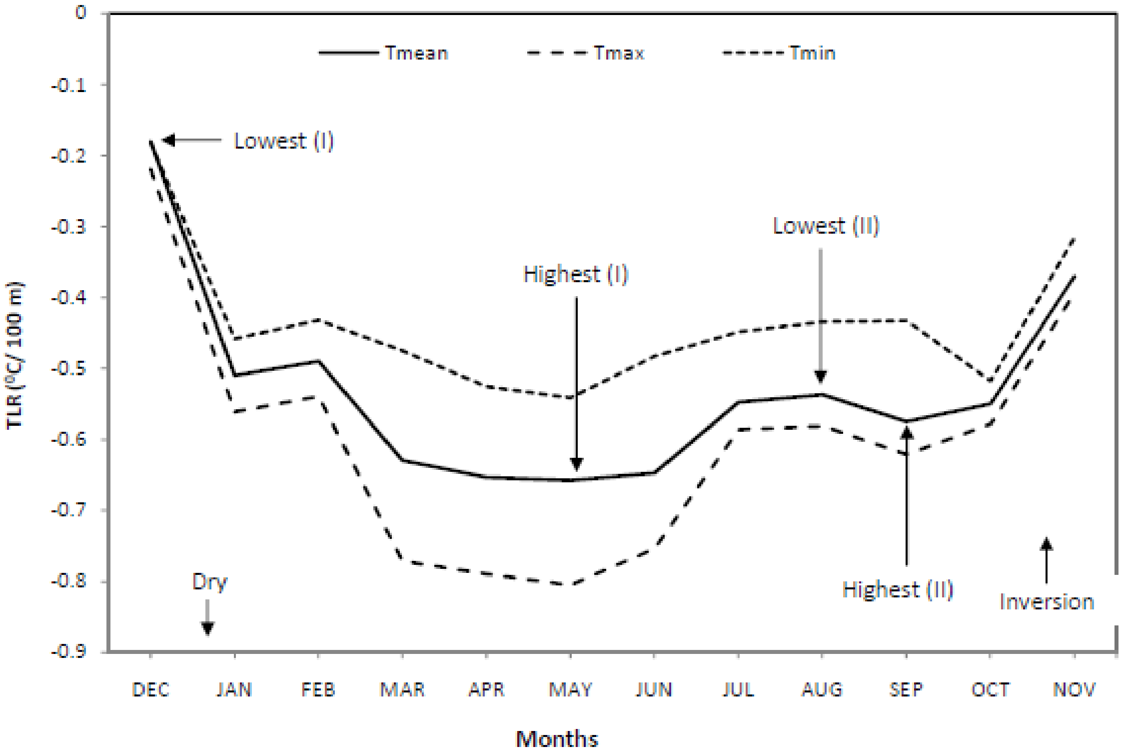

Fig. 7. Annual cycle of maximum, minimum, and mean TLR along SE aspect

pressure (e_s) lapse rate (Kattel *et al.* 2012); as a result the TLR reaches a maximum value in this season.

The second TLR peak was observed during the post-monsoon season (Fig. 6 & 7). The magnitude of mean TLR in this season was relatively lower compared with the pre-monsoon season but higher in comparison to the winter and pre-monsoon seasons. The post-monsoon season also had the least difference between the maximum (−0.41 °C/100 m for NW slope and −0.42 °C/100 m for SE slope) and minimum (−0.38 °C/100 m for NW slope and −0.48 °C/100 m for SE slope) TLR (Table 4). Weather conditions during this season are similar to pre-monsoon conditions except that the thermal forcing effect is relatively small due to the turbulence between the two climatic phases, i.e. retreat of monsoon and the onset of winter westerlies. Our results are in close proximity with the TLR values and variations in them with those of western and central Himalaya in Nepal (Immerzeel *et al.* 2014; Kattel *et al.* 2012, 2015).

The lowest mean TLR values were observed during winter season (DJF) on both the aspects. The lowest value of TLR in winter implies that other controlling factors play a more important role. During winter, sky mostly remains clear and radiative cooling is intense, leading to a stable stratification and a temperature inversion. This condition facilitates the development of suitable microclimates (Thyer 1985) for cold air deposition in low areas through down slope flow at the flat terrain and lowland valleys. The temperature inversion may be further enhanced by foggy conditions during the winter season (Rolland 2003). While reduced snow cover in the higher parts of transect is expected to reduce albedo and raise temperature, the increased aerosol concentrations in lower elevation is likely to cause cooling. These opposite trends are likely to reduce winter TLR.

The second lowest TLRs were observed during the monsoon season (JJAS) when moisture content in the air is high throughout the elevation range. This is because the air over high altitude areas is warmed by latent heat release associated with water vapor condensation, thereby rendering temperature uniformly high. Latent heat transfers depend on moisture content in the atmosphere (Marshall *et al.* 2007). Hence, in response to heavy summer rainfall, surface temperature decreases and moist adiabatic processes prevail (Thyer 1985). Thus, the stable lapse rate for both maximum (−0.67 °C/100 m) and minimum (−0.55 °C/100 m) temperature in monsoon implies a strong association with rainfall amount. This indicates that the annual cycle of varour pressure (e_s) plays a contributory role in enhancing and reducing the TLRs during dry (in pre-monsoon season) and moist conditions (in monsoon season), respectively. Furthermore, TLR variability is also governed by the cloudiness. The thick cloud cover during the monsoon months (JJAS) leads to reduction in insolation during the day (Kattel *et al.* 2012) and detention of outgoing long-wave radiation during the night time (Bhutiyani *et al.* 2007), leading to higher minimum surface temperatures regardless of elevation within a limit.

The bi-modal pattern of TLR variability observed in treeline environment of western Himalaya is distinct from other mountain regions such as south-central Idaho, Washington Cascades, Colorado Rocky Mountains, and semiarid southeastern Arizona in the USA; Northern Italy, Greece, and the Austrian Alps in Europe; and northern and southern slope of Mt. Taibai in China (Blandford *et al.* 2008; Diaz & Bradley 1997; Gardner *et al.* 2009; Harlow *et al.* 2004; Marshall *et al.* 2007; Minder *et al.* 2010; Pepin & Losleben 2002; Richardson *et al.* 2004; Rolland 2003; Tang & Fang 2006). Studies carried out in these regions have reported lower TLR in winter and higher TLR in summer due to the maximum dry convection in summer and minimum in winter on account of temperature inversion. Majority of these study regions are located in mid-latitude mountain systems, where there is no distinct summer wet season or where winter is the wettest season. The precipitation pattern of Himalayan region is determined by two atmospheric circulation patterns: one driven by the Indian summer monsoon or south-easterlies and the other driven by the westerlies in winter (Singh *et al.* 2017). Contribution of these two characteristics in Himalayan region might contribute to a distinct bi-modal pattern of TLR over the study transect. The lower values of LR of our study in comparison to those of the past might be due to enhanced elevation dependent (EDW) warming in Himalaya. Throughout the world warming is being observed more in higher elevation than lower elevation (Pepin *et al.* 2015). Such a differential warming is expected to decrease the TLR as a consequence of EDW under the influence of climate change.

Implications of low TLR for timberline elevation

Low TLRs particularly during winter and monsoon months are likely to have contributed to high treeline in Himalayas. Heat deficiency is considered to be the main cause of treeline formation (e.g., Körner 2012). Winters in Himalayas are mild (Sakai & Malla 1981) partly because day lengths remain long (> 10 hr), and days are sunny (Zobel & Singh 1997). As for growth of trees in high elevations, monsoon (warm and moist) is the key period, when much of the net primary productivity occurs (Singh & Singh 1992). Hence elevation dependent warming is likely to be now a major contribution to elevational rise of treeline.

Conclusion

This study presents initial estimate of TLR for treeline environment in western Himalaya. Our estimate of TLR based on observed data (−0.53 °C/100 m) is distinctly lower than values of TLR used in the past for Himalayan region. Since EDW results in a decrease in temperatures between low and high elevations, and is likely to be connected with global climate change, the low TLR of our study (−0.53 °C/100 m) and that reported recently in Nepal for Langtang valley (Immerzeel *et al.* 2014) may be a consequence of global warming. Our study establishes that TLR varies seasonally; it is generally lower during winters and monsoon period whereas higher during pre-monsoon and post-monsoon periods. This study has shown for the first time that TLR varies from one aspect to another, which may partially explain the aspect-related difference in treeline elevation in Himalayas (Schickhoff 2005).

The low TLR indicates that conditions in high Himalayas are likely to be warmer than generally held out. The warmer temperatures as such would promote plant growth, provided the increased evapotranspiration loss does not become limiting. The lower values of TLR may have several possible impacts on the dynamics of treeline ecotone in Himalaya. The change in snow and moisture regime, increased evapotranspiration and water stress, change in albedo and surface energy balance, and modified distribution patterns, and shift in range and growing season of alpine vegetation are some example. Considering observed variability in TLR, the present study advocate for use of seasonally varying lapse rates to assess impact of climate change on different ecosystems along altitudinal gradient. Further, information about changing climate and vegetation patterns of climatically sensitive alpine ecosystems is very crucial for a comprehensive understanding of their current and future states. The low TLR may partly explain the high treeline in Himalayas.

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Taxonomic and functional plant diversity patterns along an elevational gradient through treeline ecotone in Kashmir

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Abstract: Species distribution and community assembly patterns along elevation gradients have been studied world over but not much information in this regard is available about the Indian Himalayan region, including the Kashmir Himalaya. It is in this context that we studied elevational (2200–3800 m) patterns in plant species richness, and functional and taxonomic group diversity with particular reference to treeline ecotone (3200–3700 m). Present study revealed that the patterns of species richness were not consistent across taxonomic or functional groups of plants. Four patterns of species richness in relation to elevation were observed: low-elevation plateau with a mid-peak in bryophytes and lichens, mid-peak pattern in pteridophytes and inverted hump-shaped pattern in monocots. During the present investigation, rapid changes in species composition and physiognomy were recorded in the treeline ecotone over small elevational increases. Number of tree species in this zone declined rapidly from four species at an elevation of 3200 m to one at 3700 m. While from 2200 m to 3200 m the vegetation was predominated by fir (*Abies pindrow*) forming a closed canopy forest, but beyond 3200 m its density decreased rapidly with concomitant increase in the density of birch (*Betula utilis*). Ultimately birch was the dominant treeline species and grew in association with *Rhododendron campanulatum* up to 3700 m, beyond which treeless alpine meadow existed. The present study is first of its kind carried out in Kashmir Himalaya and would hence serve an important baseline for similar such studies that would pave way for better understanding and conservation of plant communities in such mountainous regions.

Key words: Birch, elevation pattern, fir, species richness, treeline, timberline.

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Introduction

Vegetation in mountainous areas varies in physiognomy, species richness and diversity along elevational gradients (Kluge *et al.* 2017; Manish *et al.* 2017; Peters *et al.* 2016). A number of studies in different parts of the world have revealed that species diversity shows monotonic, unimodal or multimodal patterns in relation to elevation (Rahbek 2005). Mid-gradient peaks of species richness (Mid Domain Effect) have also been reported (Colwell & Lees 2000; Colwell *et al.* 2004; Grytnes & Vetaas 2002; Grytnes 2003). Understanding the underlying mechanisms that govern such elevational patterns in species diversity not only constitutes a central theme of macroecology, but also has practical implications in discerning the response of species to climate change, particularly in mountainous areas (Saikia *et al.* 2017; Yadav *et al.* 2017). The recent meta-analyses of the studies have enhanced our understanding of the effect of climatic and spatial factors on elevational species richness species and community assembly (Kessler *et al.* 2011; McCain 2007; McCain 2010; Romdal & Grytnes 2007).

Most of the studies that have examined the patterns of species diversity along elevational

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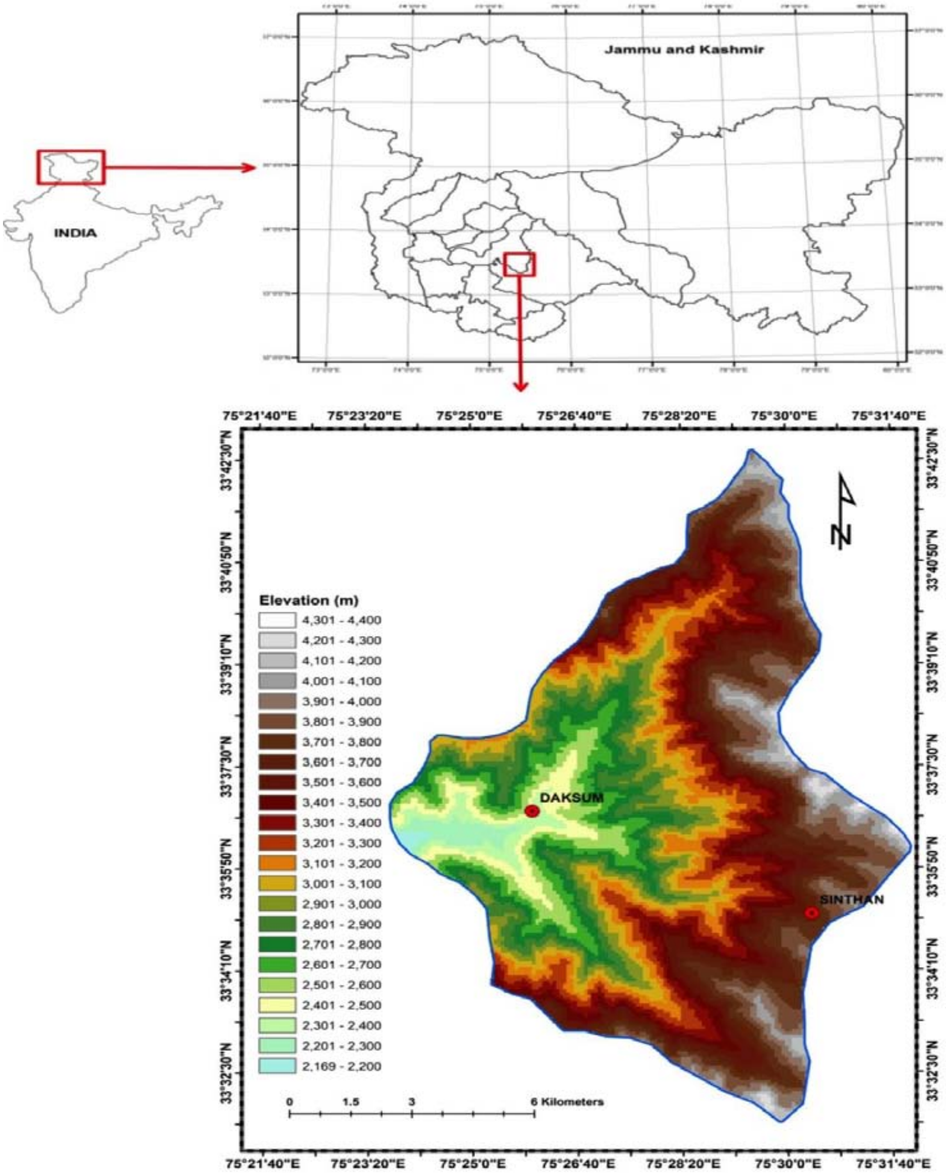

Fig. 1. Location map of the study area and study site.

gradients have used species richness as a surrogate for diversity, thereby assuming taxonomic, functional and phylogenetic equivalence among different species (Swenson *et al.* 2012). Patterns of taxonomic biodiversity along elevational gradients are also used as proxies for variation in environmental characteristics (Körner 2007) such as, climate (Schwörer *et al.* 2014; Tuhkanen 1993), temperature and length of growing season (Holtmeier 2009; Hustich 1979; Schickhoff 2005), local climate, topography, site history, and ecology of plant species, current biotic and anthropogenic influences (Holtmeier 2009). Another limitation of studies dealing with elevational pattern in species diversity is the excessive focus only on one or the other plant group assuming that diversity patterns are uniform across different groups of organisms. However, such an approach limits our understanding of the response of different organisms or taxa to complex gradient of elevation wherein other factors such as temperature, precipitation and other local ecological factors co-vary (Grytnes *et al.* 2006; He *et al.* 2018).

It is also becoming increasingly apparent that taxonomic approach does not adequately capture variation in functional and phylogenetic dimensions of diversity which often respond to environmental gradients differently than does the taxonomic dimension (Chun *et al.* 2017). Disentangling the underlying processes that govern taxonomic, functional and phylogenetic patterns is of pivotal importance (Chun *et al.* 2017) because of their conservation implications particularly in the context of Himalayas which are warming 2–5 times more than global average. It also needs to be emphasized that changes in species diversity are not uniform along the entire elevational gradient; instead changes are more rapid in the treeline ecotone which extends from the forest limit or the upper limit of the continuous closed forest canopy to the treeless alpine zone above (Dutta *et al.* 2014; Körner 2012; Tranquillini 1979; Wielgolaski *et al.* 2017; Wieser & Tausz 2007).

Thus, the present study was carried out in the Kashmir Himalaya to document taxonomic and functional diversity of all major plant groups, including angiosperms, gymnosperms, ferns, bryophytes and lichens along an elevational gradient. The present study is significant since it simultaneously studied pattern of taxonomic and functional diversity in different groups of plants unlike most previous studies that have studied only taxonomic diversity mostly of one or the other plant group. Furthermore, the present study is first of its kind in the Kashmir Himalaya and hence would add to the body of knowledge about the elevational patterns of species richness in different parts of Himalaya which is necessary to have an overarching understanding of species diversity patterns along elevational gradients particularly in the context of climate change and other anthropogenic stressors.

Materials and methods

Study area

Present study was carried out in the Daksum and Sinthan Top area of the Kashmir Himalaya (Fig. 1). Daksum lies within the geographical coordinates of 33°36'43"N 75°26'6"E and is located at an altitude of 2,200 m above the sea level at a distance of 40 km from the main district headquarter of Anantnag and about 85 km from Srinagar. Sinthan Top (3800 m) lies within the geographical coordinates of 33°34'N and 75°30'E and a road (NH1B highway) traverses through this top that connects Kashmir valley with Kishtwar which lies in Jammu province of the State. Daksum-Sinthan Top area is about 130 km south of Srinagar, 73 km from Anantnag and 48 km from Kokernag. Climate of the study area is akin to general climate of Kashmir Valley. Average annual temperature is 12.8 °C. Precipitation here averages 1035 mm. It is largely non-monsoonal and most of the precipitation falls in March averaging 161 mm.

Vegetation sampling

For vegetation sampling, the altitudinal gradient of 2200 to 3800 m in the study area was divided into seventeen (17) altitudinal bands of 100 m each. Three plots of 50 × 50 m area were established in each of these altitudinal bands. In each plot ten (10 × 10) quadrats for trees, 20 (5 × 5 m) for shrubs and 40 (1 × 1 m) for herbs were laid randomly for vegetation sampling. Thus, in each elevational band, 30 quadrats were laid for documenting the diversity of trees, 60 quadrats for shrubs and 120 quadrats for herbs. Across the entire elevational gradient, in all 510 quadrats were sampled for recording tree species richness, 1020 quadrats for recording species richness of shrubs and 2040 quadrats for recording species richness of herbs.

Taxonomic diversity

It was quantified on the basis of collection, identification and inventorization of species belonging to angiosperms, gymnosperms, bryophytes, ferns, lichens from each of the elevational bands employing quadrat method.

Functional diversity

Following functional traits of spermatophytes were studied during the present study:

Growth form**:** Trees (>2 cm dbh, height 5–15 m), shrubs (height <2 m) and herbs (height <0.5 m).

Life span**:** Annual/Perennial

Stem tissue**:** Herbs/shrubs/trees

For bryophytes and lichens following growth forms were recognized:

Bryophytes: Liverworts (leafy) and mosses

Lichens: Thallus growth form (foliose, fruticose, crustose, leprose, etc.)

Species accumulation curves for trees, shrubs and herbs and rarefaction curves for trees and shrubs were computed using EstimateS (Colwell 2013). Species accumulation curves, sometimes called collectors curves, plot the cumulative number of species recorded as a function of sampling effort, such as number of samples laid (Colwell & Coddington 1994). They were used to indicate the adequacy of sampling effort in different elevational

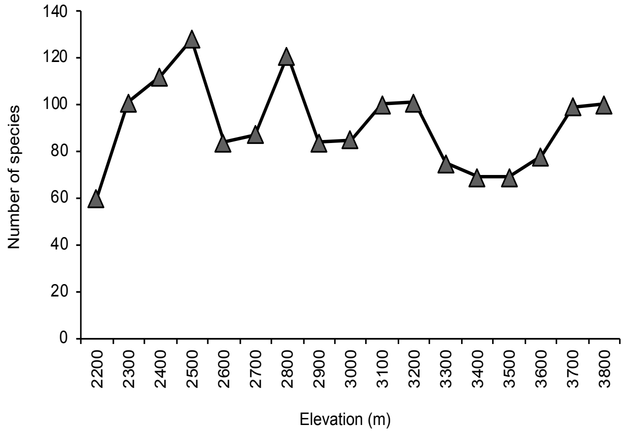

Fig. 2. Overall species richness along the elevational gradient in Kashmir Himalaya.

Table 1. Composition of plant species in the study area.

Plant group	No. of species	Genera	Families
Dicots	175	131	44
Monocots	19	16	10
Gymnosperms	4	4	2
Pteridophytes	33	16	9
Bryophytes	39	33	22
Lichens	155	68	30
Total	425	268	117

bands. Since number of individuals of trees and shrubs sampled in different elevational bands was different, a direct comparison of species richness would have been meaningless (Grytnes & Beaman 2006). Thus, rarefaction method was used to compare samples that have different numbers of specimens sampled by randomly drawing an equal number of specimens from the samples and counting the number of species drawn from each sample (Gotelli & Colwell 2001; Magurran 2004).

Statistical analyses

Relationship between different dependent and independent variables was assessed employing various regression and other statistical models. We selected the regression model based on r^2.

Results

Species richness and composition

Floristic surveys in the study area of Daksum-Sinthan Top in the Kashmir Himalaya resulted in collection and identification of 425 plant species belonging to 268 genera and 117 families (Table 1). Amongst these, the flowering plants were predominant, with dicots sharing 175 species in 131 genera and 44 families, and monocots only 19 species in 16 genera of 10 families. Gymnosperms were represented by 4 species belonging to 4 genera and 2 families. Besides, 33 species of pteridophytes in 16 genera and 9 families, 39 species of bryophytes in 33 genera and 22 families and 155 species of lichens in 68 genera and 30 families were also recorded from the area.

Elevational trend in species richness

The total species richness ranged from a lowest of 60 species at an altitude of 2200 m amsl to a highest of 128 species recorded in the elevational band of 2500 m amsl. Overall pattern exhibits a mid-elevation peak in species richness followed by decline with increase in altitude (Fig. 2) but with a moderate increase in alpine zone. The number of angiosperm species was highest in the elevational band of 3700 m with lowest in the 2200 m band (Table 2). Highest (60 spp) and lowest (30 spp) number of dicot species was recorded in 3700 m and 2200 m elevational bands, respectively. Monocots were not well represented in the study area and the number of monocot species in different elevational bands ranged from 1 to 6 species. Number of gymnosperm species was invariably higher in lower altitudes with highest being 3 species recorded upto 3000 m beyond which only one gymnosperm species was recorded in each of the elevational bands. Number of pteridophytes across the elevational gradient ranged from 4 to 16 while that of bryophytes it varied from 4 to 22 species. Number of lichen species ranged from a minimum of 9 species recorded in 3300 and 3500 m elevational band to a maximum of 36 species recorded at an elevation of 2800 m. Angiosperm species number was highest in 17 bands while in 5 bands lichens had the highest number of species. Bryophytes and pteridophytes followed them in species richness per band.

Elevational patterns of various taxonomic and functional plant groups are presented in Figs. 3–7. Angiosperms including dicots and pteridophytes show a wavy pattern distribution along increasing altitude with several peaks and troughs. Monocots showed a characteristic pattern of mid-elevational decline and subsequent increase in higher elevations while bryophytes kept on decreasing with increasing altitude. Lichen richness peaked in

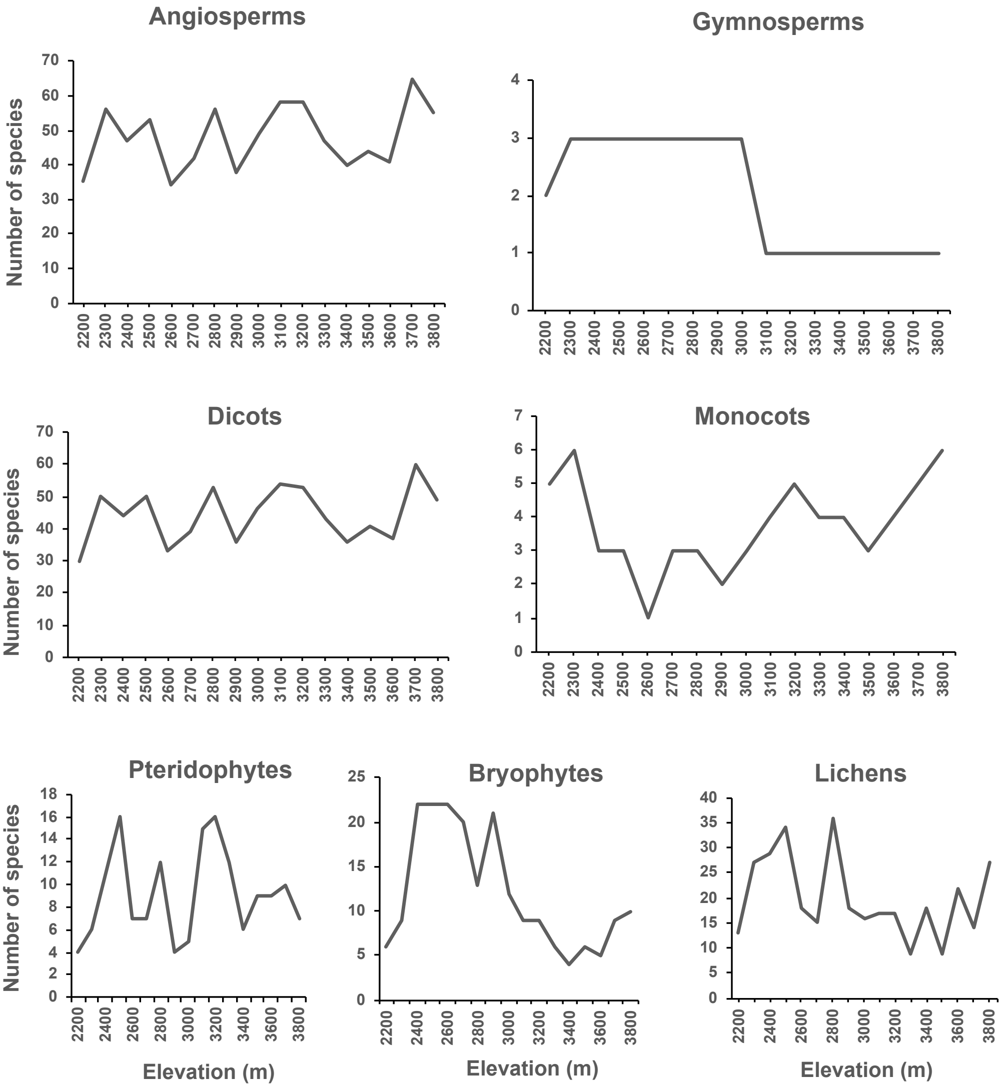

Fig. 3. Elevational pattern in species richness of different plant groups.

mid elevations and declined in higher elevations with modest increase in alpine zone (Fig. 3). In all, four patterns of species richness in relation to elevation were observed during the present study: low-elevation plateau with a mid-peak in bryophytes, mid-peak pattern in pteridophytes and lichens, and inverted hump-shaped pattern in monocots.

Functional groups of spermatophytes viz, trees, shrubs and herbs also showed specific elevational patterns in species richness (Figs. 4–7). Trees showed a characteristic mid-elevational peak, but overall curve was wavy, with several rises and falls. Shrubs, on the contrary, showed highest richness at 2300 m and thereafter declined sharply up to 2700 m, where after it leveled off. Herbs, on the other hand presented a wavy pattern with many peaks and troughs but overall curve showed no tendency for species decline within the study elevational range. Patterns of species richness studied in terms of life span of species (Fig. 5) revealed that annuals and perennials show more or less similar patterns of increase and decrease with increasing elevation. The overall trend was similar to that of herbs. Growth forms of bryophytes characterized in terms of liverworts and mosses more or less showed mid-elevation peaks and decline in higher elevations (Fig. 6). While mid-elevation peaks in species richness of lichens was observed in crustose, foliose and fruticose functional types (Fig. 7), leprose functional type showed highly irregular pattern in species richness in relation to elevation. Species richness peak occurred at 3700–3800 m for angiosperms as a whole, dicots and monocots and all herbs, at 3200 m

Table 2. Number of species of different plant groups in different elevational bands.

Plant group	Elevational band																
	2200	2300	2400	2500	2600	2700	2800	2900	3000	3100	3200	3300	3400	3500	3600	3700	3800
Angiosperms	35	56	47	53	34	42	56	38	49	58	58	47	40	44	41	65	55
Dicots	30	50	44	50	33	39	53	36	46	54	53	43	36	41	37	60	49
Monocots	5	6	3	3	1	3	3	2	3	4	5	4	4	3	4	5	6
Gymnosperms	2	3	3	3	3	3	3	3	3	1	1	1	1	1	1	1	1
Pteridophytes	4	6	11	16	7	7	12	4	5	15	16	12	6	9	9	10	7
Bryophytes	6	9	22	22	22	20	13	21	12	9	9	6	4	6	5	9	10
Lichens	13	27	29	34	18	15	36	18	16	17	17	9	18	9	22	14	27
Total species richness	95	157	159	181	118	129	176	122	134	158	159	122	109	113	119	164	155

Table 3. Taxonomic conspectus of species in the treeline ecotone. Values in parentheses are the percentage of species recorded in the entire elevation transect.

Plant group	No. of species	No. of genera	No. of families
Angiosperms	111(57.2%)	92	37
Dicots	102 (58.3%)	85	32
Monocots	9 (47.3%)	7	5
Gymnosperms	2 (50%)	2	2
Pteridophytes	21 (63.4%)	12	8
Bryophytes	16 (41.0%)	14	10
Lichens	75 (48.3%)	37	24
Total	225 (52.9%)	157	81

Table 4. Number of species belonging to different growth forms in the treeline ecotone.

Growth form	No. of species
Herbs	121
Shrubs	9
Trees	4
Total	134

for pteridophytes, at 2800 m for lichens, at 2500–2800 m for trees and 2400 m for bryophytes.

Species richness in treeline ecotone

The treeline ecotone of study area stretches from the timberline limit (3200 m asl) to the treeless alpine zone (> 3700 m asl). The treeline ecotone is species rich comprising 225 species belonging to 157 genera and 81 families (Table 3). Trends in species richness along elevational gradient in the treeline ecotone (Fig. 8) reveal that the overall species richness is in the lowest elevation of treeline ecotone (3200 m) and thereafter it declines rapidly

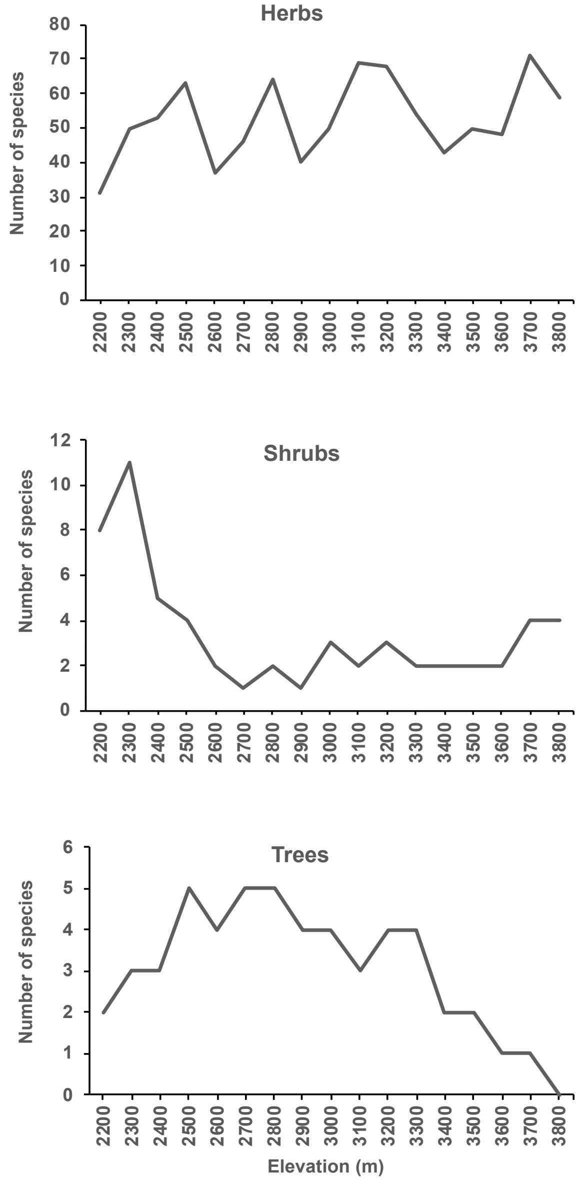

Fig. 4. Elevational pattern in growth forms of spermatophytes.

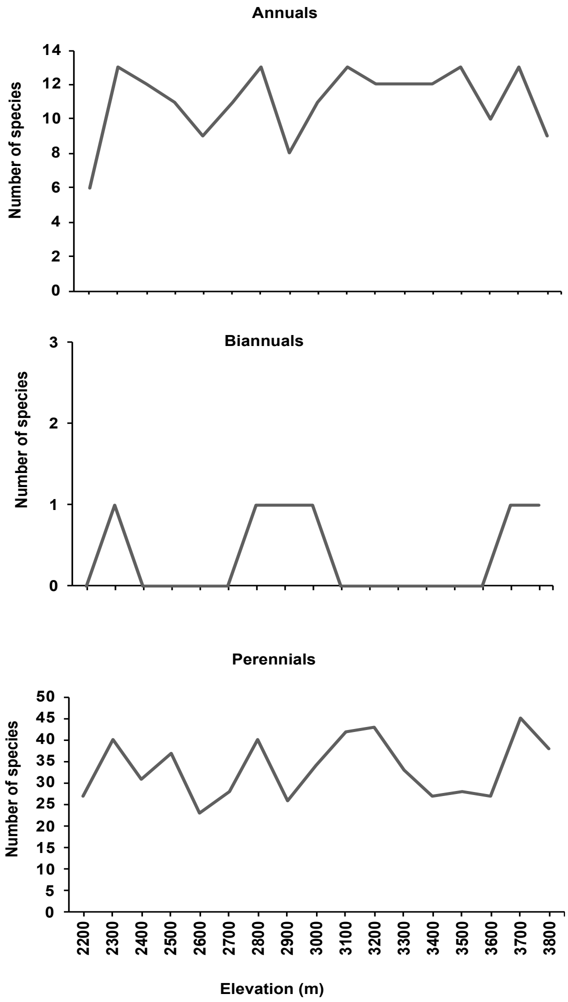

Fig. 5. Elevational pattern in species with different life spans in spermatophytes.

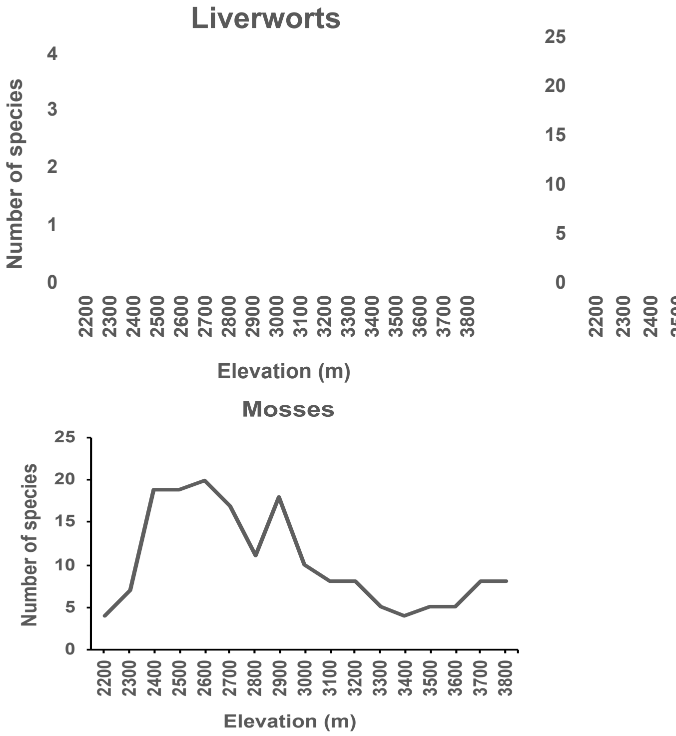

Fig. 6. Elevational pattern in growth forms of bryophytes.

and shows modest increase beyond 3600 m and more or less similar pattern in evident in respect of angiosperms and gymnosperms and lichens. Other groups of plants, such as monocots, gymnosperms, pteridophytes and bryophytes do not show any significant variation in relation to elevation in the treeline ecotone.

Relatively, treeline ecotone (ranging from 3200 to 3700 m and including six bands) is richer than the lower part of the elevation gradient (ranging from 2200 to 3200 and including twelve 100 m elevation bands). About 33% of the elevational transect that represented the treeline ecotone had about 53% of total species recorded in the transect (225 of 425 species). It contained almost 63% of pteridophytes, about half of lichens, but was relatively low in bryophytes.

Functional diversity of vascular plants characterized in terms of growth forms (Table 4) reveals that herbs predominate with 121 species (90%). Elevational pattern of herbs was more or less similar to overall species richness pattern with high species richness at 3200 m and some decline between 3000 to 3600 m and then again in increase in the elevation zone of 3700 m. Shrubs, though less in number, also show a more or less similar elevational pattern. Trees, on the other hand, showed relatively high species richness at 3200 m, thereafter declined with no tree species recorded beyond 3700 m (Fig. 8).

Perusal of data in Fig. 9 reveals that *Abies pindrow* is the dominant tree species upto 3400 m. In fact, it is the timberline species in the study area. However, *Betula utilis* which appears at an altitude of 3300 m increases in numbers relative to *Abies pindrow* and ultimately becomes the dominant tree species at 3600 m but decreases in abundance at 3700 m (Fig. 9).

Discussion

The present study demonstrates that the elevational patterns of species richness are not consistent across taxonomic or functional groups of plants. Four patterns of species richness in relation

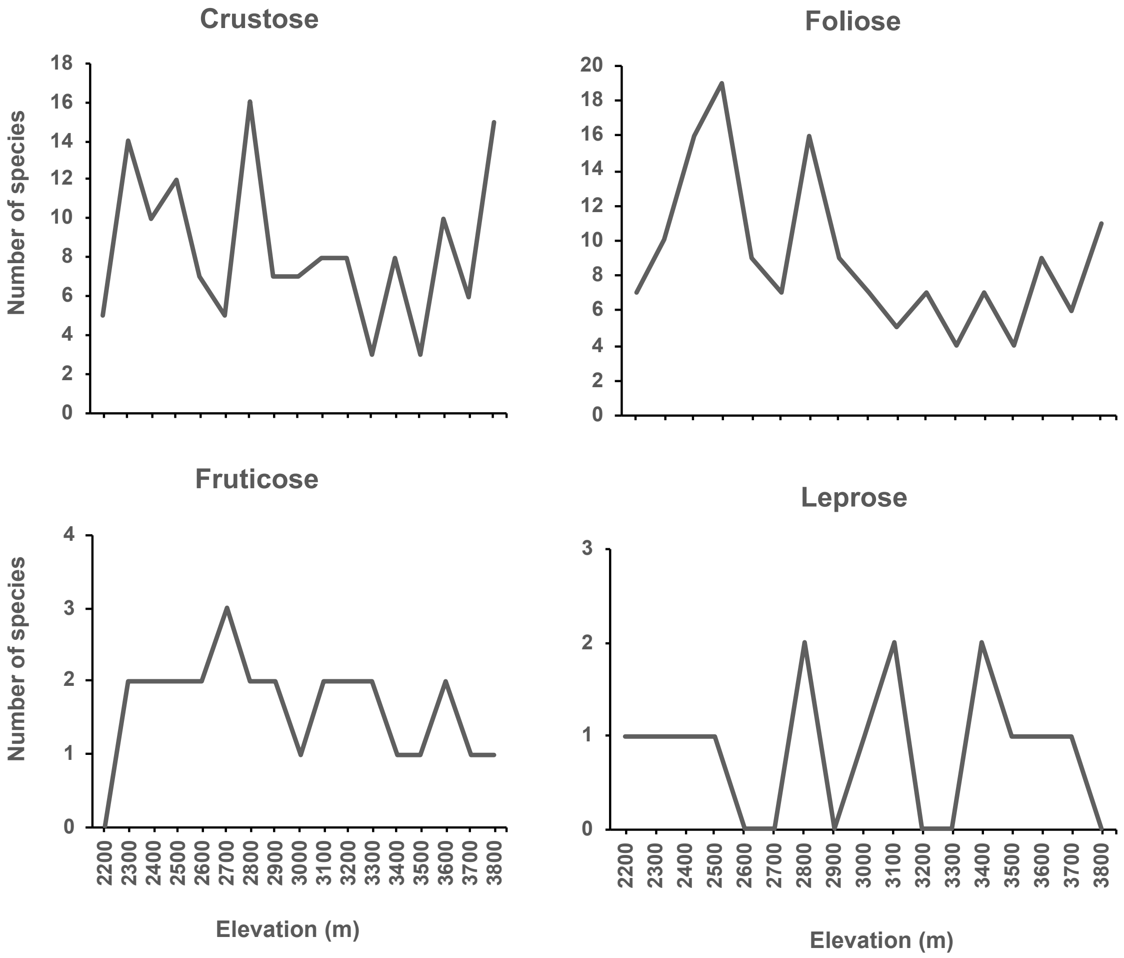

Fig. 7. Elevational pattern in growth forms of lichens.

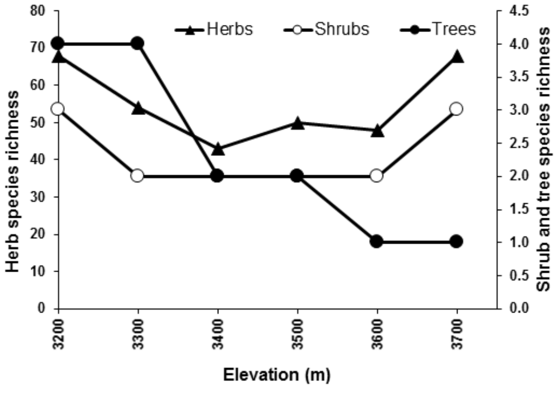

Fig. 8. Elevation pattern in species richness of tress, shrubs and herbs.

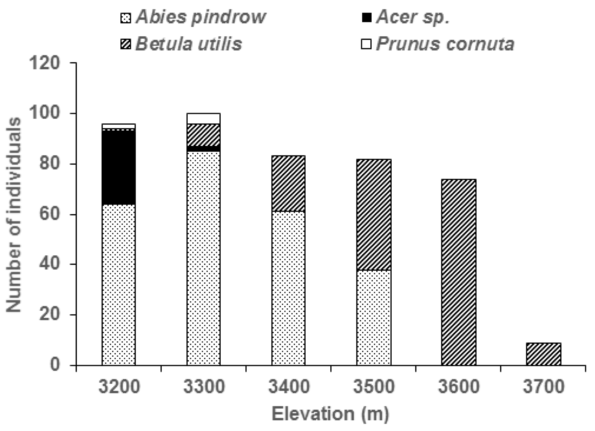

Fig. 9. Density of important tree species in the treeline ecotone.

to elevation were observed: low plateau pattern in gymnosperms, low-elevation plateau with a mid-peak in bryophytes, mid-peak pattern in pteridophytes and lichens, and inverted hump-shaped pattern in monocots (Figs. 10–11). Unlike differing elevational patterns observed in different plant groups in the present study, a hump-shaped pattern in species richness along the elevational gradient is commonly reported (Behera & Kushwaha 2007; Carpenter 2005; Sánchez-González & López-

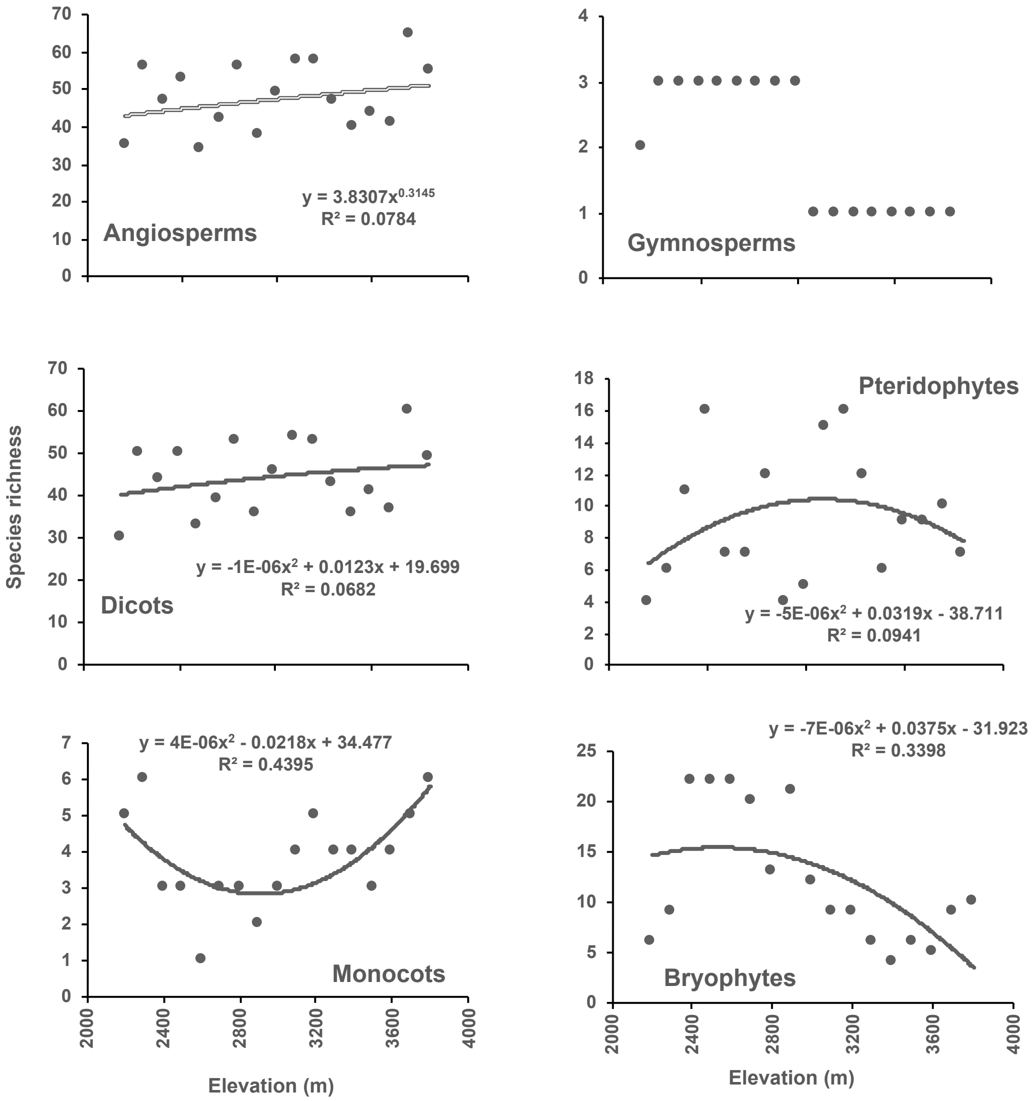

Fig. 10. Relationship between species richness of different plant groups and elevation.

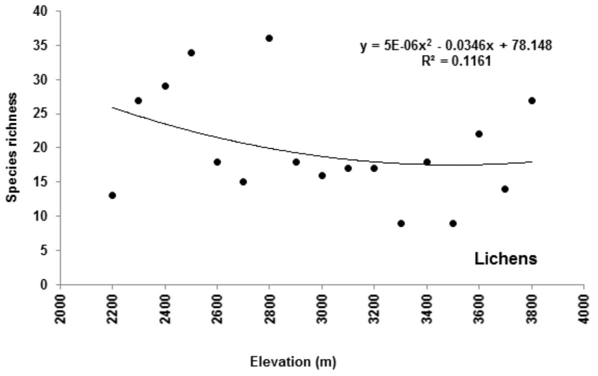

Fig. 11. Relationship between species richness of lichens and elevation.

Mata 2005; Tripathi *et al.* 2004) and for a wide range of taxa in the Himalaya, such as flowering plants (Bhattarai & Vetaas 2003, 2006; Grytnes & Vetaas 2002), seed plants (Kluge *et al.* 2017), endemic and non-endemic angiosperms (Manish *et al.* 2017), woody plants (Oommen & Shanker 2005), understorey plant species (Carpenter 2005), liverworts and mosses (Grau *et al.* 2007), orchids (Acharya *et al.* 2011), lichens (Baniya *et al.* 2010). Important determinants of mid-elevation peaks in species richness are temperature, humidity, soil characteristics (Carpenter 2005; Kessler 2001; Sánchez-González & López-Mata 2005) and mid-domain (Colwell & Hurtt 1994; Colwell *et al.* 2004; Grytnes & Vetaas 2002). Surprisingly, angiosperms and dicots did not reflect any pattern in species richness in relation to elevations in the present study though inverted hump-shaped pattern was observed in monocots. Since dicots were predominant in the

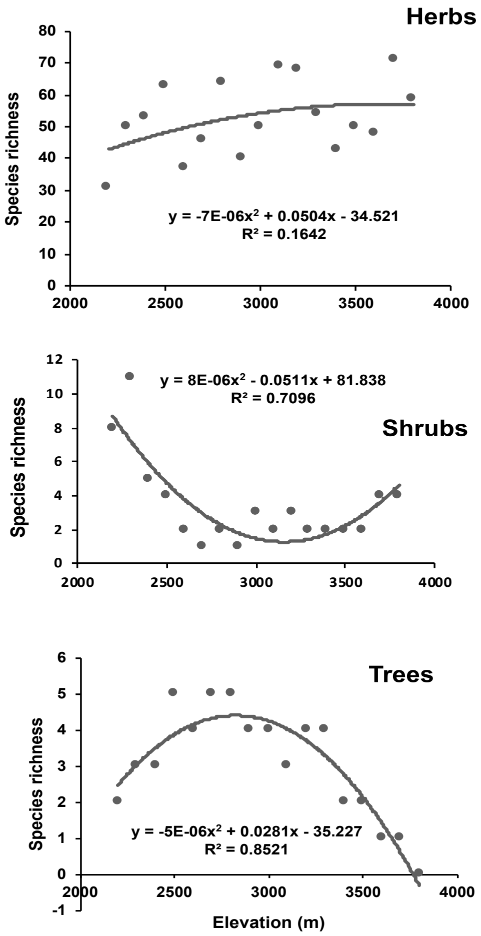

Fig. 12. Relationship between species richness of different plant functional groups and elevation.

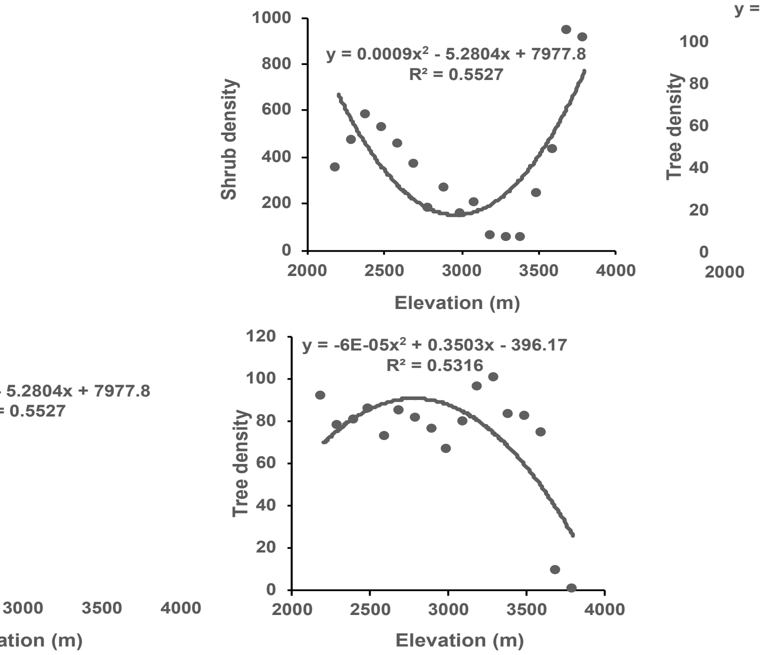

Fig. 13. Relationship between tree and shrub density and elevation.

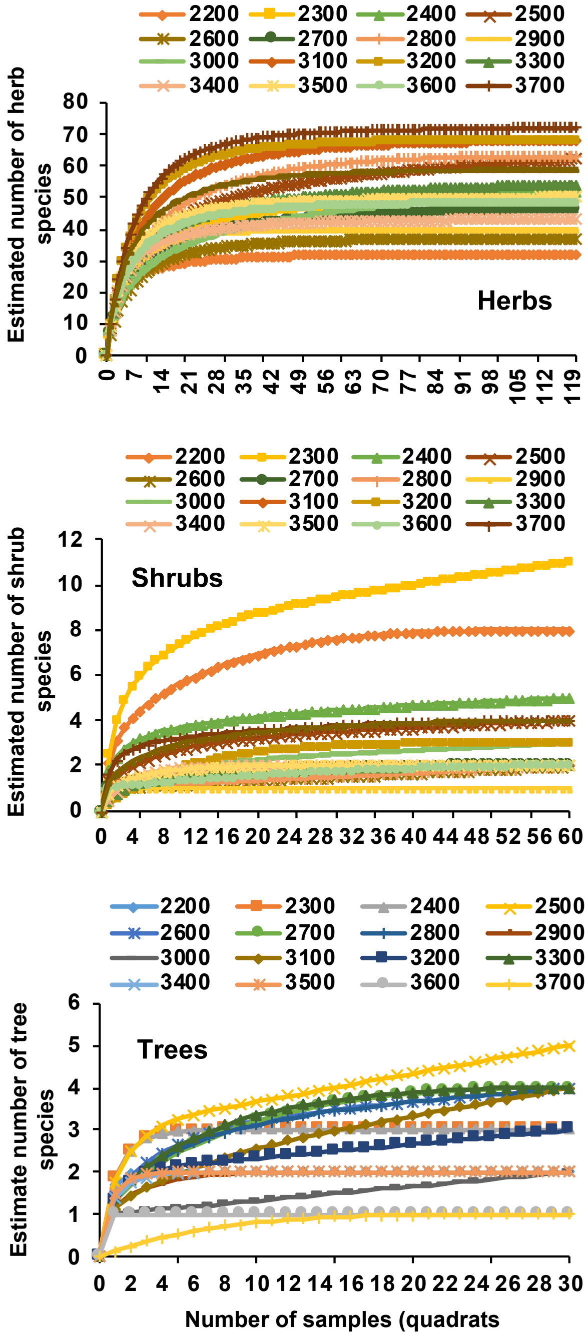

Fig. 14. Species accumulation curves for trees, shrubs and herbs in different elevational bands.

study area, the pattern in angiosperms was more due to dicots instead of monocots. It is Herb species richness did not show any particular relation with elevation which is consistent with the results of Willinghöfer *et al.* (2011). It may be because herbs have shorter generation times than trees and are morphologically more flexible in their adaptations that allows them to grow across the entire elevational gradient.

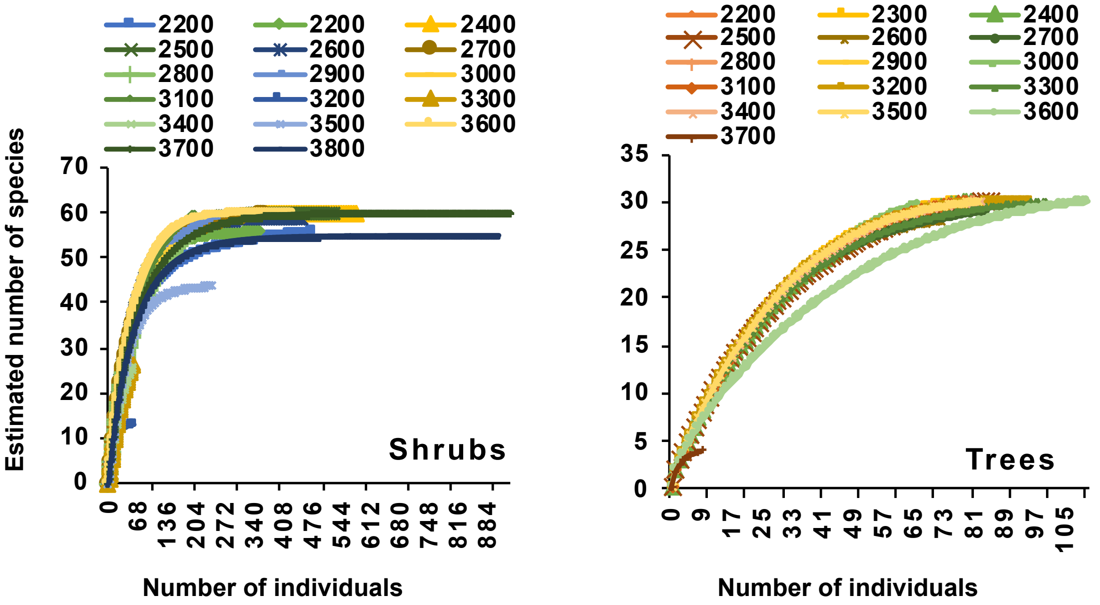

Fig. 15. Rarefaction curves based on individuals sampled for trees and shrubs in different elevational bands.

The present study thus brings out that elevational patterns are taxon-specific and often reported mid-elevational peaks (Rahbek 2005) do not necessarily reflect the over pattern of biodiversity along the elevational gradients. It has been, in fact, argued that multi-taxa elevational patterns in species diversity could be a new approach to develop more general models to explain elevational patterns in species diversity (Peters *et al.* 2016). Such taxon-specific patterns reflect the ecology of the taxonomic groups, their requirements and their response and relationship with the factors of temperature, precipitation, day length that co-vary with altitude (McCain 2009, 2010) and such observations draw support from similar findings of Grytnes *et al.* (2006) and Zhang *et al.* (2016).

During the present investigation, it became apparent that growth forms, such as trees, shrubs and herbs showed different elevational patterns (Figs. 12–13). A low-elevation plateau with a mid-peak was seen in trees, shrubs presented an inverted hump shaped pattern and herbs did not exhibit any elevation pattern. Willinghöfer *et al.* (2012) and Ohlemuller & Wilson (2000) also did not notice any particular trend in herbs in relation to elevation. However, other studies carried out on elevational patterns in herbs have reported a U-shaped pattern in Borneo (200–850 m) (Poulsen & Pendry 1995), a monotonic decline between 770 and 1520 m in central Africa (Poulsen *et al.* 2005), a hump-shaped pattern from sea level to 4094 m in Borneo (Grytnes & Beaman 2006), and a roughly monotonic increase between 1200 and 2700 m in Ethiopia (Desalegn & Beierkuhnlein 2010). Such differences could be attributed to differences in the ecological conditions in these study areas and also to the different elevational spans covered in these studies.

The alpine treeline ecotone, extending between the upper limit of closed forest (timberline) and the highest individuals of tree species showing an upright growth form (treeline), showed changes in species composition, physiognomy, density of trees and shrubs with small increments in altitude. Similar changes have been recorded by Batllori *et al.* (2009) and Orbán *et al.* (2017). In particular, *Abies pindrow,* the timberline species in the study area, decreases in density presumably because trees are reported to be sensitive to climatic variation (Theurillat & Guisan 2001). Infact, a common thermal threshold has been advanced as an explanation for limits to forest and tree growth in higher elevations (Körner & Paulsen 2004). Not only do the variations in physical environment in the treeline ecotone help explain the rapid changes in species composition, but it is quite possible that increased light availability due to sparse cover of forest trees in the ecotone may be enabling many species to grow in the alpine vegetation as has been reported by Grytnes (2000). However, it also needs to be emphasized that plant community composition at a small spatial scale is also controlled by several factors, such as microtopography, temperature, snow, wind, soil nutrients, moisture availability, pH and other biotic factors (Batllori *et al.* 2009). It is very likely that all these factors may be operative in the study area and in concert may be determining the plant community structure in the treeline ecotone.

It also needs to be emphasized that sampling robustness is essential for accurate portrayal of species richness patterns and hence it is of pivotal importance to determine whether or not sampling effort was enough (Gotelli & Colwell 2001).

The common sampling bias arises as a consequence of less and/or uneven sampling effort across the elevational gradient which can be overcome through use of sample and individual based rarefaction (Gotelli & Colwell 2001). In the present study, the sample-based species accumulation curves (Fig. 14) and individual-based rarefaction curves computed for trees and shrubs (Fig. 15) which make direct comparisons amongst communities on the basis of number of individuals in the smallest sample clearly reveal adequacy of sampling and hence conclusions drawn about elevational patterns during the present study could be considered as robust.

Acknowledgements

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Plant species diversity and rarity patterns along altitude range covering treeline ecotone in Uttarakhand: conservation implications

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Abstract: The study documents plant diversity within a forested high altitude zone (2000–3500 m asl) of Uttarakhand wherein 1471 plant species (106 trees, 233 shrubs and 1132 herbs) occur. The lowest belt, 2000–2500 m exhibited the highest diversity (815 spp.; 55.4%). A sharp decline in tree and shrub species representation was apparent with increasing altitude (low altitude: 88.7% and 66.5%; high altitude: 15.1% and 27.4%, respectively), while herb species representation did not vary (50.0–47.6%). Species to genera ratio (S/G) for entire altitude zone was 1.63 for trees, 1.97 for shrubs and 2.21 for herbs. S/G changed with elevation, but the patterns varied across growth forms. Of the total, 387 (26.3%) species were recorded from the study transects which included 52.5% (203 spp.) Himalayan natives. Rarity analysis of these natives has highlighted conservation priorities at local to regional scale. Attributes of vegetation have been described across systematically sampled 100 m altitude bands in five transects covering treeline ecotone. Altitudinal patterns varied across the transects, except for seedlings, which tended to decrease with altitude regardless of the transect. The study strongly reflects heterogeneity in patterns across altitude transects and life forms. We have used β diversity and species turn-over to shed light on local and regional conservation implications.

Key words: β diversity, conservation, life forms, rarity analysis, species richness.

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Introduction

Several studies have established that altitude plays role in regulating species richness patterns (Grytnes 2003; Kessler 2000). Therefore, altitude gradient is being increasingly recognized to offer many characteristics that make it more suitable for uncovering the underlying cause(s) of spatial variation in diversity (Sanders & Rahbek 2012). Consequently, in recent decades, there has been a noticeable increase in biodiversity research along altitude gradients in mountains (Guo *et al.* 2013; Tang *et al.* 2014).

The projected worldwide changes in vegetation distribution under the global climate change scenarios, and rapid upward shifts in vegetation boundaries in mountain ecosystems have been reported in several studies (e.g., Kapfer & Grytnes 2012; Kelly & Goulden 2008; Li *et al.* 2015; Lenoir *et al.* 2008). A multi-site and multi-partner study on European mountains indicates the species accumulation near mountain summits because of climate warming (Steinbaure *et al.* 2018). Such studies have gained greater attention to understand ecological and evolutionary responses of species to recent climate changes and consequent extinction risks at different spatial scales (Foden *et al.* 2007; Parmesan 2006; Pauli *et al.* 2006).

The Himalayan mountains, which have been globally recognized as biodiversity hotspots, provide altitude range that represents the widest bioclimatic gradient in the world (Grytnes & Vetaas 2002). Evidences suggest that Himalayas are warming at much higher rate than global average (Singh *et al.*

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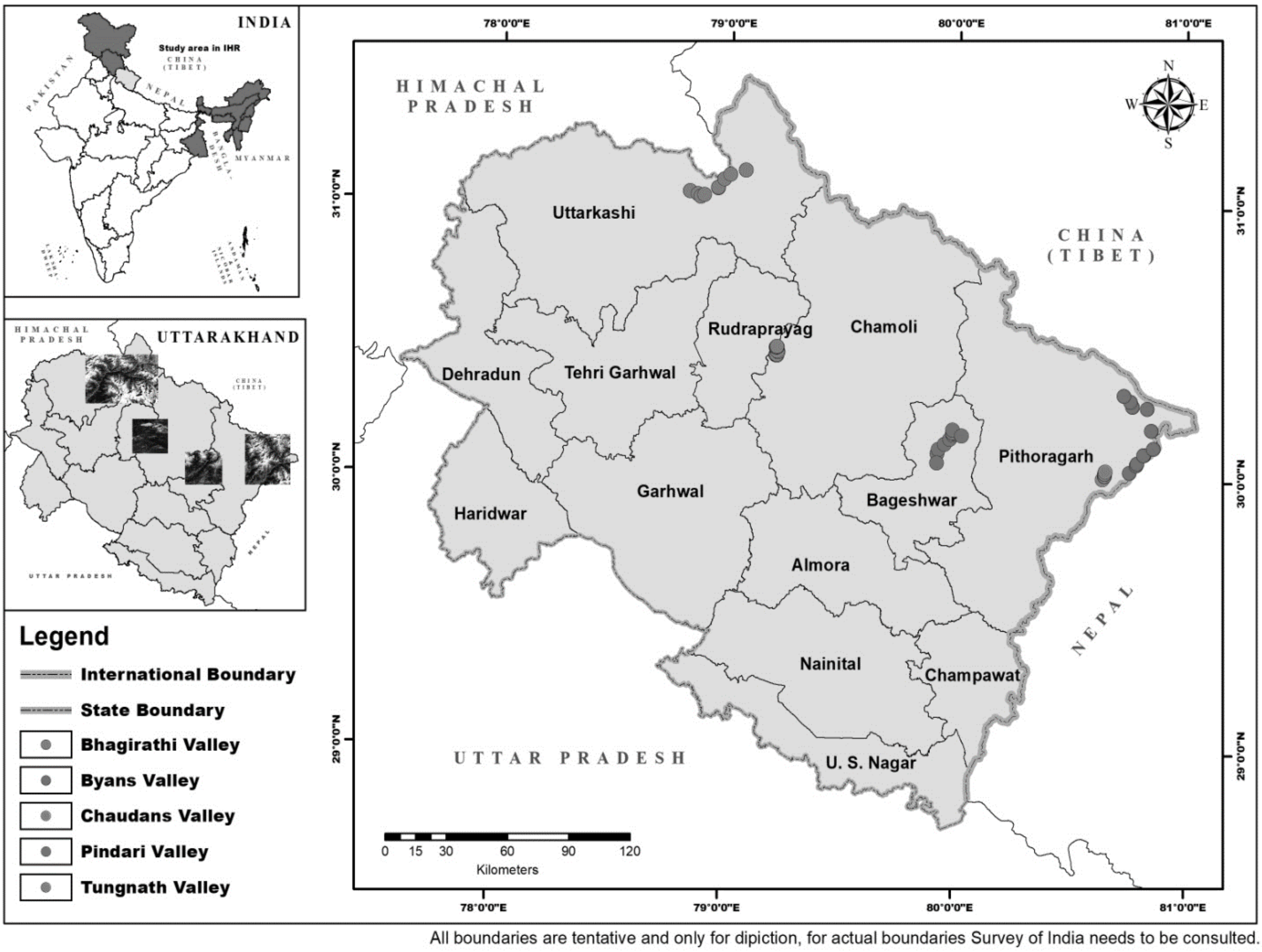

Fig. 1. Study area and location of the five studied altitude transects.

2010, 2011; Shrestha *et al.* 2012) and the extent of temperature rise is more in higher altitudes (You *et al.* 2017). This rapid warming in the Himalayas is predicted to increase upper limit of plants distribution, vegetation cover and abundance of species that get adapted to warmer climate. All these features have made the Himalayas interesting candidate for biodiversity studies along altitude gradients. However, because of the remoteness and difficult terrain in high altitude areas not many studies have been carried out on species composition and diversity of tree line areas of Himalayas. Only recently, a few investigations have been undertaken in Nepal Himalaya (Bhattarai & Vetaas 2006; Grau *et al*. 2007; Grytnes & Vetaas 2002; Vetaas & Grytnes 2002). In Indian Himalayas, Singh *et al.* (1994) reviewed patterns of leaf characteristics, forest structure, tree species diversity, biomass, and productivity across an altitude gradient of 3300 m in Kumaun part of west Himalaya. Some other studies have also provided insight on altitude patterns of forest vegetation form this region (Rawal & Pangtey 1994; Rawal *et al.* 1994). Oommen & Shankar (2005) used altitude gradient for comparing woody plant species distribution across local to landscape level in west Himalaya. In the eastern Indian Himalaya, Behera & Kushwaha (2006) and Acharya *et al.* (2011) have provided information about altitudinal patterns of tree species distribution. However, the comprehensive understanding on diversity distribution across plant life forms and spatial heterogeneity is still lacking. More importantly, the diversity patterns in higher altitude areas, which are more sensitive to climate change impacts, are poorly known.

This paper describes and discusses patterns of changes in species diversity in different life forms (herbs, shrubs and trees) along the altitude gradients in higher Himalaya that encompass treeline ecotones. This study, for the first time in west Himalaya, has considered multiple altitude transects for providing evidence based answers to the following questions: (i) how do the species diversity patterns along an altitude gradient in various life forms vary? (ii) what influences rare/occasional species have on diversity patterns? (iii) do the compositional patterns in treeline ecotones differ considerably across the region?, and (iv) do the existing patterns of diversity have conservation implications under changing climate?

Material and methods

Study area

This study was conducted in Uttarakhand (28°43' N 31°27' N and 77°34' to 81°02' E), west Himalaya. Representative altitude transects, covering forested area in high altitude zone (i.e., 2000–3500 m asl), were identified for intensive investigation (Fig. 1). The dissected topography and great variations in climatic conditions along altitude range are characteristic features of the area. While identifying the intensive study sites, the focus was kept on representing most of the broad geological and geo-morphological formations and climatic regimes (i.e., monsoonal and non-monsoonal). In this context, the study area broadly covers two distinct geological provinces, both falling under monsoonal regimes. The southern narrow altitude belt (approx. 2000–2400 m) belongs to lesser Himalayan domain. This chain suddenly rises to greatly elevated peaks of the greater Himalaya towards north. The greater Himalayan belt exhibits extremely rugged topography and is characterised by glacial features like lateral and medial moraines (Chandra 1986). This area occurs under the Indian monsoon regime. In non-monsoonal regime, the extreme north of study area, parallel to the Great Himalayan range, lies in an arid mountainous tract often known as cold desert that is constituted of the sediments of the Tethyan sea bed. The altitude on an average remains above 3000 m asl. This area is away from the Indian monsoon, and referred to as rain shadow of the main Himalayan region (Kumar *et al.* 2017).

Baseline on floristic diversity

A base line of potentially occurring plant species, across three life forms (i.e., trees, shrubs, and herbs) within the altitude range 2000–3500 in study area was prepared after review of published information, mainly the regional floras and other publications (i.e., Gaur 1999; Naithani 1984; Osmaston 1927; Rai *et al.* 2017). The broad distributional trends of plants in each life form were analyzed across three altitude zones, (2000–2500, 2500–3000, and 3000–3500 m asl). The information was also used to assess patterns of species to genera and species to family ratio for different life forms and altitude zones.

Vegetation assessment

Three representative altitude transects in monsoonal regimes (i.e., Pindari, Tungnath and Bhagirathi) and two in non-monsoonal regimes (i.e., Byans and Nelang) were investigated between 2013–2017 for generalizing compositional patterns of vegetation for target region. Among these, three altitude transects in monsoonal regime have been used to describe the altitude patterns of species diversity. Besides altitude, as apparent from evidences, these transect also represent three broad levels of anthropogenic disturbances (i.e., low disturbance-Pindari transect, medium disturbance- Bhagirathi transect, and high disturbance-Tungnath transect).

The study transects were investigated by systematically dividing the transect into 100 m altitude bands. Within each altitude band, forest vegetation was investigated using random sampling method. This approach represents a stratified random sampling. Evidently, in this approach most of the variations in vegetation are captured as the samples are distributed throughout the area (Reshi *et al.* 2017). However, since the transects in non-monsoonal sites (all above 3000 m asl) did not have continuous forest vegetation, sampling did not follow systematic 100 m bands, rather plots were laid depending on availability of forest vegetation.

In each altitude band, three plots (50 × 50 m) were marked randomly. For enumerating the vegetation, within each plot, ten quadrats (10 × 10 m) for trees and saplings, 20 (5 × 5 m) for shrubs and seedlings and 40 (1 × 1 m) for herbs were laid randomly. In case of tree species, individuals measuring > 10 cm diameter (diameter at breast height-dbh; 130 cm above ground level) were considered as trees (adults), individuals between > 3–10 cm diameter as saplings and individuals < 3 cm diameter as seedlings. For generating demographic profiles, the adult individuals were categorized following 10 cm diameter classes as, C: 10–20; D: 20–30; E: 30–40; F: 40–50;

Table 1. Defining rarity and conservation priority classes at different spatial scales (based on Rawal & Dhar 1997). Rarity increases from 1 to 8; conservation priority: I highest and IV lowest. Attributes are coded as: WGR-wide geographical range; RGR- restricted geographical range; BEA-Broad Ecological Amplitude; NEA-Narrow Ecological Amplitude; LA-Locally Abundant; LS-Locally Scarce.

Rarity	Attributes	Level of conservation priority	
		Himalaya	Study Area
1	WGR+BEA+LA	IV	IV
2	WGR+BEA+LS	IV	III
3	WGR+NEA+LA	III	II
4	WGR+NEA+LS	III	I
5	RGR+BEA+LA	II	IV
6	RGR+BEA+LS	II	III
7	RGR+NEA+LA	I	II
8	RGR+NEA+LS	I	I

G: 50–60; H: 60–70; I: 70–80; J: 80–90; K: 90–100; L: >100 cm or more diameter. Quadrat data was pooled by plots to estimate density, frequency, total basal area (TBA) and their relative values following the standard phytosociological approaches (Dhar *et al.* 1997; Gairola 2005; Mueller-Dombois & Ellenberg 1974). Importance Value Index (IVI) was calculated following Curtis (1959). Species richness is simply the number of species per unit area (Pielou 1975; Whittaker 1975).

Considering that beta diversity (ß) is an important emergent property, which describes the change in species content from one site or sample to another, it was measured using the Whittaker (1960) formula as given in Mena & Vazquez-Dominguez (2005): $\beta = (s/\alpha) - 1$; where $\alpha$is the mean number of species per altitude belt, and 's' is the total number of species recorded across the study system (i.e., altitude transect). As a measure of change in species composition, pair-wise comparison of the presence absence data was made as turnover measure across altitude belts following Wilson & Shmida (1984). The turnover was calculated with the following formula: $\beta = b + c/2a+b+c$; where 'a' is the total number of species shared by the two adjacent altitude belts, 'b' is the number of species exclusive in the higher belt and 'c' is the number of species exclusive in lower belt (Koleff *et al.* 2003).

To numerically model the distribution of species in different life forms (i.e., trees, shrubs, herbs) along the altitude gradient in different transacts, quadratic models were fitted between altitude and species distributions. Selection of the quadratic model was made based on the performance. Model performances were primarily evaluated by computing statistically significant ($P < 0.05$) r^2 values. Moreover, to assess distribution of sample means from observations and model simulations, analysis of variance (ANOVA) was carried out, particularly, estimated F value of each model was compared with critical F-value. The result section highlights those models for which a significantly high r^2 value was noted at $P < 0.05$. Subsequently, results from ANOVA for these models were elaborated.

Rarity patterns

Among the species assessed along the altitude transects, the Himalayan natives were considered as species of special interest and identified following Dhar & Samant (1993). Species with spatial range restriction in the Himalaya (i.e. Indian Himalaya, Nepal, Bhutan, Pakistan Himalaya) were considered as Himalayan endemics and the ones with range extension slightly beyond the Himalaya were referred to as 'near endemics' (Dhar & Samant 1993; Rawal & Dhar 1997). All such species were analyzed for their rarity ranking as measure of sensitivity towards endangerment. The rarity analysis approach of Rabinowitz *et al.* (1986) was used with modifications as suggested in Rawal & Dhar (1997). Three broad ecological attributes (i.e., Geographical Range- GR; Ecological Amplitude- EA; Local Abundance- LA) were considered for defining rarity class of a particular species. Further classification of GR as wide (WGR) and restricted (RGR); EA as broad (BEA) and narrow (NEA) and LA as locally abundant (LA) and locally scarce (LS) was based on Rawal & Dhar (1997). Based on the possible combinations of these attributes, total of eight classes of rarity were possible. The status of species was further described at regional (Himalaya) and local (study area) spatial scales to elucidate the conservation priorities (Table 1).

Results

Floristic diversity pool

Within the investigated altitude range (i.e., 2000–3500 m) in west Himalaya a total of 1471 plant species [106 (7.2%) trees, 233 (15.8%) shrubs and 1132 (77.0%) herbs] occur. When species distribution is seen in relation to three 500 m altitude zones (i.e.,

Table 2. Floristic diversity pool (Species- S, Genera- G, Family- F) in high altitude forest zone (2000–3500 m) of Uttarakhand.

	Trees					Shrubs					Herbs				
Altitude	S	G	F	S/G	S/F	S	G	F	S/G	S/F	S	G	F	S/G	S/F
2000–2500	93	61	35	1.52	2.66	155	97	44	1.6	3.52	567	359	88	1.57	6.44
2500–3000	45	32	21	1.40	2.14	108	69	35	1.57	3.09	529	296	75	1.79	7.05
3000–3500	16	15	11	1.10	1.45	64	31	16	2.06	4.00	539	245	62	2.20	8.69
Total	106	65	37	1.63	2.86	233	118	49	1.97	4.76	1132	511	100	2.21	11.32

Table 3. Compositional attributes of forests in three altitude transects of Uttarakhand.

Transect	Density Range (individuals ha^{-1})					TBA Range (m^2ha^{-1})
	Tree (×10)	Sapling (×10)	Seedling (×10)	Shrubs (×100)	Herbs (×1000)	
Pindari	21–80	10–41	67–950	43.5–999.0	35.2–984.0	14.8–116.9
Tungnath	11–90	00–52	2–228	4.6–57.6	44.5–351.3	3.9–99.1
Bhagirathi	54–112	14–220	20–1272	7.6–21.4	67.0–132.0	10.3–111.2

2000–2500 m lower zone, 2500–3000 middle zone and 3000–3500 m higher zone) following patterns emerge: (i) the lower altitude zone exhibited maximum floristic diversity (815 spp.; 55.4%) and the higher zone the minimum (619 spp.; 42.1%), (ii) a sharp decline in tree species number occurred from lower (93 spp.; 88.7%) to higher zone (16 spp.; 15.1%), (iii) for shrubs, the decline was less dramatic, from 66.5–27.4%, and (iv) the herb species representation remained more or less similar (50.0–47.6%) across the three altitude zones (Table 2).

While considering diversity distribution of higher level of taxa (i.e., genera and family), more rapid decline with altitude is apparent as compared to the species (Table 2). The species to genera ratio (S/G) for the entire landscape was calculated as 1.63 for trees, 1.97 for shrubs and 2.21 for herbs. However, across the three altitude zones, the S/G values declined from lower to higher zone for trees, but increased for both shrubs and herbs (Table 2). Similar trends were found for species to family (S/F) ratio (Table 2).

Analysis of rarity

While considering plant species representation, the study transects covered considerably large proportion of reported plant diversity pool in forested high altitude zone of Uttrakhand (i.e., herbs 270 spp., 23.9%; shrubs 63, 27.0%; trees 54, 50.9%). Most of these species (203, 52.5%) are Himalayan natives; of which 39.1% species are near endemics to Himalaya. Nativity across life forms ranges was 47.4% for herbs, 59.3% for trees and 68.2% for shrubs.

Frequency of native species in the eight categories of rarity across life forms is presented (Fig. 2). Altogether, most of the species (158, 77.8%) exhibited wide geographical distribution (rarity class 1–4) and more than half of these (91, 57.6%) have broad ecological amplitude (rarity class 1–2) an attribute of commonness. Forty-five species (22.2%) exhibited restricted geographic distribution (rarity class 5–8). Of these, 23 (51.1%) had narrow ecological amplitude (rarity class, 7–8), suggesting high sensitivity.

Analysis revealed that 120 taxa (59.1%) are locally abundant (rarity class 1,3,5,7) and 81 (67.5%) species of these had broad ecological amplitude, a feature contributing to commonness of taxa at local level (rarity class 1,5). Fifty-five taxa (27.1%) were locally scarce and with narrow ecological amplitude (rarity class 4, 8), hence are at high risk of becoming endangered locally. A few examples across life forms include: trees- *Acer caesium, Pyrus lanata, Syringa emodi, Ulmus wallichiana;* shrubs-*Berberis jaeschkeana, Rhododendron lepidotum, Thamnoclamus spathiflora;* and herbs-*Cypripedium cordigerum, C. elegans, Habenaria edgeworthii, Malaxis acuminata, Nardostachys grandiflora, Rheum tibeticum,* etc.

Forest vegetation composition

Broad range of compositional attributes of forests in three altitude transects indicate that their tree density and total tree basal area (TBA) ranges are comparable (Table 3). However, shrub and herb densities were distinctly higher for

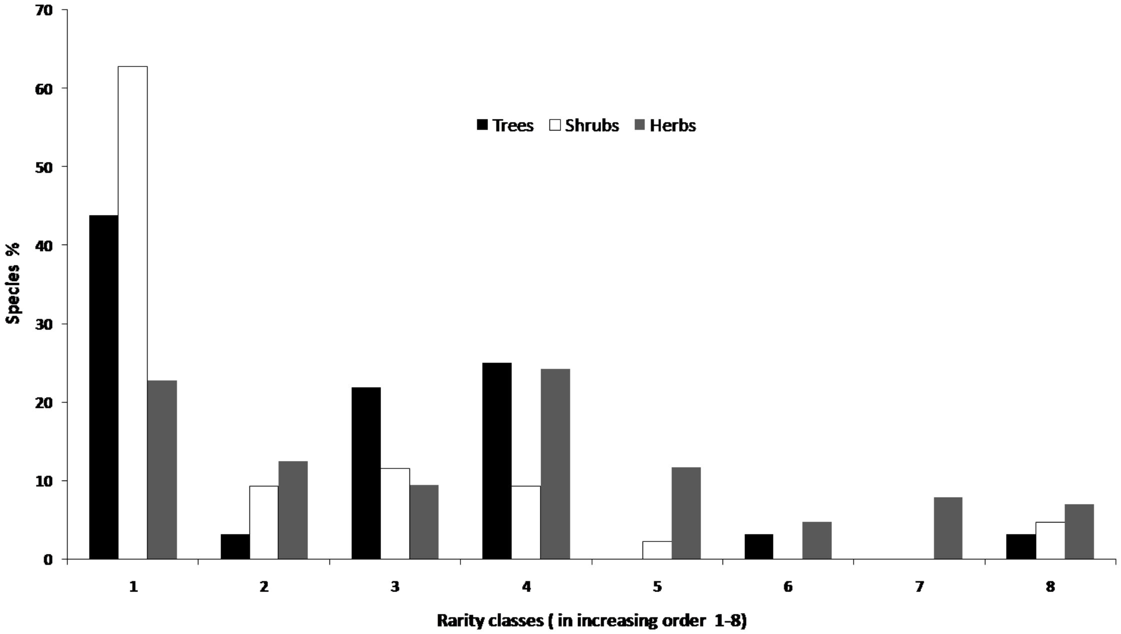

Fig. 2. Rarity distribution of Himalayan native species across life forms in studied altitude transects (level of rarity increases from 1–8).

Pindari transect. Both sapling and seedling densities were generally low but for Bhagirathi transect (Table 3).

Patterns of density distribution across altitude range were modelled for different transects. For different size classes, i.e., trees, saplings and seedlings, density distribution along altitude gradient did not follow uniform patterns (Fig. 3). Along the altitude gradient tree density either peaked around 2500 m or decreased monotonically. Sapling density varied widely along the altitude gradient. Interestingly seedling density tended to decline with altitude in all three transects (Fig. 3).

As for shrub density in relation to altitude, the three transects differed from one another. It tended to increase with altitude in Tungnath, continuously decreased with altitude in Bhagirathi and showed a mid altitude peak in Pindari. Herb density, in general, was relatively stable across the altitude transects (Fig. 4).

The Total tree basal area showed a hump shaped curve in Tungnath and Pindari, with peak around 2600 m and 2400 m, respectively. In Bhagirathi it tended to increase monotonically with altitude up to 2800–3000 m (Fig. 5).

Species richness patterns

The species richness ranged from: (i) 5–15 (Pindari), 1–7 (Tungnath) and 2–10 (Bhagirathi) for trees (100 m^2 area); (ii) 3–13 (Pindari); 2–9 (Tungnath) and 1–5 (Bhagirathi) for shrubs (25 m^2 area); and (iii) 18–53 (Pindari); 5–48 (Tungnath) and 4–11 (Bhagirathi) for herbs (1 m^2 area). Thus, for all life forms Pindari was the richest, possibly because of the lowest human disturbance.

The tree species richness along altitude gradient followed a hump shaped curve with peak in the lower half of the altitude range- around 2500 m in Tungnath and Bhagirathi, and 2700 m in Pindari (Fig. 6). In Tungnath, shrub species richness increased with altitude but it tended to decrease with altitude in other two sites. In Tungnath herbs also showed positive correlation with altitude, but in other transects the tendency was to form mid altitude peak (Pindari) or plateau (Bhagirathi).

In brief, in Tungnath tree species richness decreased sharply and shrub and herb species richness increased with altitude. In the rest, the tendency was to form mid altitude plateau.

Beta diversity and species turnover

The values of β diversity calculated for different transects for each life form (Table 4) indicated wide variations across life forms and transects. Beta diversity contributed significantly to the altitude transect level species richness of Pindari for herb and shrubs, but little for trees (Table 4). In Tungnath tree

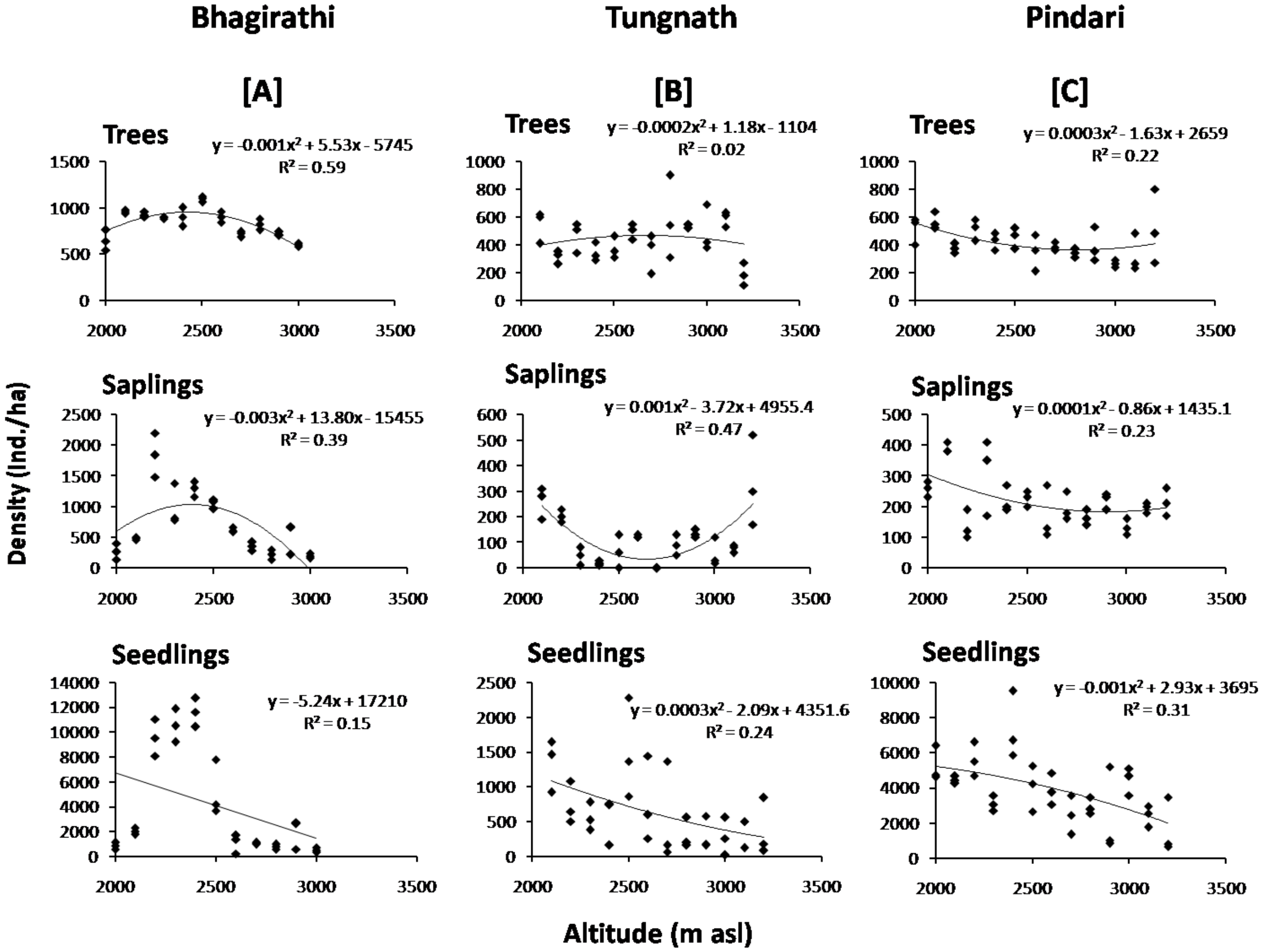

Fig. 3. Density distribution in trees, saplings and seedlings along three altitude transects: A-Bhagirathi, B- Tungnath, C-Pindari.

Table 4. Beta diversity variations across life forms and transects.

Life forms	β diversity in different transects		
	Tungnath	Bhagirathi	Pindari
Trees	5.1	3.4	2.3
Shrubs	3.1	1.8	3.3
Herbs	1.8	2.7	5.1

species change rapidly, but herbs changed slowly.

Towards understanding the species compositional heterogeneity across pairs of altitude bands in different transects, the species turnover was calculated and depicted (Fig.7). The patterns are not uniform for transects and life forms.

Composition at treeline ecotone

Considering that treeline in the study area broadly varies from 2800–4200 m (see RS based study in this volume), the studied plots falling within this altitude range were analysed separately for monsoonal and non-monsoonal sites (Table 5).

The ecotone exhibits greater richness of tree species (1–8 species per plot) and dominant/co-dominant types (i.e., *Quercus semecarpifolia, Abies pindrow, Betula utilis, Rhododendron arboreum, R. campanulatum, Taxus wallichiana, Acer accuminatum* and *Cedrus deodara)* in monsoonal sites as compared to non-monsoonal sites (1–3 spp. per plot; dominants *Pinus wallichiana, Betula utilis, Abies spectabilis, Juniperus semiglobosa).*

Discussion

Floristic diversity and representativeness

Of the known total floristic diversity pool of Uttarakhand (Uniyal *et al.* 2007), the forested high altitude zone (2000–3500 m asl) that we studied

Table 5. Forest compositional attributes at treeline ecotone of Uttarakhand.

Sites	Density h^{-1} in tree life forms			TBA (m^2 h^{-1})	Shrub density (h^{-1})	Species Richness				Dominant species (IVI)
	Trees	Saplings	Seedlings			Trees	Saplings	Seedlings	Shrubs	
Monsoonal Sites										
(i) Chaudans Site										
2900	680	400	18400	43.7	2140	8	5	6	6	*Quercus semecarpifolia* (125); *Abies pindrow* (69)
3100	520	320	1400	25.2	2700	6	2	3	4	*Q. semecarpifolia* (142); *Taxus wallichiana* (91)
3300	810	240	2400	67.7	1160	6	1	2	2	*Q. semecarpifolia* (228); *A. pindrow* (22)
3500	710	270	1200	35.1	680	1	1	1	1	*Q. semecarpifolia* (300)
(ii) Pindari Site										
2900	530	280	5200	48.1	5000	8	6	5	7	*Q. semecarpifolia* (117); *Rhododendron Campanulatum* (48)
3100	480	210	1750	28.1	4350	8	8	5	7	*Betula utilis* (113); *A. pindrow* (56)
3300	270	260	3450	7.2	1615	6	6	8	8	*Betula utilis* (172); *R. campanulatum* (42)
(iii) Bhagirathi Site										
2900	690	180	480	48.8	950	3	3	3	2	*Cedrus deodara* (231); *A. pindrow* (47)
3100	600	200	420	57.7	920	2	2	2	2	*C. deodara* (256); *B. utilis* (44)
(iv) Tungnath Site										
2900	540	133	122	46.7	2847	3	3	4	8	*Q. semecarpifolia* (199); *Acer accuminatum* (52)
3100	590	77	373	74.5	4380	3	3	3	10	*Q. semecarpifolia* (222); *R. arboreum* (50)
3300	186	330	367	5.40	2847	2	3	2	12	*R. campanulatum* (264); *Q. semecarpifolia* (35)
Non Monsoonal Sites										
(v) Byans Site										
3000	280	190	1780	9.5	1720	3	3	3	8	*A. spectabilis* (160); *Pinus wallichiana* (66)
3200	350	180	1120	23.9	2260	2	2	2	6	*A. spectabilis* (242); *P. wallichiana* (58)
3600	150	330	1400	2.5	1440	2	2	2	5	*B. utilis* (170); *P. wallichiana* (130)
4000	140	500	420	5.6	1100	1	1	1	6	*B. utilis* (300)
(vi) Nelang Site										
3100	370	0	0	3.4	2100	2	0	0	5	*P. wallichiana* (274) *J. semiglobosa* (26)
3300	530	0	0	4.5	1100	1	0	0	5	*J. semiglobosa* (300)
3500	100	0	0	2.7	1500	1	0	0	6	*J. semiglobosa* (300)

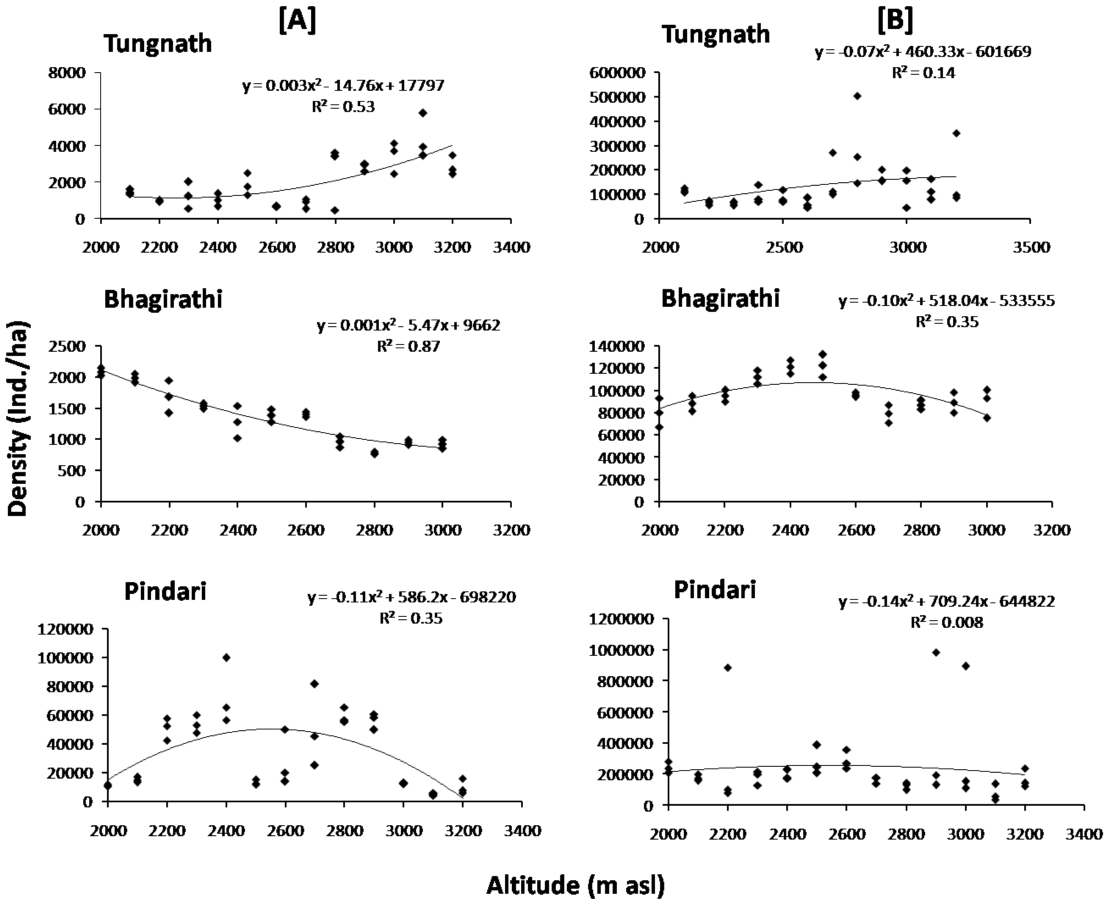

Fig. 4. Density distribution of shrubs (A) and herbs (B) along altitude transects.

accounts for 31.2% species, 45.6% genera and 83.2% families. Species level representativeness for diverse life forms ranges from 30.1% herbs, 33.3% trees to 47.9% shrubs. Even while comparing with the reported plant diversity of Himalaya (Rana & Rawat 2017), the study zone represents 14.0% species, 31.5% genera, and 59.6% family diversity of Himalaya. Therefore, from conservation perspective, any effort made to protect this altitude zone would contribute for conservation of a significant proportion of Himalayan plant biodiversity. Also, this altitude belt is left with some of the old growth forest stands, which are particularly rich in bird and some other living groups.

Recognizing that the S/G ratio have been frequently used to describe the biogeographic patterns and taxonomic structure of clades and biotas (Krug *et al.* 2008), we interpret the patterns of S/G at local scale in the light of the hypothesis that describes spatial variations of S/G as part of evolutionary dynamics wherein these ratios are related to speciation or diversification rates (Floeter *et al.* 2004). The altitudinal decrease of S/G in case of trees in study area would imply their phylogenetic over dispersion towards highest altitudes. On the contrary, the increasing S/G ratio of shrubs and herbs towards higher altitudes implies phylogenetic clumping meaning that diversification within the genera is more intense.

Rarity distribution and conservation priorities

Occurrence of 52.5% native elements of which a high proportion (39.1%) is of near endemic species in studied transects in itself reflects 'extent of rarity' (Dhar & Samant 1993; Krukerberg & Rabinowitz 1985; Rawal & Dhar 1997).

Considering the attributes of rarity, we suggest various priority classes for conservation initiatives. For instance, of the recorded native plants 22.2% taxa with restricted geographical distribution reflect higher susceptibility to endangerment at Himalayan level. This susceptibility at regional scale goes further high with narrowing of ecological

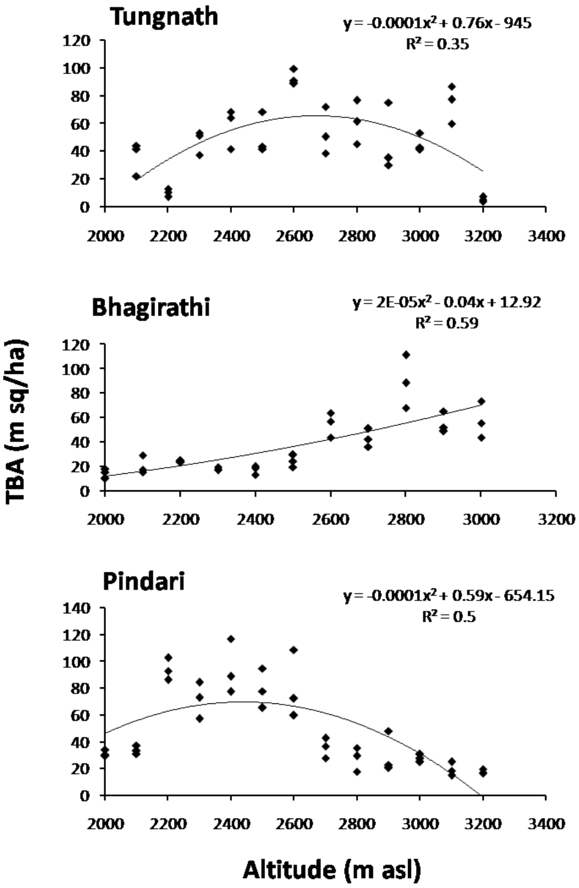

Fig. 5. Distribution of total basal area (TBA) for trees across three altitude transects in Uttarakhand.

amplitude (11.3 of native taxa). At the local level, 55 taxa with recorded low abundance and narrow ecological amplitude deserve greater attention (Rawal & Dhar 1997). However, nine species of herbs (*Andorosaces armentosa, Carex obscura, Goodeyera biflora, Habenaria edgeworthii, Lactuca lessertiana, Maharanga emodi, Primula elliptica, P. reidii, Rheum tibeticum*), two species of shrubs (*Berberis jaeschkeana, Thamnocalamus spathiflora*) and 1 species of tree (*Ulmus wallichiana*), with restricted global distribution, narrow ecological amplitude and scarce local population (rarity class 8), exhibit sensitivity both at local to regional scale, are suggested as most critical and top ranking priority taxa.

While considering the life forms, at local scale, relatively high proportion of native herbs (31.3%) and trees (28.1%) are currently threatened due to their restricted altitude range (ecological amplitude) and reduced local abundance. We argue other additional factors, such as anthropogenic disturbance, will add to their sensitivity of being eliminated at local level. However, before generalizing for entire region, there is a need to analyse these trends of rarity on a larger datasets. For instance, at least for the entire altitude transects (sub-tropical to alpine) in Uttarakhand.

Conservation imperatives of species richness and beta diversity

Towards conservation of biodiversity across spatial scales, there is a need to understand and recognize (i) the value of locally collected data sets along with the regional diversity dynamics, and (ii) the variations in mechanisms that maintain biodiversity at local to regional scale (Chesson & Kuang 2008; Socolar *et al.* 2016; Terborgh 2012).

In the above context, among various expressions of diversity, species richness has remained a major focus of biogeographical researches (Acharya *et al.* 2011; Kessler 2000; Oommen & Shankar 2005).

Considering that the total species number recorded in three study transects represented over 26.3% of species reported from entire high altitude forested zone of Uttarakhand, and this proportion of representativeness even goes higher for woody life forms (shrubs 27%, trees 50.9%), it is safe to generalize the patterns of distribution drawn from these transects for entire altitude zone (2000–3500 m) in Uttarakahnd, west Himalaya.

Our study strongly reflects that patterns of species richness distribution along altitude gradient are not uniform for transects and life forms. The tree species richness tends to form a hump-shaped relationship with altitude. Such relationships are typically reported for species richness in different parts of Himalaya (i.e., Sikkim Himalaya- Acharya *et al.* 2011; Nepal- Grytens & Vetaas 2002; west Himalaya- Oommen & Shanker 2005). However, we argue, since the present study confines only to the upper half (2000–3500 m) of entire altitude transect, which can go down to <500 m altitude, there exists a strong possibility for another tree species richness peak in lower half of the altitude transect (i.e., between <500–2000 m). This possibility can be tested through evidences generated in lower half of altitude transects. In present case, the altitude bands between 2300–2500 m support the highest tree species richness. The diversity in patterns of shrub and herbaceous life forms along altitude gradient implies increasing the role of other site-specific factors. For instance, Tungnath transect (disturbance intensive species poor) suggests increasing richness of shrubs and herbs with altitude. Whereas for Pindari transect

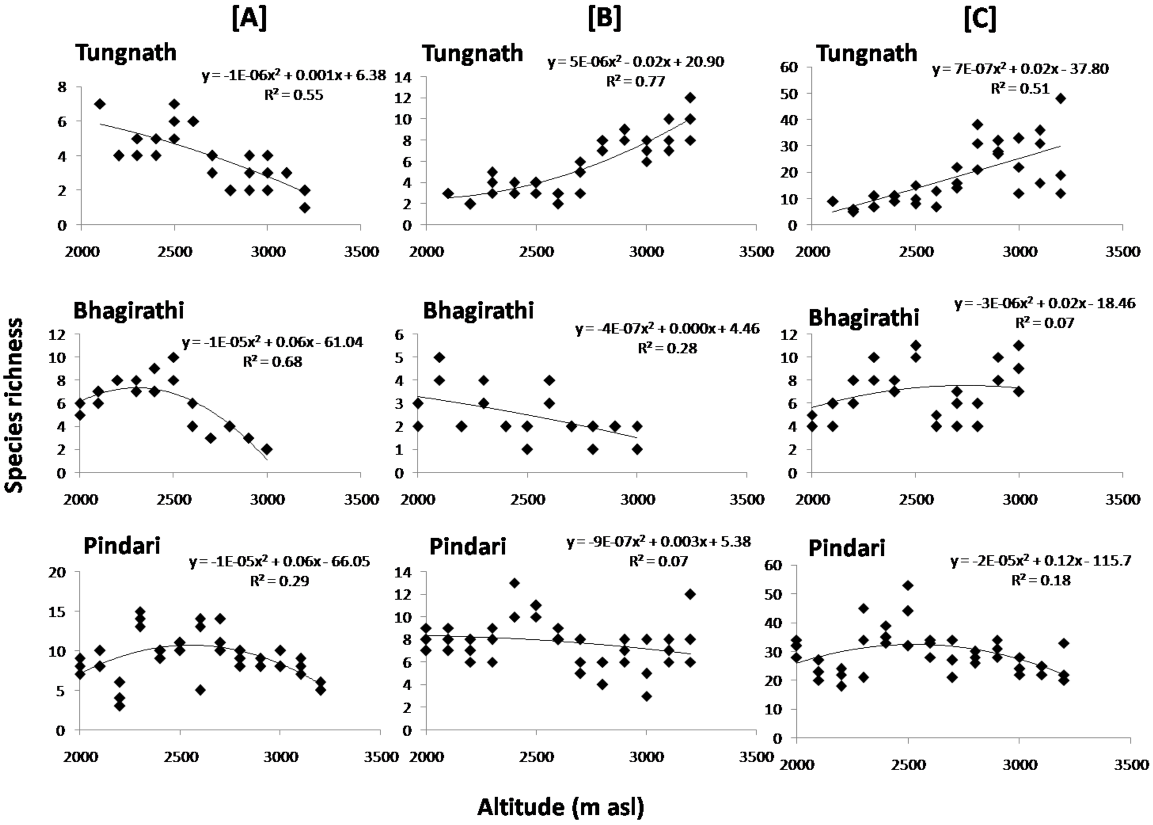

Fig. 6. Species richness distribution in different life forms (A- trees, B- shrubs, C- herbs) along altitude transects.

(least disturbed and species rich), decline in species richness with altitude is noticed. Since the species richness (Socolar *et al.* 2016) and ecological disturbances are hypothesized to alter community assembly process that ultimately influences variations in composition (i.e., ß diversity), we further build our arguments, specifically pertaining to conservation, on ß diversity assessments.

Recognizing that the patterns of ß diversity differ considerably across transects and life forms, we argue the level of disturbance plays differential role in its determination across life forms. While relatively high level of disturbance and poor species pool (i.e., Tungnath and Bhagirathi) leads to greater ß diversity in trees, it reflects reverse trend for herbs. The shrubs remain somewhere in between. Our study suggests, relatively pristine sites with high species packaging (i.e., Pindari) remain more homogenous in case of tree species distribution (low ß diversity) but become highly heterogeneous for herbs (high ß diversity). It appears such pristine sites provide more scope for occurrence of rare/occasional herbaceous species along altitude range, which contributes for higher heterogeneity of species composition. It is reported that the rare species usually constitute a heterogeneous pool of occasional plants of low persistence and low fidelity of association with specific community (Grime 1998). This role of rare/occasional species irrespective of their overall abundance and their fidelity of association with specific community types is further described. However, considering the evidence-based arguments that species differ widely in their capacity to track shifting climate envelops, depending mostly on their capacity of dispersal (Pearson 2006), indicates possible dominance of more dispersive taxa in future (Socolar *et al.* 2016). Also, climate driven declines in specialist taxa is expected leading to increased homogenization of communities in both natural and anthropogenic landscapes (Socolar *et al.* 2016; Urban 2015). This calls for attention with relation to patterns of ß diversity under changing climate, particularly in relatively pristine sites in the region (e.g., Pindari transect) where proportion of rare/occasional herbaceous species is high.

Studies have indicated that the pair-wise dissimilarities can be used to identify key spatial or environmental gradients where turn-over occurs, and such analysis before and after disturbance could pinpoint the environmental gradients along

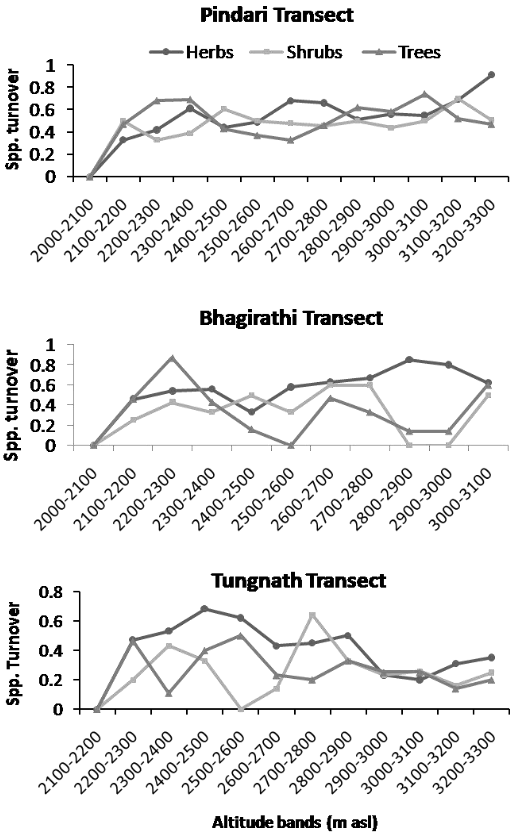

Fig. 7. Species turnover rate along altitude range of studied transects.

which beta diversity has been lost, thereby directing the preservation or restoration of key feature (Socolar *et al.* 2016).

Altitude relationship of compositional features

In the Himalayan region, strong relationship of compositional features, such as density and total basal area, with altitude are often exhibited (Dhar *et al.* 1997; Singh *et al.* 1994). However, studies have not considered multiple transects and multiple life forms to describe the patterns. In this context, present study, provides first of its kind data sets to discuss patterns drawn based on three comparable altitude transects. Barring anthropogenically disturbed altitude transect (i.e. Tungnath), the density and altitude exhibit significant quadratic relationship for different growth stages of trees in relatively less disturbed transects [Pindari: trees- $F = 5.935$, $P < 0.01$; saplings- $F = 8.149$, $P < 0.01$; seedlings- $F = 16.265$, $P < 0.01$ and Bhagirathi: trees- $F = 4.78$, $P < 0.05$; saplings- $F = 5.515$, $P < 0.05$; seedlings- $F = 5.595$, $P < 0.05$], and this model is well acceptable with $F > F_{crit}$. This suggests altitude relationships of density in case of tree species, irrespective of growth stage (tree, sapling, seedling), which gets modified by disturbance (e.g., Tungnath).

With the rejection of null hypothesis ($F > F_{crit.}$), modelled TBA distribution is acceptable in case of less disturbed sites (Pindari: $F = 11.95$, $P < 0.01$; and Bhagirathi: $F = 42.830$, $P < 0.01$). However, relationships are not uniform. The Pindari transect with sharp decline of TBA at upper elevation end differs from Bhagirathi transect where TBA continues to be high up to 3000 m. This phenomenon can be partially explained due to sharp changes in topographic and climatic feature of the Bhagirathi transect, which abruptly gives way to non-monsoonal Nelang transect beyond 3000–3100 m altitude band. At this altitude band of the Bhagirathi transect full grown *Cedrus deodara* forests dominate resulting in high TBA.

Non-significant altitude relationships for herbs ($F < F_{crit}$) across transects would imply that the herb density distribution is independent of altitude position. This calls for finding the other environmental factor(s), which govern density of herbs in the region.

Composition at treeline ecotone

Compositional features of vegetation at treeline ecotones in the Himalaya are relatively less explored. Most of our understanding comes from studies available for Tibetan Plateau. It is reported that the coniferous species in sub-alpine belt of southern part of the Tibetan Plateau (i.e., Hengduan mountain range) and southern slopes of Himalaya are highly diverse (16 species of *Abies*, *Picea*, six species of *Larix* and 11 species of *Junipers*). Of these 14 species of *Abies*, five species each of *Picea* and *Juniperus*, and four of *Larix* reach climatic forest limit to form timberline. In addition sclerophyllous *Quercus* and deciduous broad-leaved *Betula* also form timberline species in Tibetan plateau. *Juniperus indica, J. recurva, Abies spectabilis, A. densa, A. pindrow,* and *B. utilis* are reported to form timberline on southern slopes of the Himalaya (Rawal & Pangtey 1994; Schweinfurth 1957). Most of these reports have, however, subjectively described the vegetation at timberline zone. As compared to these reports, this study provides evidences from very systematically analysed data sets to establish that (i) the monsoonal treeline ecotones are most often rich in tree diversity with considerable variation in dominant and co-dominants across sites/plots; (ii) the non-monsoonal treeline ecotones remain poor in tree species richness and exhibit less variation of dominant/co-dominant types; and (iii) the compositional attributes (density, TBA, etc.) in monsoonal sites are relatively closer to those of the rest of the lower transect. This would imply that the vegetation composition in treeline ecotones in monsoonal and non-monsoonal sites in the region differ considerably. Also, the composition of treeline ecotone in this part of Himalaya varies significantly from other reported compositions in treeline/timberline ecotones elsewhere in Himalaya.

Conclusions

The study concludes the following: (i) the forested high altitude (2000–3500 m asl) zone of Uttarakhand represents a significant proportion of provincial (west Himalaya) and regional (Himalaya) plant diversity pool; (ii) the broad patterns of floristic diversity distribution vary across altitude zones and life forms; (iii) of the total plants recorded from study transects 52.5% are Himalayan natives, and rarity analysis of these natives reveals 22.2% taxa with restricted geographical distribution reflect higher susceptibility to endangerment at regional scale, whereas 27.9% taxa with narrow ecological amplitude and scarce local abundance deserve conservation support at local level; (iv) the species richness and β diversity patterns are sensitive to human disturbances and climate change; (v) the altitude patterns of vegetation vary considerably across sites (i.e. altitude transects) thereby suggesting stronger influence of micro level factors.

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The easternmost timberline of the Indian Himalayan region: A socio-ecological assessment

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Abstract: The present study provides a socio-ecological assessment of the timberline zone falling in Tawang and West Kameng districts of Arunachal Pradesh, the easternmost state of India. Satellite imageries were used to stratify land use-cover, slope, and aspects, vegetation types, along with ground-truthing of floristic diversity and forest structure. The region comprised >70% of the total geographical area under forest (82% under dense cover) divisible into eight forest types. The timberline takes a zig-zag course between 3600 and 4600 m. A reconnaissance of vegetation and species richness revealed that the tree and shrub richness peaked in lower one-third of the elevation gradient, whereafter declined sharply with the rise in elevation. In timberline area there were only 5 tree and 11 shrub species. The timberline area, however, comprised 152 plant species, which is significant. A comparison of timberline across Himalayan states reveals that the upper timberline limit increases from northwest to northeast. In Arunachal Pradesh timberlines are dominated by *A. densa*, which is associated with several species of *Rhododendron* and *Sorbus* species. In recent times the timberline ecotone has been subjected to increased developmental activists, such as road construction and fulfilling diverse community needs, viz. timber, firewood, medicinal herbs, grazing grounds. Management of grazing areas, which used to be done by traditional village institutions that maintained the quality of pastures, has been gradually losing its effectiveness. The study emphasized the need for more coordinated researches to develop a better understanding of the timberline area in near future.

Key words: Biotic pressure, eastern Himalaya, implications for management, timberline ecotone, tree structure.

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Introduction

World over the timberline areas, which represent the transition from forest to treeless alpine areas by forming a distinct ecological boundary within the altitudinal vegetation zones, are considered extremely sensitive to climate change and anthropogenic pressure (Holtmeier & Broll 2005; Schickhoff 2005). It is assumed that in the event of warming, treeline will advance to higher elevations (Körner & Paulsen 2004; Singh *et al.* 2012). Himalayan treeline zone is known for widespread pastoralism with varied institutional arrangements and practices across the Himalayan Arc (Dutta 2011; Singh *et al.* 2002; Singh & Sundriyal 2005; Sundriyal 1994, 1995). The lacks of research and data have been the main constraint to take up any remedial measure in such areas. While treelines/ timberlines in Europe have numerous long term studies and data, Himalayan treelines however, have remained unattended. It is argued that in comparison to the Himalayan region the

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timberline researches in other areas are in a much advance stages. Within Himalayas the timberline in the western part of the country is more investigated in comparison to the eastern Himalayan region (Dutta *et al.* 2014). There have been several studies on forest structure and composition from western Himalaya (Bisht *et al.* 2014; Gairola *et al.* 2008; Rai *et al.* 2012; Sundriyal & Bisht 1988), central Himalaya (Gaire *et al.* 2010), and Tibet plateau (Qingshan *et al.* 2007, Shaoliang & Ning 2013; Zhang *et al.* 2009, 2010). However, such information is scanty for the eastern Himalayan region (Chettri *et al.* 2002), and almost no reports are available from Arunachal Pradesh, which makes the easternmost limit of Indian Himalayan region. The state is biologically special as it is situated at the confluence of Indo-Malayan, Afro-tropic, and Indo-Chinese biogeographical realms, and has wide vegetation zones, viz. tropical, sub-tropical, temperate, sub-alpine and alpine that vary in vegetation composition and species richness (Baishya *et al.* 2001; Champion & Seth 1968; Deb & Sundriyal 2007; Hajra *et al.* 1996; Kaul & Haridasan 1987; Rau 1975; Rao & Hajra 1986; Rao & Panigrahi 1961; Sahni 1981).

The eastern Himalayan region is more humid hence supports tree growth up to much higher elevation than western region (Dutta *et al.* 2013). Tawang and West Kameng districts harbor a significantly important part of eastern Himalayan timberline. The forests in the region harbor rich vegetation and species diversity (Roy & Bahera 2005; WWF & ICIMOD 2001). The region is currently subjected to expansion of roads and communication services for both civil and defense needs, which are impacting forest structure, composition and ecological balance of the area (Behera *et al.* 2001). In view of the lack of information on broad physiognomic features, land use-land cover, and vegetation composition it is difficult to devise management and conservation strategies for the timberline area (Dutta 2011). To address the issues of environmental problems at timberline areas, it is important to understand interactions between the social systems and ecological processes (Bennett *et al.* 2009; MEA 2005; Milner-Gulland 2012). Here our aim is to give an introductory report on the timberline area of Arunachal Pradesh based on (i) general land use pattern, (ii) basic features of timberline flora and vegetation, and (iii) anthropogenic factors affecting timberlines in the regions. We used remote sensing techniques to analyse spatial features of this India's most remote forest-rich region. Our paper will provide a baseline for detecting future changes due to global climate change and other anthropogenic factors.

Materials and methods

The study area comprises Tawang and West Kameng districts (26°53′22.11 to 27°51′47.15 N and 91°31′57.37 to 92°50′39.39 E) in Arunachal Pradesh. It is surrounded by Tibet (China) in the north and northeast, Bhutan in the west, Assam state in the south, and East Kameng district on the eastern side (Fig. 1). The study was conducted during 2009–2011 and repeated in 2012–13, and followed a standard research protocol for satellite imagery procurement, analysis, ground truthing, vegetation mapping, floristic diversity assessment, laying forest plot at different sites, and data collection and analysis.

Assessing land use-land cover

To carry out land use land cover mapping remote sensing maps and GIS tools were used at Indira Gandhi Conservation and Monitoring Centre (IGCMC), WWF-India, New Delhi. The investigation covered Tawang and West Kameng districts using IRS P6 LISS III & PAN data acquired from NRSA (Table 1). The data transferred into the computer, geometric rectification was carried out in each image to provide latitude and longitude information into raw satellite scene using raster-based geometric corrections, and finally, the geographical area of Tawang and West Kameng districts was extracted. Further, the extent of timberline was delineated between 3900 and 4200 m altitudes using multiple GPS coordinate. This was the central part of timberline elevation, which roughly ranged from 3600 m to 4600 m. Subsequently, the ground truthing was done at the study sites to finalize the land use-cover and vegetation type maps covering both the districts and the timberline zone. To capture diverse features like drainage, road network, settlements, water bodies, and others, the toposheets of 1:200,000 were acquired and scanned, and geo-referencing technique was used to combine the data. Thereafter the target area was clipped from the toposheets for two districts (Tawang and West Kameng) along with timberline zone. Various thematic layers were digitized to delineate administrative boundaries, contour and spot heights, road network map (associated attributes: type of road), drainage and water bodies map, and location of villages and towns. Different vegetation

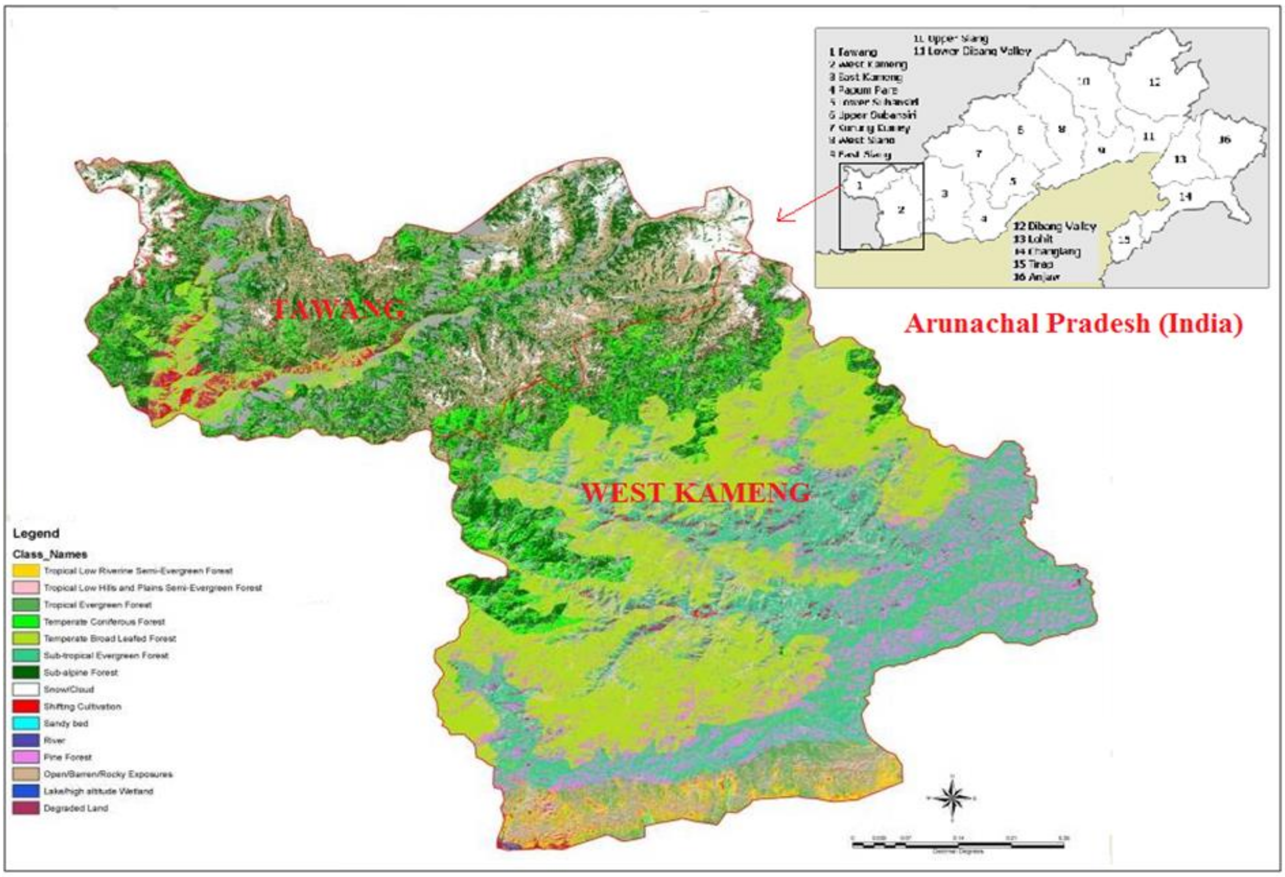

Fig. 1. Land use - land cover map of Tawang and West Kameng districts, Arunachal Pradesh, India

Table 1. Details of the imageries, their spatial resolution and date of procurement.

Sensor	Path-Row	Spatial Reso-lution	Swath	Month & Year
LISS III	110 – 52 111 – 52	23.5 m	141 km	7th Jan 2008 19th Dec 2007
PAN	110 – 52 A 111 – 52 A	5.8 m	70.3 km	14th Dec 2007 19th Dec 2007

layers, non-forest layers and water layers which were classified by above techniques, merged together to get the one classified image. Finally, based on spectral signatures, GPS location, and ground truthing details, information (images) on different land use-land cover classes and vegetation composition were extracted. Thus for two districts, the major outputs were derived, in the form of land use-cover, vegetation type, and distribution of vegetation along slopes and aspects maps. In this the focus was on timberline ecotone. More details regarding satellite imageries, RS-GIS tools and processing of data, and its analysis are available (Dutta 2011).

Assessing floristic diversity

Repeated surveys were made to different parts of Tawang and West Kameng districts, particularly the timberline areas. Based on elevation and dominant vegetation types, the study area was broadly classified into tropical evergreen forests (< 900 m elevation), subtropical-broadleaved forests and sub-tropical pine forests (900–1800 m), temperate broadleaved forests (1800–3000 m), sub-alpine forests and forest limit and alpine vegetation (> 3000 m) (Bahera *et al.* 2001; Kaul & Haridasan 1987; Roy & Bahera 2005). The composition of dominant vegetation types at all elevations was noted. For tropical and subtropical zones only important trees species were enumerated. However, for temperate broadleaved forest and the upper forest limit, a detailed list of species at the top- and mid-canopy levels along with the small trees and shrubs, climbers and epiphytes were recorded. Field notes were prepared on plant distribution range, habit, and time of flowering. The plant specimens were collected and made into herbarium. Each plant was identified to species level with the help of subject experts and existing flora at State Forest Research Institute, Itanagar and Botanical Survey of India, Itanagar.

Sampling for forest structure

Based on the field observations and physiognomic features of forests, three forest stands located at Sela-Nuranag (Stand-1), Pangila (Stand-2), and Sela Pass-Baisakhi (Stand-3) were investigated for detailed information on the tree structure and species composition. For the structural analysis of forest stands a representative plot of 100 × 500 m (5 ha) was earmarked using grid map at each forest stand; the plot was further subdivided into five 100 × 100 m sub-plots. Tree structure was analyzed using 10 × 10 m quadrats, randomly placing six quadrats in each sub-plot. Each stand was sampled with 50 quadrats. To study tree species regeneration and shrub species density, 5 × 5 m quadrats were randomly placed, two quadrats in each 10 × 10 m quadrats that were used for tree sampling. Thus, a total of 100 quadrats were laid and analyzed at each forest stand. Tree individuals having DBH > 10 cm were categorized as adult trees, DBH < 10 cm but height > 30 cm as saplings, and height < 30 cm as seedlings (Sundriyal & Sharma 1996). Data were pooled separately for each forest stand and calculated for measuring frequency, density, total basal area, relative density and dominance of each species.

Local community dependence on resources

Information on timber and firewood, medicinal plant collections, and grazing were collected. For data on timber and firewood collection, three investigated forest stands (Stand 1 to 3) were targeted. All trees cut and lopped at each site were counted and extrapolated for per hectare values. Accordingly, the forest stands were identified as least, moderately, and highly disturbed stands. For collecting data on medicinal plant extraction, information from local villagers involved in this trade was gathered through personal interviews and semi-structured questionnaires. A total of 34 villagers representing 6 villages were interviewed. Besides, records of the Forest Department were gathered in relation to number of permits issued for medicinal plant collection, sites visited, and the name of the permit holders and quantity collected. The plants were categorized as medicinal, aromatic, resin, dye and spices along with their market rates. Based on the information collected, the analysis was done to have an idea of change in the trend in terms of availability of different plants at various sites.

The timberline and alpine areas are visited by nomadic graziers for summer grazing. For the study, a total of 23 herders from 10 villages were interviewed with regard to the changes in livestock population in past ten years, grazing routes, movement, and period of camping at different stations in the pastures. Considering that some pastures were owned by the community, the villagers were enquired about traditional rules and regulations for pasture management and change in such practices, if any. They were also questioned the challenges of pastures and animal management. Finally, after field verification of the information, a map was prepared to understand the movement patterns during grazing.

Data analysis

Statistical analysis of the data and differences in mean values of the studied parameters was done by determining the analysis of variance (ANOVA) using SPSS statistical programme. The graphical representation of data is done using MS Office Excel.

Results

Land use-cover of the region and delineation of timberline area

Tawang and West Kameng districts comprised a total geographical area of 2470 km^2 and 4883 km^2, respectively, divisible into 15 land use-cover classes (Fig. 1, Table 2). Of the total geographical area of two districts, 73% was under forest (with 82% was under dense-category) (Fig. 2). We identified eight forest types: the temperate broad-leaved forest exhibited the highest forest area (32.6%), followed by sub-alpine forest (20.9%), sub-tropical evergreen forest (19.1%), pine forest (9.1%), temperate coniferous forest (6.9%) and tropical semi-evergreen forest (6.3%). A reconnaissance of the timberline area revealed that the minimum and maximum altitudinal limit of timberline was 3600 to 4600 m above sea level (Fig. 3). An analysis of the broad vegetation types within this elevation belt revealed that the largest area was under sub-alpine forest. Within the timberline area the temperate conifer

Table 2. Land use - land cover of Tawang & West Kameng districts, and timberline area in Arunachal Pradesh, Northeast India.

Land use - land cover type	Tawang district		West Kameng district		Timberline zone (3900–4200 m)		Total of two districts	
	Area (sq km)	% of total district area	Area (sq km)	% of total district area	Timber-line area (sq km)	% area within this zone	Area (sq km)	% of total area
A. Broad Vegetation Classes:								
Tropical Evergreen Forest	0.40	0.02	155.47	3.18	0	0	155.87	2.12
Tropical Low Hills and Plains Semi-Evergreen Forest	2.29	0.09	332.63	6.81	0	0	334.92	4.56
Tropical Low Riverine Semi-Evergreen Forest	1.25	0.05	111.65	2.29	0	0	112.91	1.54
Sub-tropical Evergreen Forest	0.02	0	1022.35	20.94	0.21	0.03	1022.37	13.91
Pine Forest	2.34	0.09	486.70	9.97	0	0	489.04	6.65
Temperate Broad Leaved Forest	142.40	5.77	1602.45	32.82	11.90	1.91	1744.84	23.73
Temperate Coniferous Forest	180.16	7.29	193.99	3.97	33.90	5.45	374.14	5.09
Sub-alpine Forest	771.13	31.22	345.68	7.08	194	31.20	1116.81	15.19
Total forest	1099.99	44.53	4250.92	87.06	240.01	38.59	5350.90	72.78
B. Other Categories:								
Agriculture and human settlement	35.10	1.42	12.34	0.25	6.31	1.01	47.43	0.65
Sandy bed	2.66	0.11	9.52	0.20	0.50	0.08	12.18	0.17
River	0.37	0.01	3.38	0.07	0.40	0.06	3.75	0.05
Snow/Cloud	217.37	8.80	39	0.80	28.92	4.65	256.37	3.49
Open/Barren/Rocky Exposures	727.21	29.44	168.73	3.46	170.79	27.47	895.95	12.19
Degraded Land	44.74	1.81	104.62	2.14	6.29	1.01	149.37	2.03
Lake/high altitude Wetland	5.52	0.22	1	0.02	0.42	0.07	6.52	0.09
Hill Shadow	336.85	13.64	293.20	6	168.17	27.05	630.04	8.57
Total Non-forest	1369.82	55.45	631.79	12.94	381.80	61.40	2001.61	27.22

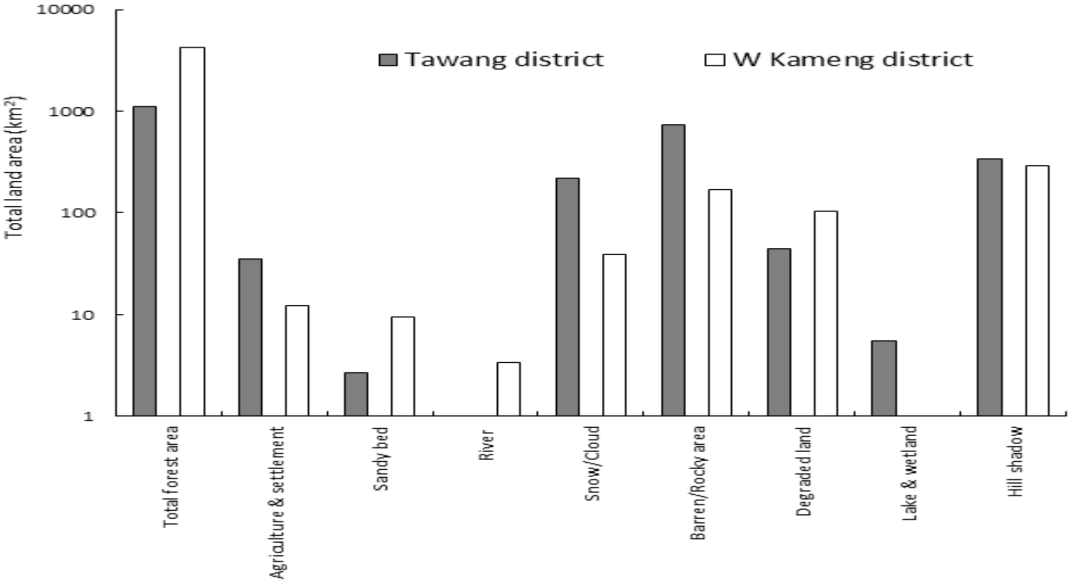

Fig. 2. Land use-cover statistics of Tawang and West Kameng districts, Arunachal Pradesh.

<table>
<tr><td></td><td></td></tr>
<tr><td>Plate 1. Timberline at Thembang</td><td>Plate 2. Scattered Abies near Sela</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Plate 3. Rhododendron above timberline</td><td>Plate 4. Road construction in alpine areas</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Plate 5. Timber & firewood collection at timberline</td><td>Plate 6. Sheep grazing in alpine area</td></tr>
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Plates 1–6: Pictorial view of the timberline at Tawang and West Kameng districts of Arunachal Pradesh

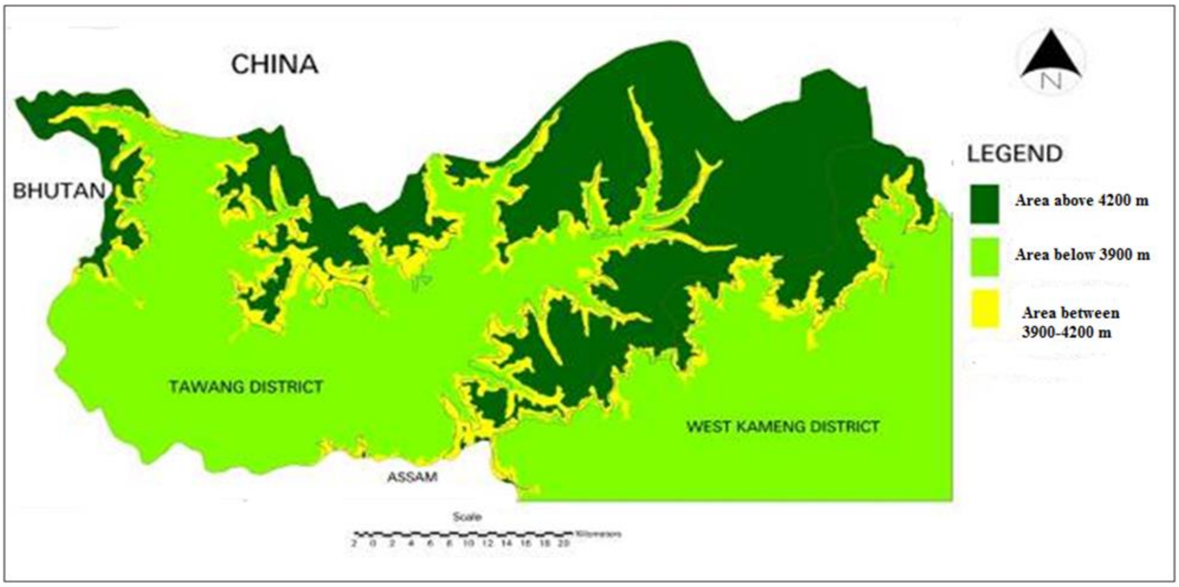

Fig. 3. Distribution of timberline area (between 3900 to 4200 m elevations) in Tawang and West Kameng districts.

forest comprised more area than temperate broadleaved forest (Fig. 4). A pictorial view of timberline and diverse biotic pressure at high altitude areas is provided (Plate 1 to 6).

Elevation pattern of species richness and floristic composition

Tree species number increased somewhat from tropical evergreen forests (< 900 m) to subtropical broadleaved forests (900–1800 m), thereafter declined sharply in temperate broadleaved forests (1800–3000 m) (Fig. 5). The shrub species number peaked in the temperate broadleaved forest. Although a complete inventory of the herbaceous species was not made, an increasing trend in species number was observed with increasing altitude. For climbers, a decreasing trend in species richness with altitude was observed, while epiphytes showed an inconsistent trend.

The important tree species of tropical evergreen forests were *Terminalia myriocarpa* (hollock), *Altingia excelsa* (jutuli), *Ailanthus grandis* (borpat), *Amoora wallichii* (amari), *Canarium strictum* (dhuna), *Duabanga gradiflora* (khokhan), *Mesua ferrea* (nahar), *Morus laevigata* (bola), *Albizia arunachalensis* (siris), *Kydia glabrescence* (pichola), etc. Above this zone, forest was evergreen broadleaved with the dominance of *Quercus lamellosa*, *Quercus pachyphylla*, *Q. griffithii, Q. serrata, Michelia* sp., *Magnolia* sp., etc. There were also patches of *Pinus roxburghii* and *P. wallichiana*. In temperate broad-leaved forest areas *Quercus griffithii* and *Q. lanata* grew in association with *Rhododendron arboreum*, *Magnolia campbellii, Michelia doltsopa,* etc. There was usually dense undergrowth, mostly of bamboo-like *Chimonobambusa callosa*. Patches of deciduous species like *Acer oblongum, A. pectinatum, A. campbellii,* and *Betula alnoides,* along with *Alnus nepalensis,* could be seen along water courses. The mid-story was predominated by small trees and shrubs like *Pyrus polycarpa, Pyrus pashia, Sorbus foliolosa, Prunus cerasoides, Illicium griffithii, Rhododendron falconeri, R. grande, R. edgworthii, Spiraea micrantha, Symplocos racemosus*, *Lyonia ovalifolia, Cotoneaster frigidus, Corylopsis himalayana,* etc. Though the climbers showed low density in these forests, a few climber species recorded from the forests comprised *Clematis buchananiana, C. connata, C. barbellata* and *C. cadmia*. Among the epiphytic elements orchids like *Cymbidium grandiflorum, C. giganteum, Eria coronaria* and *Pleione praecox* were common along with some ferns like *Arthromeris himalayense, Clenopteris subfulcata,* and *Asplenium ensiforme* etc.

Timberline physiognomy and floristic

The Temperate coniferous stands consisted of several conifers and rhododendrons; *Rhododendron falconeri, R. cinnabarinum* and *R. barbatum* at lower limits, and mixed coniferous vegetation of *Abies densa, A. delavayi, Cupressus corneyana, Taxus walli-*

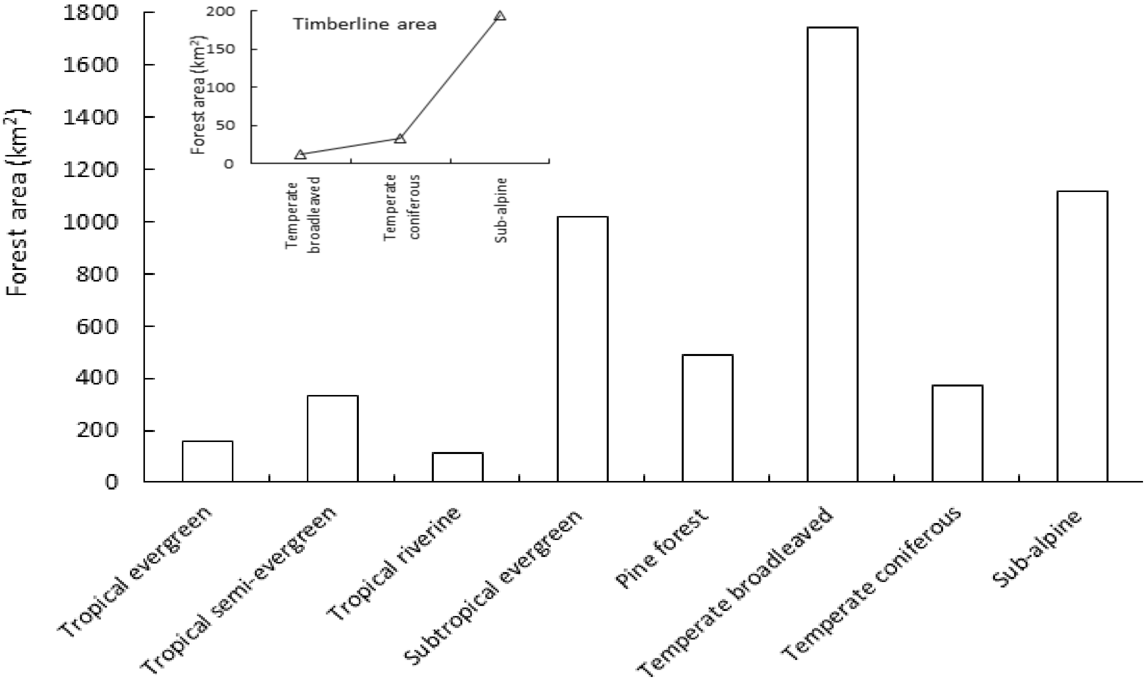

Fig. 4. Broad vegetation types and respective forest land in Tawang and West Kameng districts (bar diagram) and timberline area (subset line graph).

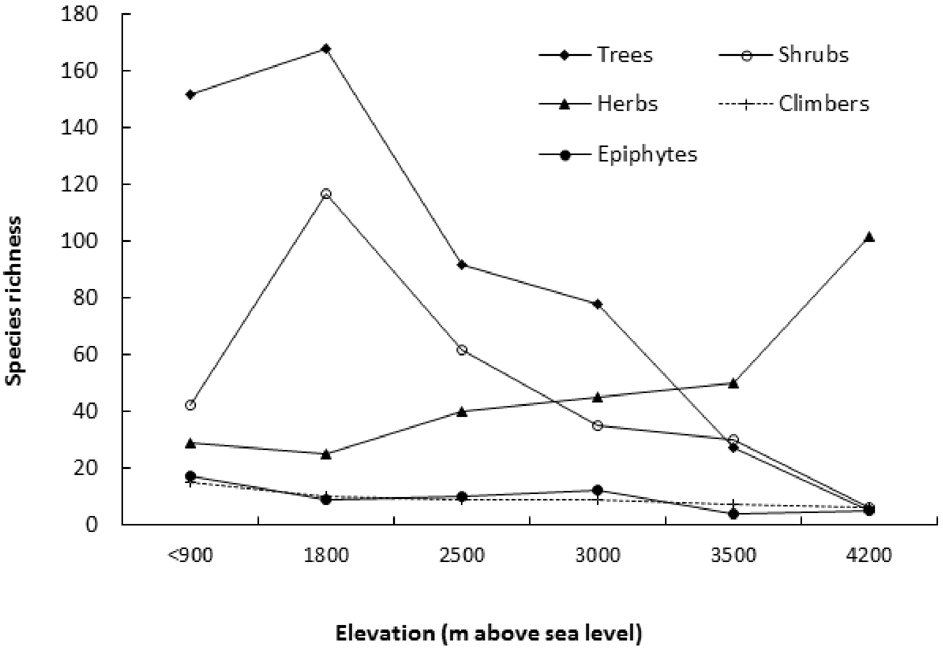

Fig. 5. Species richness and life forms at different elevations at Western Arunachal Pradesh.

chiana var. *baccata*, *Tsuga dumosa*, *Larix griffithiana*, etc. towards upper limits. Besides, patches of *Rhododenron grande* and *R. hodgsonii* were also found within this belt. The shrub layer of such forest type comprised *Berberis* spp., *Mahonia nepalensis, Leycesteria formosa, Rhododendron camelliiflorum, R. dalhousiae, Gaultheria fragrantissima, Satyrium nepalense, Calanthe manii, Bergenia purpurascens, Nellia thyrsiflora, Rosa sericea, Rubus paniculatus* and *R. biflorus*. There were many climber, epiphytes, and herbaceous species.

A detailed survey of Baisakhi-Sela, Pangila and above in West Kameng district and Sela-Nurunang, Bhagajang, Nagula and Lumpo area of Tawang district revealed that the upper timberline elevation limit was 4600 m. The timberline physiognomy varied from place to place. At many places it was abrupt type with alpine meadows above it (Plate 1), while at other places the timberline was fringed by rhododendron bushes and/or patchy and scattered trees (Plate 2). The timberline was made up of *Abies densa* with short tree and/or dwarf bushes of *Rhododendron hogdsonii, R. thomsonii, R. lapidotum, R. bhutanense, R. anthopogon, R. campanulatum x barbaratum, R. cinnabarium* and other rhododendron species (Plate 3). *Abies densa* formed a mono-dominant stands on north slope, however with moderate biotic pressure it occurred with other tree species on south slope. East slope was relatively more disturbed. *Sorbus* species was also found on south and east facing slopes. *R. campanulatum* and *Juniperous indica* were recorded only on south slope (Table 3). Among shrubs *Berberis* sp. was most dominant.

Altogether the timberline area comprised a total of 5 tree species and 11 shrub species (Table 3, 4). The tree density was the highest at moderately-disturbed site (Stand 2), followed by least-disturbed site (Stand 1) and minimum at highly-disturbed site (Stand 3). Among the tree species, *Abies densa* was present in all the stands, and *Sorbus microphylla* in two stands. Among the shrub species, only *Berberis* sp. was recorded from all the stands (Table 3). A conspicuous feature of the timberline was the dominance of *Abies densa* under all levels of biotic pressure (Table 3). The biotic pressure at north, south, and east was recorded least, moderate and high and *Abies* recorded a height of 5.00 ± 0.12 m, 16.04 ± 0.27 m, and 5.06 ± 0.32 m at north, south and east slopes, respectively, which exhibits that south slopes support better growth condition may be due to higher solar radiation. The density of saplings and seedlings of all the tree species also differed in the three timberline forest stands. *R. lapidotum, R. barbaratum* and *Rhododendron thomsonii* were other important shrub species at timberline. And among all, the highest relative density was of *Berberis* sp. at timberline (Table 4).

The vegetation above 4000 m composed of herbaceous and deep-rooted cushioned plants, such as *Aconitum fletcherianum, Meconopsis paniculata, Potentilla peduncularis, Rhodiola himalensis, R. wallichiana, R. quadrifida, Sedum multicaule, Saxifraga hispidula, Epilobium tetragonum, Geranium lamberti, Primula denticulata, P. elongata, Swertia hookeri, Polygonum macrophyllum, P. vaccinifolium, Bistorta affinis, Rumex nepalensis*, etc. Some common grass and sedge species of the alpine meadows were *Kyllinga odorata, Chrysopogon aciculatus, Carex haematostoma* and *Agrostis zenkeri*. The timberline flora comprised a total of 152 plant species, 52 of them were recorded within timberline and below (about 100 m below), 28 species along timberline and above (about 100 m above), and 76 species distributed both below and above timberline zone (Fig. 6). The dominant shrub at timberline and below was *Berberis* (5 species), although it was totally absent above timberline. Genus *Senecio* (with 3 species) was recorded growing along timberline and below. *Saxifraga* (3 spp.) was a dominant genus at timberline and above. Other prominent genus recorded growing both below and above timberline zone were *Primula, Rhododendron, Potentila*, and *Cyananthus*. The study also reveals that some species have high conservation significance, viz. *Rhododendron nevium, R. sikkimense, Aconitum ferox, Nardostachys grandiflora, Picrorhiza kurrooa, Nardostachys grandiflora, Saussurea yakla, Saussurea globossa* and *Primula poluninii* because of their endemic and restricted distribution as well as due to their high demand mainly for medicinal purpose.

Socio-economic dependence on and around timberline area

i) Collection of timber and firewood

In the three timberline stands, the number of trees cut and lopped (branches) was 23, 54, and 121 per ha in stand 1, 2, and 3, respectively, which exhibited high pressure on forests. The area has been subjected to road construction for civil and defense need that also led to huge quantity of timber and firewood collection (Plate 4 and 5).

ii) Collection of medicinal plants

Local dwellers visit as many as 37 sites for collection of medicinal plants in a season. In total 16 plant species were collected for commercial use, of which kutki (*Picrorhiza kurrooa),* nying (*Aconitum ferox*), and yartsa-gambu (*Cordyceps sinensis*) were collected at and above timberline and lishi *(Illicium griffithii),* chirata *(Swertia chirata*), langyeru (Indian Madder) *(Rubia cordifolia*), taxus (Himalayan Yew) *(Taxus baccata*), boch *(Acorus calamus*), pangpos (*Valeriana jatamansi*), dalchini *(Cinnamomum verum*), ginseng *(Panax pseudo*

Table 3. General characterisitics of three study sites at timberline zone of western Arunachal Pradesh.

Name of the species	Stand 1	Stand 2	Stand 3
Location	Sela - Nurunang	Pangila	Sela Pass - Baisakhi
Elevation range	4000 m to 4100 m	3900 m to 4100 m	3900 m to 4100 m
Aspect	North facing	South facing	East facing
Slope	25° to 30°	15° to 60°	35° to 55°
Distance from settlement area	25 km*	4 days trek	12 km
Biotic pressure	Low	Medium	High
Forest Type	Temperate Conifer	Temperate Conifer	Temperate Conifer
Tree Species richness	1	5	2
Shrub Species richness	6	7	5
Tree Density (ha^{-1})	627.27	671.29	205.26
Basal area ($m^2\ ha^{-1}$)	13.60	42.36	4.86
Sapling density (individuals ha^{-1})	160.00	1803.14	115.79
Seedling density (individuals ha^{-1})	333.30	19142.86	94.74
Shrub density (individuals ha^{-1})	1933.33	2074.29	2515.79

Table 4. Relative density (%) of tree and shrub species at different forest stands at timberline zone of western Arunachal Pradesh.

	Species	Stand-1	Stand-2	Stand-3
Trees	*Abies densa*	100	54.46	76.92
	Rhododendron hogdsonii		18.30	
	Rhododendron sp. 3		14.05	
	Sorbus microphylla		5.53	23.08
	Sorbus sp.		7.66	
Shrubs	*Berberis* sp.	30.72	8.26	79.5
	Rhododendron thomsonii		66.12	4.6
	Rhododendron lapidotum	22.88		10.04
	Rhododendron bhutanense	12.23		3.35
	Rhododendron anthopogon	7.52		
	Rhododendron campanulatum x barbaratum	17.55	8.82	
	Rhododendron cinnabarium		5.79	
	Rhododendron campanulatum		0.83	
	Rhododendron sp. 2		3.31	2.51
	Juniperous indica		6.89	
	Unidentified 1	9.09		

ginseng), s-panja *(Gymnadaenia orchidis*), lham *(Pinus wallichiana),* and kaifal, poonpo, pilla-zari (unidentified) were gathered from temperate forests. All the species were collected in large quantities.

A discussion with community revealed that in recent years there had been a net decline (by about 37%) in the availability of medicinal plants. Therefore, the collectors were moving to new sites which occur in more remote areas than before. Although the prices of most of the medicinal plants have increased over the years, the people prefer to collect them from remote sites because they fetch high prices. There was a set procedure for collection and selling medicinal plants from the region, which has been in place for many decades.

iii) Grazing pressure

Brokpa, the nomadic pastoral community of the Monpa tribe, is known to rear sheep, yak (pure

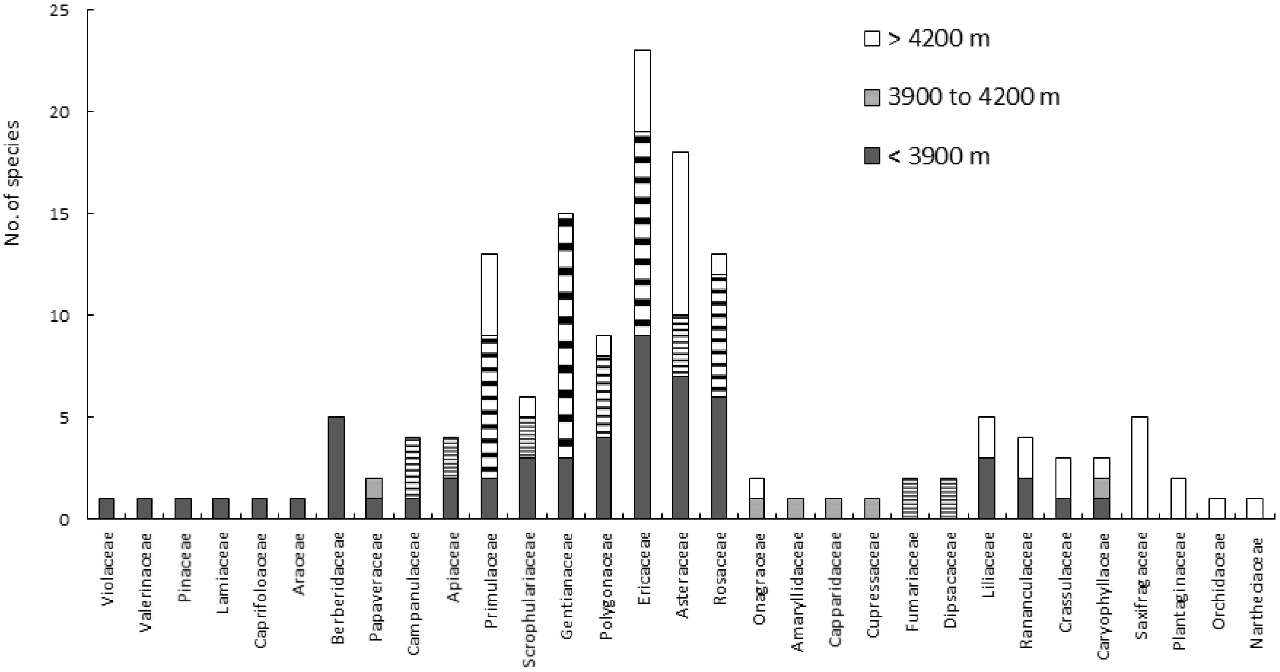

Fig. 6. Plant families recorded at timberline area at the eastern Himalaya, Arunachal Pradesh.

male), bree (pure female), dzo (male crossbred), dzomo (female crossbred), galang (male crossbred) and kot (female crossbred), and for that they visit alpine meadows (4000 to 4500 m) during May to October (Plate 6). Because of a preference for selected pasture, local graziers follow certain routes. Interestingly some villagers (e.g. Thembang village of West Kameng district) hold traditional rights on alpine pastures and they impose a tax on the herders for grazing in areas under their jurisdiction. Meat, milk, butter, cheese, and wool were most common animal-products which were either self consumed or sold in market to earn cash. For stay at high altitude areas graziers build temporary sheds using considerable quantity of timber. Besides, a significant quantity of firewood is also used by them. Some graziers also collect wild plants for food and medicinal purposes. During winter months all domestic animals move to lower elevations between 2000–2500 m.

Comparative account of timberline in the Himalayan region

A comparative analysis of timberline across Himalayan states reveals that upper timberline elevation increased from northwest to northeast and attained maximum in Arunachal Pradesh as recorded in this study (Table 5). The general floristic and physiognomic pattern of upper timberline in the western Himalayan region comprised birch (*Betula utilis*) and several conifers (*Abies pindrow*, *Pinus wallichiana*, *Picea smithiana*). *Rhododendron campanulatum* and *Juniperus* spp. occurring both inside and outside timberline forests. The krummholz formation is common, particularly in areas with heavy snowfall. In the eastern part of Nepal and towards Sikkim the dominance of birch drops sharply. Many rhododendron species express their predominance at upper timberline from Sikkim to Arunachal Pradesh (Table 5). In this study, the uppermost timberline is dominated by *Abies densa* either as single conifer species or interspersed with *Rhododendron* spp. and *Sorbus* sp. Some other species, viz. *Picea* spp., *Larix griffithiana* are also reported from other timberline areas but relatively at lower elevations.

Discussion

Timberlines in Tawang and West Kameng districts of Arunachal Pradesh, the easternmost Himalayan state of India occurred between 3600 and 4600 m above sea level. It consisted of the eastern Himalayan fir, *Abies densa,* with *Rhododendron hodgsonii* and *Sorbus* spp. as its associates. The shrub in timberline forests mostly comprised *Berberis* sp. (dominated in two stands)

Table 5. Timberline location, physiognomy and floristic pattern in the Himalayan region.

Region	Locations	Lat./ Long.	Timberline elevation	Species	Authors
Jammu–Kashmir	Wardwan, Chenab valley, Bhadarwah Hills	32°–33°48–55'N/ 75°40'–50'E	3500–3600 m	*Betula utilis, Abies pindrow, Pinus wallichiana, Salix* sp., *Juniperus* spp., *Rhododendron campanulatum*	Kaul & Sarin 1974; Gupta & Kachroo 1983; Singh & Kachroo 1983
Himachal Pradesh	Chamba, Sutlej valley, Ladhakh	32°–34°23–58'N/ 77°02'–40'E	3500–4200 m	*Quercus semecarpifolia, Pinus wallichiana, Betula utilis, Sorbus aucuparia, Salix* spp., *Rhododendron campanulatum, Juniperus excelsa*	Rau 1974; Seybold & Kull 1985; Gupta 1994
Uttarakhand	Nanda Devi, Pindari, Sarju Valley, Tungnath, Valley of Flowers, Gangotri, Tons & Bhagirathi valley	30°–31°07–55'–N/ 78°–79°4'–50'E	3300–4100 m	*Betula utilis, B. alnoides, Abies pindrow, Quercus semecarpifolia, Juniperus recurva, Sorbus* sp., *Rhododendron arboreum, R. barbatum, R. campanulatum*	Gupta 1983; Sundriyal & Bisht 1988; Singh & Singh 1992; Rawal & Pangtey 1994; Garkoti & Singh 1994; Rawal & Dhar 1997; Maikhuri *et al.* 1998; Kala *et al.* 2002; Schickhoff 2005; Gairola *et al.* 2008; Rai *et al.* 2012; Bisht *et al.* 2014
Nepal	Buri Gandaki, Barbung Khola, Ghasa, Helambu, Langtang, Marpha, Chulungche	27°–28°36–56'N/ 83°–86°49' E	3600–4400 m	*Betula utilis, Abies spectabilis, Rhododendron campanulatum, R. barbatum, Juniperus* sp., *Pinus wallichiana, Larix griffithiana, Sorbus microphylla*	Metz 1998; Miehe *et al.* 2000; Schickhoff 2005; Gaire *et al.* 2010
Sikkim	Singalila National Park, Jelep La, Zemu valley, Kangchendzonga Biosphere Reserve	26°–27°27–47'N/ 87°–88°21–59'E	3600–4200 m	*Abies densa, Betula utilis, Quercus lineata, Betula* sp., *Rhododendron arboreum, R. campanulatum, R. hodgsonii, R. falconeri, R. grande, Arundinaria aristata, Juniperus* sp.	Pradhan *et al.* 2001; Chettri *et al.* 2002; Singh *et al.* 2003

Contd…

Table 5. Continued.

Region	Locations	Lat./ Long.	Timberline elevation	*Species*	Authors
Bhutan	Black Mountains, Sankosh Valley, Tremo La, Bumthang V.; Pologong Chu, Narimthang	27°17–55’N/ 89°–91°13’-42’E	3700–4100 m	*Abies densa, Juniperus* sp., *Rhododendron hodgsonii, R. campylocarpum, R. campanulatum, R.lanatum, Picea* sp., *Arundinaria* sp.	Schickhoff 2005
Arunachal Pradesh	Sela, Nurunang, Pangila, Baisakhi, Lohit valley, Walong, Mishmi Hills, Lepa	26°–29°03–53´N/ 91°–97°05–3´E	3600–4600 m	*Abies densa, Sorbus* spp., *Rhododendron* spp., *Juniperus* spp., *Larix griffithiana*	Rao & Panigrahi 1961, Present study

and *Rhododendron thomsonii* (dominated in one stand). Apart from these, many *Rhododendron* species *(R. lapidotum, R. bhutanense, R. anthopogon, R. campanulatum x barbaratum, R. cinnabarium, R. campanulatum)* and *Juniperous indica* occurred in the timberline ecotone. Overall, the timberline ecotone was species rich (152 species in total occurred). From timberlines of other parts of the Arunachal Pradesh state other than *Abies* sp., *Picea* sp., *Larix griffithiana* are also reported, but generally below upper timberline (Rao & Panigrahi 1961). Considering that the vegetation of the area has been least investigated (Dutta *et al.* 2014; Schickhoff *et al.* 2015), we made an effort to delineate major land use-cover categories. Eight forest types that included almost all forest types of northeast Himalaya (FSI 2015) occurred in the state. Tree species richness was high up to 1800 m, then declined sharply with increasing elevation, while shrubs increased in number from < 900 m to 1800 m, whereafter it declined with elevation. In contrast, herb species richness increased with elevation, the rise being particularly sharp from 3500 m to 4200 m, possibly because forest trees become sparser. Species richness peak in the lower one-third of elevation gradient, as found for trees and shrubs in our study, is a common feature of the relationship between species richness and elevation (Trigas *et al.* 2013). A taxonomic exploration of West Kameng district has shown the presence of 1428 plant species belonging to 690 genera and 163 families (Paul *et al.* 2010; Sarmah 2005). Species, in general have affinities with Indo-Malayan, Afrotropic, and Indo-Chinese region (Hajra *et al.* 1996, Paul *et al.* 2010). The altitudinal variation in species can also be attributed to different environmental (climatic) variables, spatial features (area, size, and geometric constraints), evolutionary history, and biotic processes at different altitudes (McCain & Grytnes 2010; Roy & Behra 2005).

The timberline ecotones of the present study has 5 tree species, which is higher than that of the western Himalayan region (Gairola *et al.* 2015; Kharkwal *et al.* 2005), and similar to the tree species richness of timberlines in Nepal and Tibet (Gaire *et al.* 2010; Zhang *et al.* 2009). Interestingly, *Rhododendron campanulatum*, which is a common timberline species in the western and central Himalayan regions, was inconspicuous in Arunachal Pradesh. Birch (*Betula utilis*), the flagship timberline species in much of the Himalayas was absent here; possibly, conditions are too moist for birch to compete with evergreen tree species. An analysis of birch distribution in Arunachal reveals that it is found 200–300 m lower than that of the fir. However, more investigations are required to ascertain the relative position of birch in Arunachal. In western Himalaya, birch (*B. utilis*) exceeds the upper limit of all other tree species.

The upper timberlines in western Himalayan region generally have birch (*B. utilis*) and conifers (like *Abies pindrow*, *Pinus wallichiana*, *Picea smithiana*). There *Rhododendron campanulatum* and *Juniperous* spp. are also common. *Quercus semecarpifolia* an evergreen oak forms abrupt type of timberline, particularly in Himachal Pradesh and Uttarakhand (Bisht *et al.* 2014; Gairola *et al.* 2008; Rai *et al.* 2012; Rau 1974; Rawal & Pangtey 1994; Seybold & Kull 1985; Sundriyal & Bisht 1988). In Nepal timberline forest comprised *Abies* *spectabilis* with birch and rhododendron species (Gaire *et al.* 2010; Metz 1998; Miehe & Miehe 2000). Timberlines in Sikkim and Bhutan also have a dominance of conifers and rhododendrons (Chettri *et al.* 2002; Schickhoff 2005). Interestingly, *Quercus* and *Betula* species that form an important part of Western and Central Himalayan timberlines were absent at upper timberline in Arunachal Pradesh. This exhibits a gradual shift in floristic composition from deciduous birch in northwest to evergreen fir and rhododendron in northeast. From eastern Nepal to Sikkim, birch drops in importance while conifers and rhododendrons increase. Many rhododendron species express their predominance in upper timberline from Sikkim to Arunachal Pradesh. Perhaps decreasing winter cold and increasing humidity in the northeast favour rhododendrons (Schickhoff *et al.* 2015). In Tibet timberlines are dominated by *Abies forestii* var. *georgei, Abies georgei* var. *smithii, Juniperus saltuaria, Lonicera* spp., *Rhododendron* spp., *Sabina saltuaria,* and *Spiraea* sp. (Qingshan *et al.* 2007; Shaoliang & Ning 2013; Zhang *et al.* 2009, 2010). In this study the timberline forest comprised *Abies densa, Rhododendron hodgsonii* and *Sorbus microphylla* and in comparison to other areas krummholz formation was least evident.

The upper limit of timberline elevation increases from western to eastern Himalayan region and reaches upto 4600 m in Arunachal Pradesh, as recorded in this investigation. The upper timberline in Arunachal is higher than those reported for many western and central Himalayan sites, though generally timberlines are higher in drier climates (Körner 2012). Because of the use of remote sensing method, this study captured a larger view of timberline distribution. Manual sampling is limited to a few spots of timberline, so fails to assess its entire elevation range. In moist sites snow may stay longer, and thus, suppress tree growth. However, in Arunachal Pradesh early arrival of rains (May-end) would result in early snow melt. Arunachal is close to Tibetan Plateau where occurs the most elevated timberline of the Northern Hemisphere (at 4700 m elevation, Shi & Wu 2013).

Changing anthropogenic activities

Biotic pressure has high impacts on the Himalayan timberline. In Arunachal Pradesh, the timberline areas along with the alpine regions are under intense anthropogenic pressures, leading to a widespread degradation. A large number of migratory graziers visit the area during summer months, practice seasonal agriculture, and build temporary shelters. They also harvest NTFPs, particularly medicinal plants. Herder take sheep and yaks to graze pastures between 4000 and 4500 m. Notably, at many places pastures were under local jurisdiction and community control. In recent years, however, the number of households involved in pastoral activities has declined in view of changed perception and more education which is leading to adopt new livelihood opportunities and living style. Change in the socioeconomic condition of local communities is also responsible for such a shift. This is also true for many other regions including Arunachal Pradesh and Nepal where traditional societies are registering a decrease in the number of families involved in grazing due to change in lifestyle (Farooquee & Rao 2001; Pandey & Chetri 2005). The traditional pasture management system has been useful in avoiding overgrazing; however, no effort was made to conserve such practices. Tibet and Bhutan have made some efforts in this direction and that has contributed to sustainable grazing (Derville & Bonnemarie 2010). To obtain higher economic benefits herders also collect high-value medicinal plants (such as aconitum, kutki, and cordyceps), despite a ban imposed on their collection (Singh & Sundriyal 2005). The medicinal plant collection has increased in recent years and newer sites are being visited for this purpose. In view of the rapid change of values, the management of natural resources is weakening, thus threatening timberline areas. However, moderate grazing contributes to maintaining several species and to species diversity.

Implications for management and conclusion

The present study highlights that integration of RS-GIS can contribute to better understanding of vegetation cover and floristic diversity of the region, which could be utilized in management planning for the region. In recent times the timberline zone has been under increased developmental activists, such as road construction and infrastructure development, which have led to significant increase in extraction of timber, firewood, and medicinal herbs. Besides, the traditional management of high altitude pastures, which used to be done by traditional village institutions, was gradually declining in view of the change of socio-economic fabric of communities. Such an increase in biotic pressure poses a considerable threat to species diversity and landscape. It may affect land cover, species composition, and structure in near future. Climate change may also add to such changes, however, it needs further authentication. There is a need to promote conservation education among graziers and medicinal plant collectors, and adoption of alternate means of energy at such high altitude areas as it may lead to improving the species status at highly degraded stands. Besides, promoting new economic opportunities, such as ecotourism, can bring better livelihood option to local communities for which their capacity needs to be built. Developing community skills on sustainable harvest of medicinal plants and making them aware of the ill effects of overgrazing along with the involvement of government and village level institutions in management activities would greatly help to improvise situation of timberline area. There is also a need to take up more coordinated researches for developing a better understanding of the timberline area and its management, which can contribute to the sustainable conservation of the region.

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Changes in vegetation attributes along an elevation gradient towards timberline in Khangchendzonga National Park, Sikkim

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Abstract: In this preliminary elevation gradient (3000–4000 m) study of high ranges forest of Sikkim (eastern Himalayas), we have analyzed the (i) species composition, (ii) tree species richness, density, basal area and distribution range, and (iii) forest structure by diameter at breast height (DBH) classes. The main purpose was to identify the role of elevation in tree dominance, and species richness in the subalpine forests of eastern Himalaya. The study was conducted in the Yuksam-Dzongri transect nested within the Khangchendzonga National Park, west district of Sikkim state. The quadrat method was used to sample vegetation and sampling was done at every 100 m steps between 3000 m and 4000 m elevations, eventually ending up in the timberline ecotone. A total of 109 species belonging to 80 genera and 46 families were recorded. The species richness and total tree basal area (TBA) declined monotonically along the elevation gradient. Tree density in present elevation transect was significantly higher than its western Himalayan counter parts of Indian Himalayan region. The presence of 23 tree species in the highest 1000 m forested zone highlights the high tree species richness of the eastern Himalaya. It was largely because of the speciation of *Rhododendron* spp. Further investigation is required to develop a holistic understating of these vegetation patterns across the Indian Himalayan region.

Key words: Distribution range, eastern Himalaya, elevation gradient, forest structure, subalpine forest.

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Introduction

Worldwide, the effects of global climate change on ecosystems have been of increasing concern (Christensen *et al.* 2007), and studies have indicated ecological fingerprints of recent global warming across a wide range of habitats (Root *et al.* 2003; Walther *et al.* 2002) and vegetation (Pauli *et al.* 2012). In a warming world, species are expected to shift their distributions pole-ward in latitude and upward in elevation (Walther *et al.* 2002). At global scale, studies are witnessed on elevational expansion of the forest line in many mountain ranges, including the Polar Urals, Russia (Devi *et al.* 2008), the central Swiss Alps, Switzerland (Vittoz *et al.* 2008), western Himalaya, India (Panigrahy *et al.* 2010), Rocky Mountains, Southern Alberta (Cullen & Marshall 2011), and the central Himalaya, Nepal (Gaire *et al.* 2014). This upward forest expansion is expected to shrink the extent of the alpine ecosystems and, possibly cause species loss and ecosystem degradation through greater fragmentation (Forrest *et al.* 2012; Macias-Fauria & Johnson 2013; Peel *et al.* 2007; Randin *et al.* 2009). To understand the impacts of climate change on patterns of vegetation distribution and conser-

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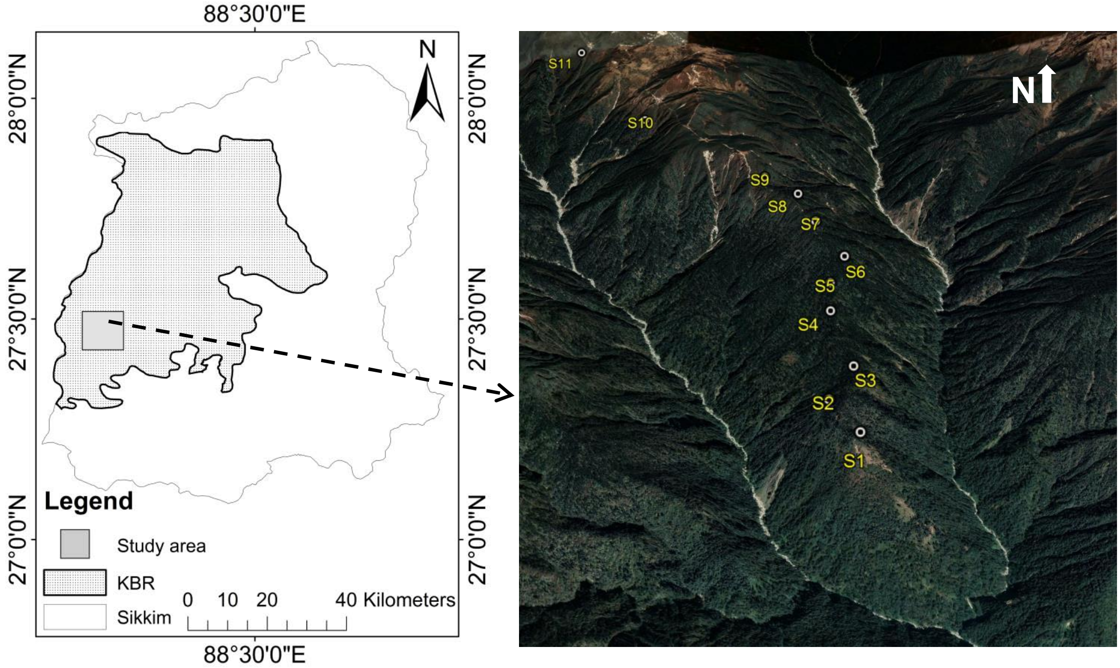

Fig. 1. Study area map of subalpine forest in Khangchendzonga National Park, West Sikkim. S denotes sites at different elevation gradients. (The Inset Map source: Google Earth)

vation of biological diversity, knowledge of the biogeographical variation in species richness is critical (Vetaas & Grytnes 2002). In mountain ecosystems, species richness varies along the elevation gradients which can be used to study the trends of vegetation responses under the changing climate scenario.

The elevation gradient in Himalayas is one of the longest bioclimatic elevation gradients in the world and sustains rich biological diversity, within only a stretch of 150 km one can move from a tropical zone to a zone of permanent frost. These climatic, topographic, geological, and altitudinal variations have created unique landscapes, eco-systems, and biota in the Himalayas. The eastern Himalaya (EH), stretching from eastern Nepal to Yunnan in China, between 82.70°E and 100.31°E longitude and 21.95°N and 29.45°N latitude, covers an area 524,190 km^2. States of north-eastern region of India fall under this region and shares (52.03%) of the total EH region (Tse-ring *et al.* 2010). Sikkim Himalaya, due to its complex topography and highly diverse biological system (Acharya *et al.* 2011) offers an excellent opportunity to address the questions dealing with vegetation community and species response to the climate change.

Of the 825 ecoregions in the world (Olson & Dinerstein 2002), 13 are present across the Himalayan arc (Shrestha *et al.* 2012), and 5 are represented in the Sikkim. Among them, the Eastern Himalayan sub-alpine forests represent the transition (ecotone) from the forested ecoregions to treeless alpine meadows and boulder-strewn alpine screes (Olson *et al.* 2001). Besides functioning as a potential indicator for trends of climatic change, this ecotone is valued as a unique habitat for representative, specialized and sensitive biodiversity elements including distinct biological assemblages, native and endemic floral and faunal species, and economically important species (Dhar 2000; Rawal & Dhar 1997). A few elevation gradient studies with focus on plant diversity patterns along elevational gradients have been made in the Central Himalaya (Bhattarai & Vetaas 2006; Bhattarai *et al.* 2004; Carpenter 2005; Grau *et al.* 2007; Vetaas & Grytnes 2002), in the Western Himalaya (Gairola *et al.* 2015; Oommen & Shanker 2005; Sharma *et al.* 2009; Sharma *et al.* 2010) in the Eastern Himalaya (Acharya *et al.* 2011; Behera & Kushwaha 2007).

The present study is aimed to understand and analyse the patterns of vegetation structure, species composition, and distribution along an elevation gradient leading to timberline ecotone in eastern Himalayan sub-alpine forests. It gives a preliminary account of changes in species diversity and species population dynamics in response to changing climate along a 1000 m elevation range between 3000–4000 m.

Materials and methods

Study area

The study was conducted in the Khangchendzonga National Park (KNP) in the Sikkim state of India (Fig. 1). The KNP landscape [area: 1784 km^2; location: between 27°03'41" and 28°7'34" N latitude and, 88°03'40" and 88°57'19" E longitude; elevation: 100 m asl (foothill) to 8548 m asl (Mount Khangchendzonga peak)] is famous for its rich biodiversity, extreme topographic variations, and alpine and sub-alpine ecosystems. The Sikkim is a well-recognized biodiversity hotspot area, and KNP is recently inscribed as the first mixed world heritage sites of India by UNESCO (http://whc.unesco.org/en/newproperties).

The present study area largely comprises sub-alpine forests of mountainous landscape of the Mount Khangchendzonga (India), ranging from 3,000 m above sea level to the elevation limit of the forest (timberline) in Yuksam-Dzongri transect, nested in KNP. This area falls under moist pre-monsoon and dry winter precipitation regime and receives 1021.0 ± 157.01 mm annual precipitation. The study area experiences mean annual temperature 5.68 ± 1.79 °C with maximum temperature of warmest month 15.93 ± 1.64 °C and, minimum temperature of coldest month −8.36 ± 3.47 °C. The climate data of the study area was procured from WorldClim dataset (Hijmans *et al.* 2005; http://www.worldclim.org/bioclim.htm). To understand the patterns of the vegetation and community structure, vegetation of the identified transect was surveyed in each 100 m elevation band up to the timberline (Fig. 1).

Vegetation sampling and data analysis

Three 0.1 ha plots (dimensions: 50 m × 20 m) were sampled in each 100 m elevational difference across the subalpine forests (3000–4000 m) of KNP landscape. In each 0.1 ha plot, five 10 m × 10 m quadrats were laid randomly for enumerating trees and saplings, and in each 10 m × 10 m quadrat one 5 m × 5 m sub-quadrat was laid randomly for enumerating shrubs/seedlings of tree species, and four 1 m × 1 m random quadrats to sample herbs. The sample plots were established and surveyed during May-June and September-October to avoid snow and heavy rain period. All individuals present within the quadrats were enumerated. Woody stems were measured for size and the circumference at breast height (CBH, *i.e.* 1.37 m above the tree base) for the determination of tree basal area, and in case of small-saplings and seedlings, it was taken at collar height and finally calculated as $(C)^2/4\pi$ (where C = mean circumference of a tree and π = 3.14). Thus, the total basal area (TBA) of each tree was calculated as the mean basal area of a tree × density. TBA values of the three plots of each elevational site were averaged to obtain the final TBA value for each site. Woody stems having ≥ 30 cm CBH were considered trees; individuals with 10 to 30 cm CBH as saplings; and those with CBH less than 10cm were considered as seedlings. The survey data were quantitatively analyzed to obtain the values of density, frequency, and total basal area (TBA) following Misra (1968) and Mueller-Dombois & Ellenberg (1974). Importance value index (IVI) was the sum of relative frequency, relative density and relative dominance (Phillips 1959) of a species. Density and TBA values were converted to per hectare (ha^{-1}) basis for extrapolation of the results. Total basal area (m^2 ha^{-1}) was used to determine the relative dominance of a tree species. Shannon diversity (H'), Simpson's index of Dominance (C), Margalef's Index of Species richness (S) and Shannon Index of species evenness (*E*) were computed following Magurran (1988). Species richness was determined as the total number of species in sampled area for different life forms. Analysis of variance (ANOVA) was used to compare the differences in means of important value index (IVI) of woody stems between different elevations and the significant differences were tested using the Duncan's multiple range test (DMRT; $P < 0.05$). Linear regression analysis was used to understand the linear/quadratic relationship between tree diversity and tree richness with elevational gradients.

Results

Elevation pattern of species composition

A total of 6,488 individuals were recorded in tree layer of which 2,483 were adult trees, 2,633 saplings, and 1,372 seedlings belonging to 10 families, 11 genera, and 23 species from the subalpine forest of KNP. Ericaceae was represented by 10 tree species i.e., *Lyonia villosa, Rhododendron arboreum, R. barbatum, R. decipiens, R. falconeri, R. fulgens, R. hodgsonii, R. lanatum, R. thomsonii* and *R. wightii*. The stand tree density (mean ± SE; 1,504 ± 209 individuals ha^{-1}) varied significantly ($P < 0.05$) along the elevation gradient,

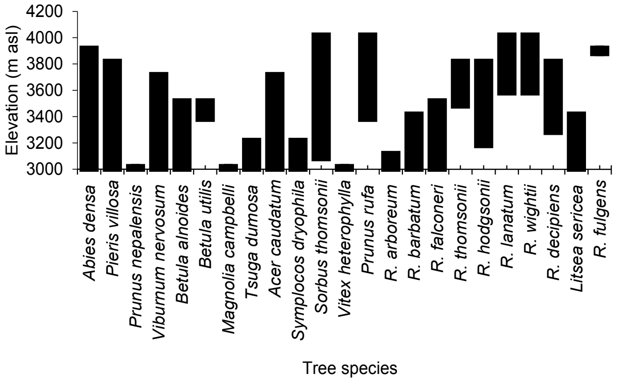

Fig. 2. Elevational range of tree species across the subalpine forest of Khangchendzonga National Park, Sikkim. *(R. = Rhododendron)*

with significantly higher stand density (2,593 individuals ha^{-1}; $P < 0.05$) in *Abies* dominated forest at the 3300 m and minimum stand density (307 individuals ha^{-1}; $P < 0.05$) at timberline (3989 m). The sapling density peaked (3,460 individuals ha^{-1}; $P < 0.05$) in *Tsuga* mixed forest, at the lower elevational end (3000 m) and seedling density peaked (6,293 individuals ha^{-1}; $P < 0.05$) in *R. hodgsonii* forest at the middle elevation 3600 m (Table 1). Among the tree species, the maximum density was observed for *R. hodgsonii* and minimum for *Lyonia villosa* (Table S1). Most of the tree species had shown the restricted distribution range and none of the species occurred all along the gradient (Fig. 2). The widest amplitude was observed for *A. densa* (3000–3900 m) and *Sorbus microphylla* (3100–3989 m). A few species, such as *Prunus bracteopadus* and *Magnolia campbellii* were confined to the lower end of the elevational transect, as these are species of temperate belt. In contrast *Rhododendron fulgens* was confined to the upper end of the forest range. Among the tall tree species, *A. densa* goes up, the highest formed forest patches above the timberline (Fig. 2). Small tree species like *Sorbus microphylla, Prunus rufa, R. lanatum*, *R. wightii*, were observed growing as under canopy of *A. densa* up to 3900 m, where after they formed small forest patches without the presence of *A. densa* up to 4000 m. Above 4000 m these species occurred as solitary individuals. Unlike to western Himalaya, where *Betula utilis* is the principal treeline species, in Sikkim *A. densa* along with the associated species mainly *R. wightii*, *R. lanatum* are the principal treeline species.

The TBA values (mean ± SE; 19.02 ± 4.57 m^2 ha^{-1}) differed significantly ($P < 0.05$) along the elevation gradient ranging from 0.93 ± 0.53 m^2 ha^{-1} at highest elevation site to 52.52 ± 14.53 m^2 ha^{-1} at low elevation (3200 m). Based on the important value index (IVI) of tree species separated by the Duncan's multiple range test (DMRT), the sampled area can be subdivided in to six different forest communities (AF: *Abies* dominated forest; RhF: *R. hodgsonii* forest; RSMF: *Rhododendron, Sorbus* mixed forest; RwF: *R. wightii* forest; TRMF: *Tsuga, Rhododendron* mixed forest; TVMF: *Tsuga, Viburnum* mixed forest) (Table 2).

In shrub layer, a total of 2,419 individuals belonging to 22 species, 17 genera, and 11 families were enumerated along the studied gradient (Table S2). Ericaceae was the most dominant family, represented by 9 species, followed by Rosaceae (3 species), and Berberidaceae (2 species). The mean shrub density (5,605 ± 1,097 individuals ha^{-1}) was observed significantly higher (12,747 individuals ha^{-1}; $P < 0.05$) at low elevation 3,200 m and decreased towards mid and high elevations. The species density was recorded maximum for *Rubus* sp. however, *Viburnum cotinifolium, Rhododendron camelliflorum* and *Mahonia napaulensis* shared minimum density values for the shrub layer.

In herbaceous layer, a total of 7,024 individuals of 64 species were recorded belonging to 53 genera and 29 families, in addition to 8 unidentified herb species. Compositae was the most dominant family represented by 7 herb species, followed by Polygonaceae, Primulaceae, and Rosaceae represented by 5 herb species each (Table S3). The density value for herb species significantly ($P < 0.05$) differed across the study area and a significantly higher density value (2,04,000 individuals ha^{-1}; $P < 0.05$) was recorded in mid-elevation (3,400 m) of *A. densa* dominated forest and (1,99,167 individuals ha^{-1}, $P < 0.05$) in *Tsuga, Rhododendron* mixed forest at low elevation (3000 m) (Table 1). The *Fragaria daltoni* emerged as the most dominant herb species with widest amplitude across the area (Table S3).

Diameter class distribution and elevational trend of growth forms

The diameter class wise distribution of tree species richness, and total basal area (TBA) along different elevational ranges (high, middle and low) represented reverse J-shaped, interrupted reverse J-shaped, and hump shaped patterns (Fig. 3a–c). Overall the TBA peaked at 3200 m in *A. densa* dominated forest (Fig. 4). Among the life-forms, tree density peaked in *A. densa* dominated forest

Table 1. Patterns of vegetation composition along the elevational gradient in subalpine forest of Khangchendzonga National Park, Sikkim.

Forest Communities	Elevation (m asl)	TBA (m^2 ha^{-1})	Tree density (Individuals ha^{-1})	Sapling density (Individuals ha^{-1})	Seedling (Individuals ha^{-1})	Shrub density (Individuals ha^{-1})	Herb density (Individuals ha^{-1})
TRMF	3000	4.99±1.70cd	1073.33±179.75cd	3460.0±120.554a	2533.3±1239.64bcd	9946.67±765.01ab	199166.67±24251.0a
TVMF	3100	3.27±0.99cd	606.67±173.72de	720.0±257.16de	1840.0±697.42bcd	2480.0±454.89d	98166.67±5833.33bc
AF	3200	52.52±14.53a	2220.0±196.98ab	1880.0±522.047b	4613.33±515.02ab	12746.67±943.89a	34833.33±12125.5c
AF	3300	37.25±9.51ab	2593.3±81.10a	2780.0±220.0a	3200.0±922.61abcd	9146.67±933.33b	79333.33±23566.1bc
AF	3400	17.60±1.65bcd	1700.00±87.18bc	1993.33±213.65b	3120.0±561.9abcd	7173.33±986.67bc	204000.0±25059.93a
AF	3500	20.96±6.02bcd	1186.67±256.21cd	953.33±206.67cde	4400.0±697.42ab	5493.33±1326.92cd	19833.33±1092.9c
RhF	3600	23.06±3.19bc	1553.33±127.19bc	1413.33±198.77bcd	6293.3±2145.8a	2533.33±1365.74d	75666.67±37251.8bc
RhF	3700	20.37±6.38bcd	1813.33±213.33bc	1586.67±373.51bc	2373.3±907.84bcd	2693.33±1554.23d	92333.33±40270.27bc
RSMF	3800	13.17±1.42cd	1340.0±254.03c	1240.0±280.0bcd	4000.0±1883.54abc	4000.0±1019.28cd	159166.67±26461.2ab
AF	3900	15.06±3.05cd	2146.67±497.64ab	1220.0±61.10bcd	740.0±174.36cd	3253.33±1755.35d	80666.67±26032.6bc
RwF	4000	0.93±0.53d	306.67±177.51e	360.0±94.52e	313.33±52.07d	2186.67±232.47d	127500.0±39585.35ab
Average		19.02±4.57	1,504±209	1,601±272	3,036±529	5,605±1097	1,06,424±18,236

Values representing the mean±SE, mean values within each column (elevation sites) followed by same letters are not significantly ($P< 0.05$) different, separated by Duncan's Multiple Range Test (DMRT). Forest communities-AF: *Abies* dominated forest; RSMF: *Rhododendron, Sorbus* mixed forest; RhF: *Rhododendron hodgsonii* forest; RwF: *Rhododendron wightii* forest; TRMF: *Tsuga, Rhododendron* mixed forest; TVMF: *Tsuga, Viburnum* mixed forest.

Table 2. Patterns of forest communities along the elevation gradient in subalpine forest of Khangchendzonga National Park, Sikkim.

Tree species	TRMF (3000 m asl)	TVMF (3100 m asl)	AF (3200 m asl)	AF (3300 m asl)	AF (3400 m asl)	AF (3500 m asl)	RhF (3600 m asl)	RhF (3700 m asl)	RSMF (3800 m asl)	AF (3900 m asl)	RwF (4000 m asl)
Abies densa	11.65± 7.05bc	19.34± 12.16bc	109.57± 4.62a	85.16± 8.33a	92.50± 9.74a	126.93± 3.12a	102.98± 3.83b	54.85± 23.43b	51.21± 14.80ab	122.55± 27.27a	-
Acer caudatum	20.78± 2.99bc	50.19± 18.99ab	20.25± 5.28d	39.43± 5.65c	15.54± 1.81cd	-	4.27± 4.27d	10.19± 1.36c	-	-	-
Betula alnoides	19.96± 6.06bc	-	6.88± 3.58ef	15.70± 1.94d	26.03± 1.07c	3.75± 3.75e	-	-	-	-	-
Betula utilis	-	-	-	-	5.54± 0.21de	12.03± 8.14d	-	-	-	-	-
Litsea sericea	-	7.71± 7.71bc	-	-	19.26± 11.89c	-	-	-	-	-	-
Lyonia villosa	6.17± 3.63c	-	-	-	-	-	-	-	2.09± 2.09e	-	-
Magnolia campbelli	7.66± 7.66c		-	-		-	-	-	-	-	-
Prunus bracteopadus	13.79± 3.12bc	-	-	-	-	-	-	-		-	-
Prunus rufa	-	-	-	-	-	3.29± 3.29e	9.89± 5.75d	17.57± 13.11c	29.43± 14.20bcd	14.75± 14.75bc	58.46± 30.60b
Rhododendron arboreum	50.07± 18.49a	16.53± 16.53bc	-	-	-	-	-	-	-	-	-
Rhododendron barbatum	1.80± 1.80c	9.97± 8.94bc	59.66± 4.31b	30.22± 5.64c	24.10± 7.10c	-	-	-	-	-	-
Rhododendron decipiens	-	-	-	6.96± 12.14d	4.50± 2.35de	-	-	2.82± 2.82c	6.96± 6.96de	-	-
Rhododendron falconeri	56.29± 16.14a	45.11± 6.56abc	47.32± 2.12c	-	-	-	-	-	-	-	-
Rhododendron fulgens	-	-	-	-	-	-	-	-	-	0.43± 0.43c	-

Contd…

Table 2. Continued.

Tree species	TRMF (3000 m asl)	TVMF (3100 m asl)	AF (3200 m asl)	AF (3300 m asl)	AF (3400 m asl)	AF (3500 m asl)	RhF (3600 m asl)	RhF (3700 m asl)	RSMF (3800 m asl)	AF (3900 m asl)	RwF (4000 m asl)
Rhododendron hodgsonii	-	-	-	68.49± 13.04b	79.80± 9.64b	95.71± 3.90b	125.38± 2.19a	103.23± 12.36a	66.85± 6.83a	-	-
Rhododendron lanatum	-	-	-	-	-	-	5.63± 5.63d	16.74± 9.85c	27.10± 7.30cd	82.53± 23.19b	14.52± 14.52c
Rhododendron thomsonii	-	-	-	-	-	-	9.38± 5.36d	12.04± 7.12c	39.09± 10.06bc		
Rhododendron wightii	-	-	-	-	-	-	2.65± 2.65d	5.51± 2.85c	9.52± 5.92de	40.75± 13.75b	178.11± 20.94a
Sorbus microphylla	-	5.51± 5.51c	9.12± 4.74e	7.32± 0.85d	2.31± 2.31de	13.67± 7.56d	27.61± 5.82c	64.88± 17.99b	67.77± 22.56a	39.00± 34.39b	48.91± 28.47b
Symplocos dryophila	38.28± 7.89ab	14.97± 14.97bc	-	-	-	-	-	-	-	-	-
Tsuga dumosa	54.48± 25.74a	66.98± 46.17a	1.73± 1.73f	-	-	-	-	-	-	-	-
Viburnum nervosum	6.89± 3.62c	63.69± 27.44a	20.92± 3.72d	30.71± 10.46c	24.77± 1.91c	45.86± 3.28c	12.21± 12.21d	12.16± 9.01c	-	-	-
Vitex quinata	12.19± 12.19bc	-	24.54± 2.24d	12.42± 7.99d	5.65± 5.65de	-	-	-	-	-	-

Values representing the mean±SE, mean values within each column (elevation sites) followed by same letters are not significantly ($P < 0.05$) different, separated by Duncan's Multiple Range Test (DMRT). The tree IVI values followed by the letter 'a' in each elevation site indicates the significantly higherdominance of species. Forest communities-AF: *Abies* dominated forest; RSMF: *Rhododendron, Sorbus* mixed forest; RhF: *Rhododendron hodgsonii* forest; RwF: *Rhododendron wightii* forest; TRMF: *Tsuga, Rhododendron* mixed forest; TVMF: *Tsuga, Viburnum* mixed forest.

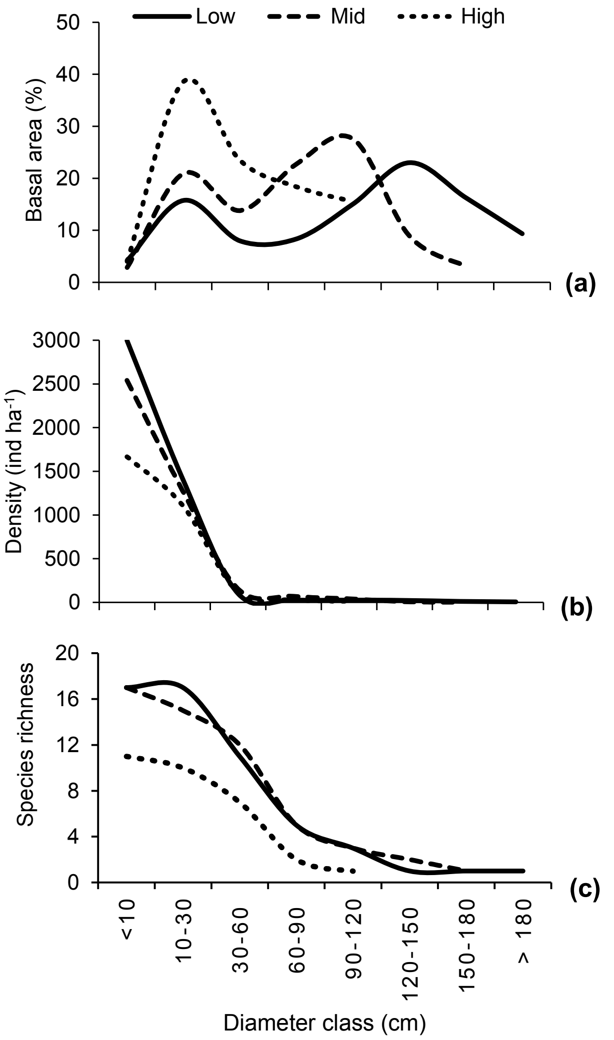

Fig. 3. Tree species richness, density and percent basal area by DBH classes (cm) at different altitudes (Lower 3000–3300 m; Middle: 3400–3700 m asl; Higher: 3800–4000 m asl). The diameter class < 10 cm (CBH: < 30 cm) includes seedlings and saplings.

at lower elevation (3300 m), and shrub density also peaked in *A. densa* dominated forest at lower elevation (3200 m). However the herb density peaked in both *Tsuga, Rhododendron* mixed forest at 3000 m and *A. densa dominated* forest at 3400 m (Fig. 4).

The total species richness (including herb, shrub and tree) followed a reverse J–shaped pattern along the elevation gradient. A significant decline in species number was observed towards the higher end of the elevation gradient. Regression drawn between species richness and elevation showed a significant quadratic relation ($R^2 = 0.74$, $P < 0.01$).

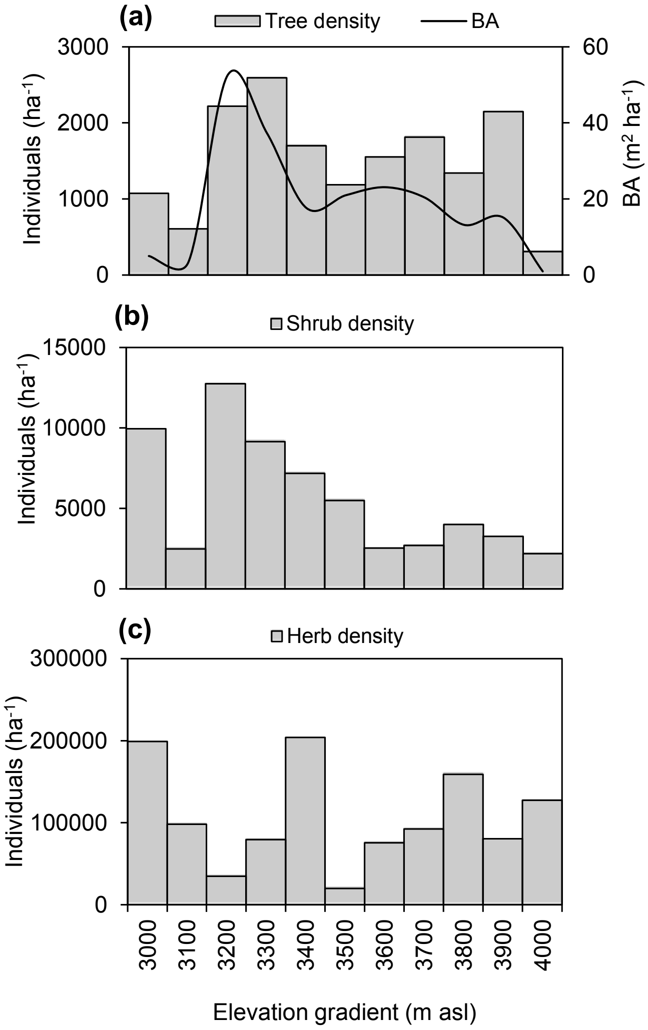

Fig. 4. Elevational trends of different growth forms in subalpine forest of Khangchendzonga National Park, Sikkim.

Species richness of trees followed a hump-shaped relationship with elevation, showing a peak at around 3400 m. Shrub species richness followed a reverse J shaped curve and peaked at 3200 m. The herb species richness followed a reverse hump shaped curve and species richness declined towards mid-elevation (Fig. 5).

The relationship between elevation and tree species composition

Regression drawn between elevation and tree species composition (Shannon diversity and Margalef's index of species richness) showed a significant quadratic relation (Fig. 6). The tree species diversity declined monotonically with elevation. The

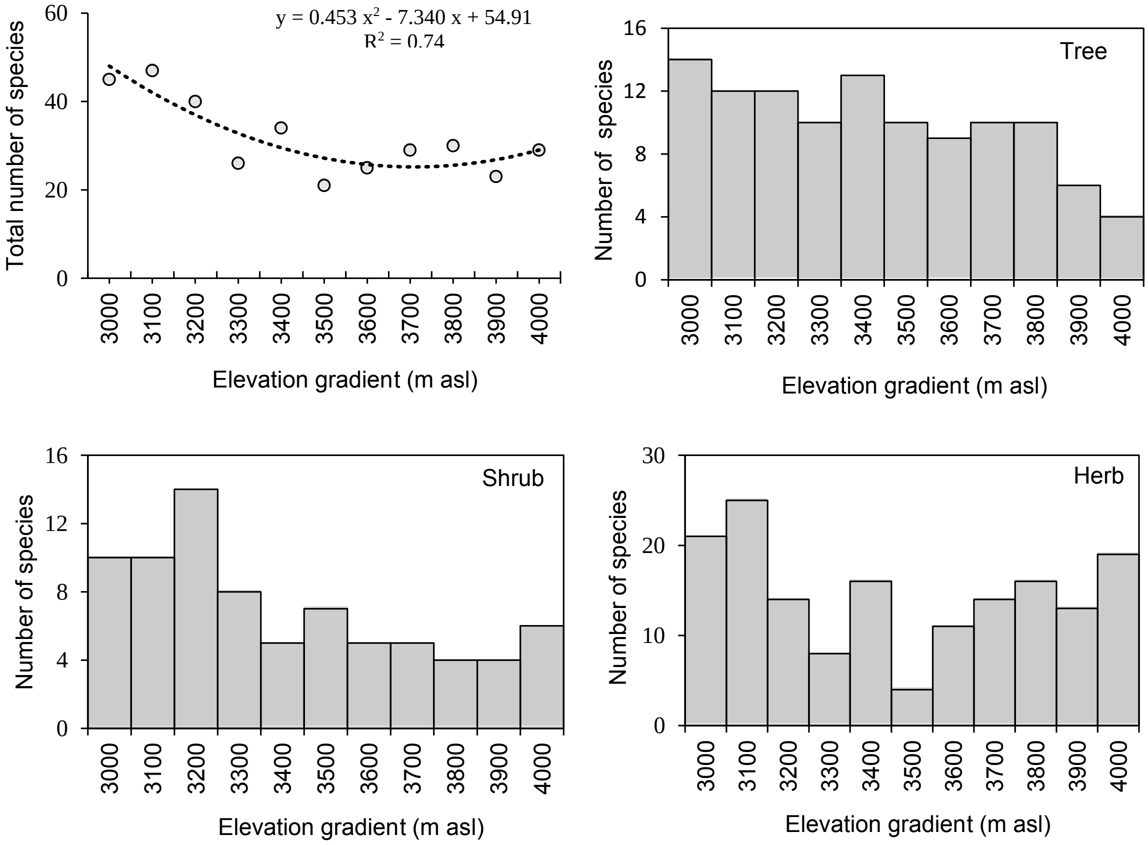

Fig. 5. Trends of species richness along the elevation gradient in subalpine forest of Khangchendzonga National Park, Sikkim.

Shannon diversity (H') was 1.86 at the 3000 m, which gradually decreased up to 1.26 for near timberline forest 3900 m, and reached finally up to 1.44 at the timberline forest 4000 m. Species evenness did not vary significantly along the gradient and the Shannon's index of species evenness value was observed between 0.68–0.88. The species richness showed a significant decreasing trend towards the higher elevation and the Margalef's index values of species richness varied between 10.82 at 3000 m to 5.06 at the timberline forest (4000 m) (Fig. 6). The dominance increased with an increase in the elevation and Simpson's index value was 0.22 at 3000 m which gradually increased towards the higher elevations.

Discussion

In Sikkim along the elevation gradient, the maximum tree density (1,675 individuals ha^{-1}) is reported between 2800–3800 m (Acharya *et al.* 2011), which is comparable with the recorded tree density (1,504 ± 209 individuals ha^{-1}) in the present study from the subalpine forest (3000–4000 m). However, the tree density values of Sikkim Eastern Himalaya are comparatively higher than the western Himalayan (728 individuals ha^{-1}) subalpine forests (Gairola *et al.* 2015), and (546–616 individuals ha^{-1}) different ridge top forests of Uttarakhand west Himalaya (Sharma *et al.* 2017). This variation in tree density can be attributed to the forest community type, forest age, site history and site condition (Parthasarathy 2001; Kumar *et al.* 2006). The tree density in present study showed an irregular trend along the elevation gradient and the maximum tree density was recorded from *Abies* dominated forests which can be correlated to their high regeneration potential and less vulnerability to herbivory (Begon *et al.* 2006). Further, the presence of *Rhododendron* spp. in under-canopy makes these forests denser. These dense canopies help to retain the moisture, which supports the establishment of shade adapted seedlings. However, the density values for shrub and herb species in the present study area are slightly higher than the western Himalayan subalpine forests

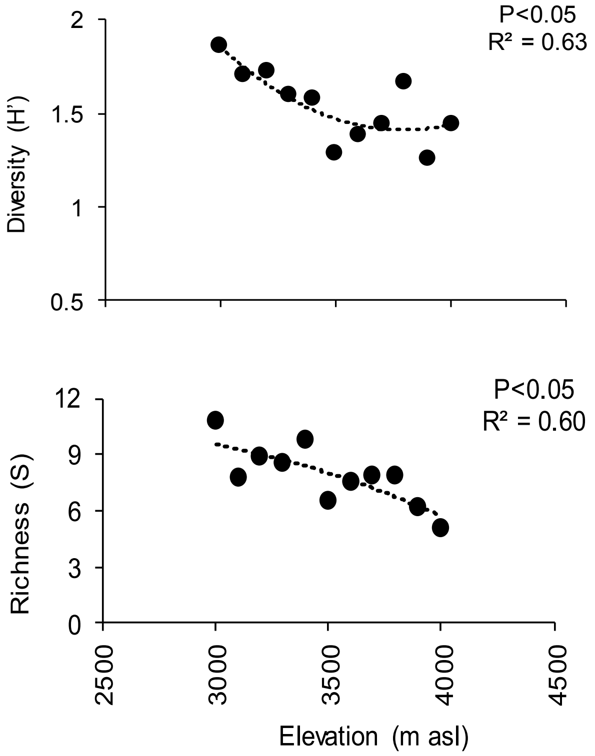

Fig. 6. Relationship between elevation and tree species composition were; H′: Shannon index of diversity; S: Margalef's Index of Species richness.

(Gairola *et al.* 2015) and significantly lower than the eastern Himalayan forests in Arunachal Pradesh, north-eastern region of India (Saikia *et al.* 2017). Overall, the present study recorded Ericaceae as the most dominant family with 19 spp., where as Compositae was the dominant family in the Western Himalayan forests of India (Sharma *et al.* 2014) and Fabaceae was the most species rich family in eastern Himalayan forests in Arunachal Pradesh, Northeast India (Saikia *et al.* 2017). This difference can be related to the variations in growth forms, species composition, and study area, as the study area is rich in *Rhododendron* spp. and contributes to both tree (9 spp.) and shrub (5 spp.) layers.

The mean basal area (19.02 ± 4.57 $m^2 ha^{-1}$) of 6,488 individuals of tree species in present study was found lower than the reported basal area (72.1 ± 69.8) of 3,874 individual trees species between 300–4700 m elevations in other parts of Sikkim (Acharya *et al.* 2011). This variation in the basal area may be attributed to altitudinal variations, species composition, age structure and successional stage of the forest (Swamy *et al.* 2000). The present study covers the area of subalpine forest (3000–4000 m) and consists of the high density of low girth class tree species such as rhododendrons in understory layer. However, the TBA value of present study (0.93–52.52 $m^2 ha^{-1}$) is comparable with various sub alpine forests of Uttarakhand west Himalaya such as Nanda Devi Biosphere Reserve (2300–3800 m asl) 14.68–80.28 $m^2 ha^{-1}$ (Joshi & Samant 2004), Valley of Flower National Park (2750–3250 m asl) 17.87–86.75 $m^2 ha^{-1}$ (Gairola *et al.* 2015), and Tungnath (3000–3200 m asl) 8.94–69.84 $m^2 ha^{-1}$; Lata (3000–3200 m asl) 15.29–35.33 $m^2 ha^{-1}$; Pindari (3000–3200 m asl) 16.75–37.16 $m^2 ha^{-1}$ (Gairola *et al.* 2014).

A total of six forest types (communities) were observed along an elevation gradient, among them *A. densa* dominated forest community was the most common and represented by 5 elevation sites. In the present study, we documented 23 tree species and the number of species declined with increasing girth size. Similar trend was exhibited by various taxa along elevational gradients in the mountain ecosystems (Acharya *et al.* 2011; Cardelus *et al.* 2006; Gaston 1996; Graham 1990). This posits narrow tolerance to climatic variations by the species, therefore unable to extend their ranges beyond certain elevation range (Jetz & Rahbek 2002). Further, the factors like habitat availability, seed dispersal and establishment abilities, competition, local abundance, climatic or environmental tolerances and historical incidences are the determinants of species range limit (Gaston 1996).

The relationship between species richness and evenness across communities remains an unsettled issue in ecology from both theoretical and empirical perspectives (Zhang *et al.* 2012). The recorded Shannon diversity values for trees in the present study ranged between 1.2–1.9 which is slightly higher than the temperate forests of western Himalaya. Further tree diversity decreased with increasing elevations, which was in accordance to the reported studies in the western Himalaya (Sharma *et al.* 2009; Singh & Kaushal 2006). Similarly, the species richness decreased with increase in elevation, which is in agreement with earlier studies (Bachman *et al.* 2004; Jacquemyn *et al.* 2005; Trigas *et al.* 2013). Overall the surveyed subalpine forest of Sikkim Himalaya possess good regeneration status seedling (3039 individual ha^{-1}) > sapling (1601 individual ha^{-1}) > tree (1504 individual ha^{-1}). Among the tree species, most of the *Rhododendron* spp. followed similar trend. Interestingly, the presence of *R. hodgsonii* seedlings in the higher elevations indicate the tolerance capacity of the species to the harsh climatic conditions of the higher elevation and in near future this species has the possibility to establish itself to comparatively higher elevations. However, further attention is required to develop a holistic understanding of ecosystem functioning across this highly diverse area.

Conclusion

The present study analyses vegetation structure along an elevation gradient of 3000–4000 m in subalpine forest zone up to timberline of Sikkim East Himalaya. The overall species richness and total basal area declined monotonically with elevation. The amplitude (range) of tree species varied across the gradient. The area possesses three layers of trees, i) understory layer of low DBH trees, ii) canopy layer of *Betula* spp.,*Vitex quinata, Rhododendron* spp., and iii) emergent layer of *Abies densa* and *Tsuga dumosa*. The lower elevation contributed the most in the total basal area (TBA). The tree species richness and diversity significantly decreased towards the higher elevation. The forest vegetation has species combinations of two contrasting sizes and densities of trees: large trees of conifers, particularly *A. densa* and small trees in very high densities of Ericaceae family, particularly *Rhododendron* spp. These two groups combine to give high tree basal area up to 3900 m. However, absence of conifers and low species richness of trees at the diffused timberline of the region correlated to lower basal area at the highest elevation site 4000 m. Under the current climate change scenario, this understanding of species distribution along the elevational gradient across remotely located subalpine forests will be helpful for planning management and conservation of biodiversity in the Himalayas.

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Supporting Information

Additional Supporting information may be found in the online version of this article.

Table S1. Status of tree species along the subalpine conifer forest in Khangchendzonga National Park.

Table S2. Status of shrub species along the subalpine conifer forest in Khangchendzonga National Park.

Table S3. Status of herb species along the subalpine conifer forest in Khangchendzonga National Park.

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An overview of treeline response to environmental changes in Nepal Himalaya

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Abstract: Changes in treeline dynamicsare, considered reliable indicators of rapidly changing climate in Himalayan mountains. This paper is aimed at exploring treeline forming species in Nepal Himalaya, their growth-climate relationship and shifting response of climate change to improve our understanding on existing methodologies of treeline studies. It was found that the treelines in Nepal Himalaya are both temperature and moisture sensitive. The reconstruction of stand stage structure has been the common method of treeline studies in Nepal Himalaya; this showed site and species specific response to environmental changes. The recent stand densification and higher shifting rates are observed for *Abies spectabilis*, whereas both stand densification and shifting are slow for *Betula utilis*. There still exists a gap in knowledge regarding microtopography, soil properties, biotic interaction among species and influence of land use change with rapidly changing climate in the treelines of Nepal Himalaya.

Key words: Recruitment, regeneration, timberline, treeline, treeline shift.

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Introduction

Treeline in a broad sense refers to the ecotone representing the transition between timberline and the treeless alpine vegetation (Körner 2003); as the broad area of 50 to 100 m below the treeline to the line bounding the full forest (closed timberline forest) (Fig. 1). Since the timberline and treeline are coupled boundaries, the fundamental mechanisms causing their general position is considered to be similar (Körner 1998).

Treelines are widely used as an indicator for observation of landscape response to climatic change. The life and growth form of trees change sharply due to the severe climate at the upper edge of mountain forests, and form at least four types of treelines; diffuse, abrupt, island, and krummholz 'Diffuse treeline' is characterized by a gradual decrease in the height and density of trees; 'abrupt treeline' is a continuous forest of > 2 m tall trees directly bordering low alpine vegetation, trees may be present above a continuous forest but their presence is infrequent; clumped patches or linear strips ('fingers') of krummholz or trees above the continuous forest limit forms the 'island treeline'; and severely stunted or deformed multi-stemmed trees occurring in clumped patches above the upright forest forms a 'krummholz treeline', also referred to as krummholz-island treelines (Harsch & Bader 2011).

The highest elevation treeline in northern hemisphere is formed by *Juniperus tibetica* Kom in south west of Tibet at 4900 m asl (Miehe *et al.* 2007). Temperature is described as the main influencing abiotic factor to delimit the elevation of alpine treeline and to constrain the growth and regeneration of tree species in treelines (Harsch *et al.* 2009; Holtmeier & Broll 2007; Körner 2003). The germination of seeds and seedling recruitments in treeline ecotones are limited because of thermal deficiency and soil moisture scarcity, particularly in inner ranges. Given the repeated climatically caused treeline fluctuations during the Holocene (MacDonald *et al.* 2000; Reasoner & Tinner 2009)

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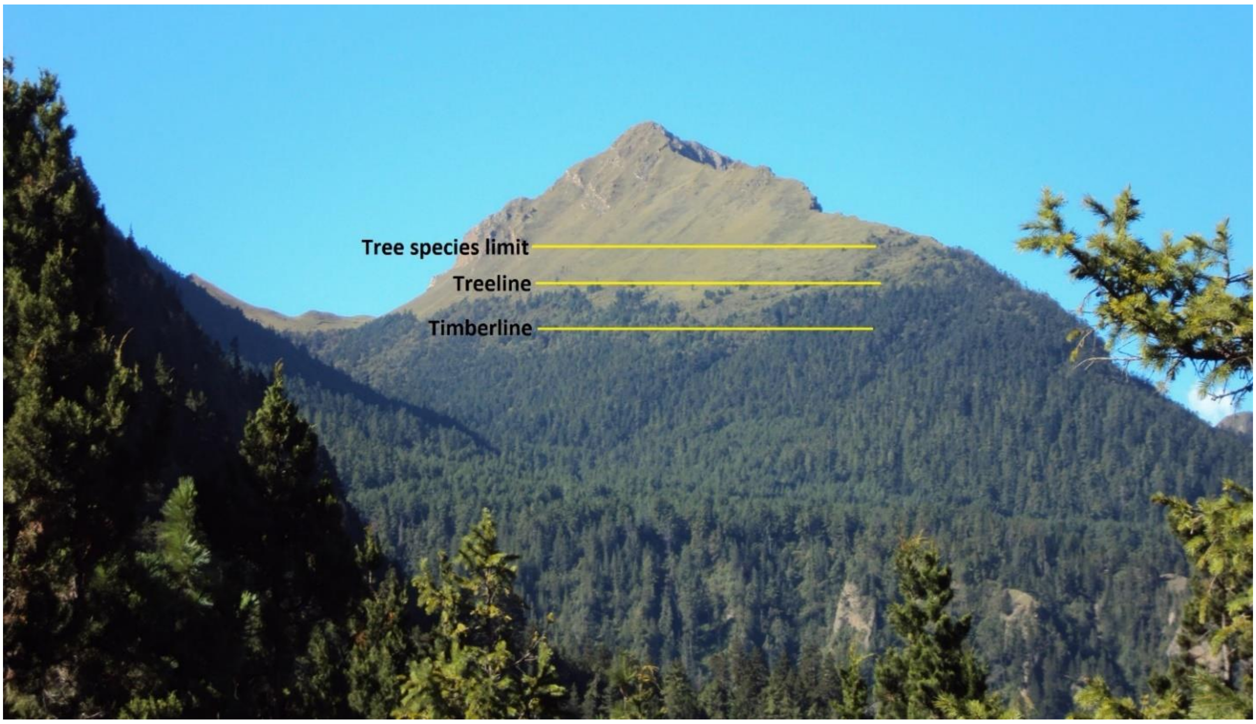

Fig. 1. Position of tree species limit, treeline and timberline in a sub alpine forest (Marche, Mustang Nepal) (Photograph by A. Tiwari, 2014).

and the general dependency of the upper limit of tree life on thermal balance, it seems apparent that climate warming will improve growth conditions of treeline forest stands, generate higher stand densities and induce treelines to advance to higher elevations (Dullinger *et al.* 2004; Grace *et al.* 2002; Smith *et al.* 2009). And, there is increasing evidence that rate of climate warming is amplified by elevation and latitude (IPCC 2014; Huang *et al.* 2017; Pepin *et al.* 2015). As a consequence, the polar and high elevation treelines are generally shifting upward in response to global warming despite their complex ecology and dynamics (Grace *et al.* 2002; Harsch *et al.* 2009; Holtmeier & Broll 2007; Jobbagy & Jackson 2000; Kullman 2001; Liu *et al.* 2002; Malanson 2001; Payette 2007).

Physiographic factors including soil moisture at different slopes may exert remarkable variation in the spatiotemporal patterns of regeneration, tree establishment, and stand density at upper treelines (e.g. Daniels & Veblen 2004; Elliott & Kipfmueller 2011), and the related patterns differ between slope aspects due to the differential presence of permafrost (Danby & Hik 2007; Elliott & Kipfmueller 2010). Besides, interaction among species has also been found to be the important factor on modulating altitudinal treeline dynamics (Liang *et al.* 2016; Schwab *et al.* 2017).

Himalayan mountain system is often rugged terrains, hence the regional distribution of temperature and precipitation is greatly varied even over short geographic distances (Schickhoff 2005; Tiwari *et al.* 2017b). Due to this, a higher spatial heterogeneity in elevation of treelines and their regeneration dynamics is expected. Upper timberline trees should primarily move upslope in the mountains due to warming, owing to the altitudinal temperature gradient, as has been frequently documented during the recent decades (Gottfried *et al.* 2012; Kelly & Goulden 2008). The mountains usually have conical shape; hence the upslope movement inevitably results in range loss and may even lead to 'mountain-top extinctions' (Colwell *et al.* 2008) in extreme cases. Hence treeline dynamics of ecotone would also supplement the existing knowledge on the future of mountain top species and their distribution range. This article gives an overview of treeline forming species, climatic trends, growth limiting factors and treeline dynamics representing the treeline sites studied in Nepal Himalaya (Fig. 2). The existing methodologies and rate of treeline shifting in the region have also been evaluated.

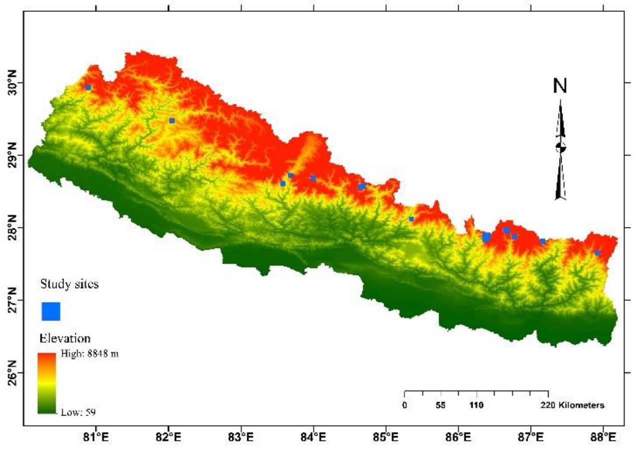

Fig. 2. Map of Nepal showing treeline sites explored.

Research methods to detect changes in treelines

The common methodological practices of monitoring treeline shifting involve monitoring, recruitment patterns of trees in identified plots, reconstruction of stand age structure, the use of historical aerial photographs (Baker & Moseley 2007), and an analysis of remotely sensed data. In northwestern Yunnan (Hengduan Mountains), several sets of historical photographs showed that shrubs were encroaching into alpine meadows and treeline showed substantial shifting in elevation (Baker & Moseley 2007; Moseley 2006). However, an upward altitudinal shifts in treelines could be due to the cessation of pastoral use and other human disturbances than the climatic change. Besides, treeline dynamics can also be monitored using images from remote sensing satellites, which helps to overcome the difficulties posed to direct observation by the poorly accessible Himalayan terrain (Rawat 2012).

From Himalayan region stand age structure and recruitment pulses are only studied in order to describe treeline dynamics. However, there still exist differences in quantification of inertia of treeline, which mainly involve non-uniformity in procedure and outpost tree response, besides the challenging task of disentangling the climatic and anthropogenic impact on treeline formation.

Treeline forming species in Nepal Himalaya

The most common species in terms of distribution and exploration in Nepal is *Abies spectabilis* (Table 1). Plot based studies to explore treeline dynamics have been conducted on only few species (*Abies spectabilis, Betula utilis, Pinus wallichiana, Rhododendron campanulatum*) are included so far. *A. spectabilis* and *B. utilis* treelines are shown in Fig. 3 as typical example from Nepal.

Climatic trends in Nepal Himalaya

The summer season is dominated by a south-westerly flow from the Bay of Bengal, which pushes moist air masses into the eastern Himalayas leading to summer precipitation up to 3000 mm in mountains in general, but up to 5000 mm on the windward Himalayan slopes in central Nepal. The winter climate is determined by a uniform westerly flow leading to occasional precipitation events, particularly in the western Himalaya (Böhner 2006; Maussion *et al.* 2013). Hence the eastern Himalaya receives about 80% of the annual precipitation during summer, and the far western parts receive up to 50% of the annual precipitation during winter. Himalayan region sustains mainly dry conditions throughout the transition season, although infrequent convective precipitation is common at south facing slopes (Romatschke *et al.* 2010).

Great variation in elevation and topography have distinctly modified regional and local climate of treelines in Nepal Himalaya. The precipitation pattern at the local-scale is mainly influenced by wind- and leeward positions furnished by topography and local scale circulation patterns (Gerlitz *et al.* 2014). Studies showed that the rate of future mid-latitude warming will be enhanced at higher elevations in comparison to the surrounding landmass at the same latitude, particularly in the colder seasons (Pepin *et al.* 2015; Rangwala *et al.* 2013), hence high mountain regions are particularly sensitive to climatic changes. More rapid changes in high-mountain climates would have consequences far beyond the immediate mountain regions, as mountains are 'water towers' and the major source of water for large populations in downstream and they are critical to people and ecosystems (Christensen *et al.* 2007).

Himalayas are warming at higher rates than global average rate of 0.74 °C during the previous century. In high elevation areas of Himalayas, the warming rate is reported to be between 0.6 and 1 °C decade^{-1} (Shrestha *et al.* 1999). Elevation and bias-adjusted ERA-Interim reanalysis and spatial high-resolution temperature trends over the Himalaya for the period since 1989 showed that the winter season maximum temperature trends of up to +0.8 °C decade^{-1}. Similarly, the pre-monsoon season

Table 1. Treeline forming species in Nepal Himalaya.

Species, distribution range (m asl)	Species characters	Remarks
Abies spectabilis (3000–4000 m)	Dominant tree in the central and western Himalaya, grows better on cool and moist north facing slopes. It commonly occurs as a canopy dominant species, accompanied by different species of *Rhododendron* as well as *Betula utilis* (Chhetri 2008).	Most explored species in treeline in Nepal Himalaya
Betula utilis (2700–4300 m)	Only broadleaved angiosperm tree species in the Himalaya which dominates an extensive area in subalpine altitudes (Zobel & Singh 1997), and forms tree line vegetation all along the Nepal Himalaya (TISC 2002)	Only a broadleaved tree forming treeline in Nepal Himalaya
Pinus wallichiana (2000–3600 m)	Found in temperate to sub-alpine zones, typically in mountain screes and glacier forelands, the highest altitude records of 4400 m in *Pinus-Betula* woodlands of Dolpa (Miehe *et al.* 2015)	Forms treeline in relatively drier regions such as Trans-Himalaya like Manang (Shrestha *et al.* 2014)
Juniperus spp. (3700–4400 m)	*J. indica* is found in upper montane coniferous forest and woodland in pure stands, or with e.g. *Abies, Pinus, Cupressus torulosa*, or in *Betula utilis* subalpine woodland, to alpine heath and grassland and into the bare moraines and scree of the niveous zone. *J. recurva* has the highest record of a tree in Nepal at 4400 m (Miehe *et al.* 2015)	*J. indica* reported from upper treeline on sunny slopes of Mustang, 3,600 m, 28°53'N/83°45'E (Miehe *et al.* 2015). *J. recurva* at highest elevation in Khumbu valley.
Quercus semecarpifolia (1700–3800 m)	Evergreen oak of the middle cloud forest belt of the Central Himalaya with moderate monsoonal rainfall, montane climax forest. Those reaching the upper treeline on southern exposures have snow deformed trunks.	Reported in the form of abrupt treeline in western Nepal (not verified)
*Rhododendron campanulatum** (2800–4400 m)	Major understory component of sub-alpine forest, and forms pure stand above treeline in Nepal Himalaya (Polunin & Stainton 1997; Rajbhandari & Watson 2005).	Regeneration dynamics studied in Nepal (Rana *et al.* 2017)

*Shrub forming krummholz plot based regeneration dynamics studied in Nepal

maximum temperature trends were also found to be increasing for the entire Himalayan Arc. The warming trend has subsequently decreased frost days (up to –17 days decade) in the Nepal Himalaya, with substantial increase of growing degree days for the southern slopes of the Himalaya at elevations between 2000 and 3500 m (Gerlitz *et al.* 2014).

Negative trends of annual precipitation (up to 20% for the previous century) were reported over the western Himalaya (Bhutiyani *et al.* 2010; Duan *et al.* 2006; Jain *et al.* 2013). Long-term trends of winter precipitation rates are slightly negative but not statistically significant (Bhutiyani *et al.* 2010). The enhanced frequency of winter and pre-monsoon drought events since the early 1980s has been particularly reported for western Nepal Himalaya (Panthi *et al.* 2017; Wang *et al.* 2013). However, eastern Himalaya has shown no change in annual precipitation (Jain *et al.* 2013). The warming in high mountains in the central Himalaya is mainly due to substantial increase of day temperature (Tmax), and some regions are experiencing decreasing trend of mean minimum temperature (Tmin) (Rana *et al.* 2017; Tiwari *et al.* 2017b). Both increasing (Tiwari *et al.* 2017b) and decreasing trends (Rana *et al.* 2017) of rainfall have been

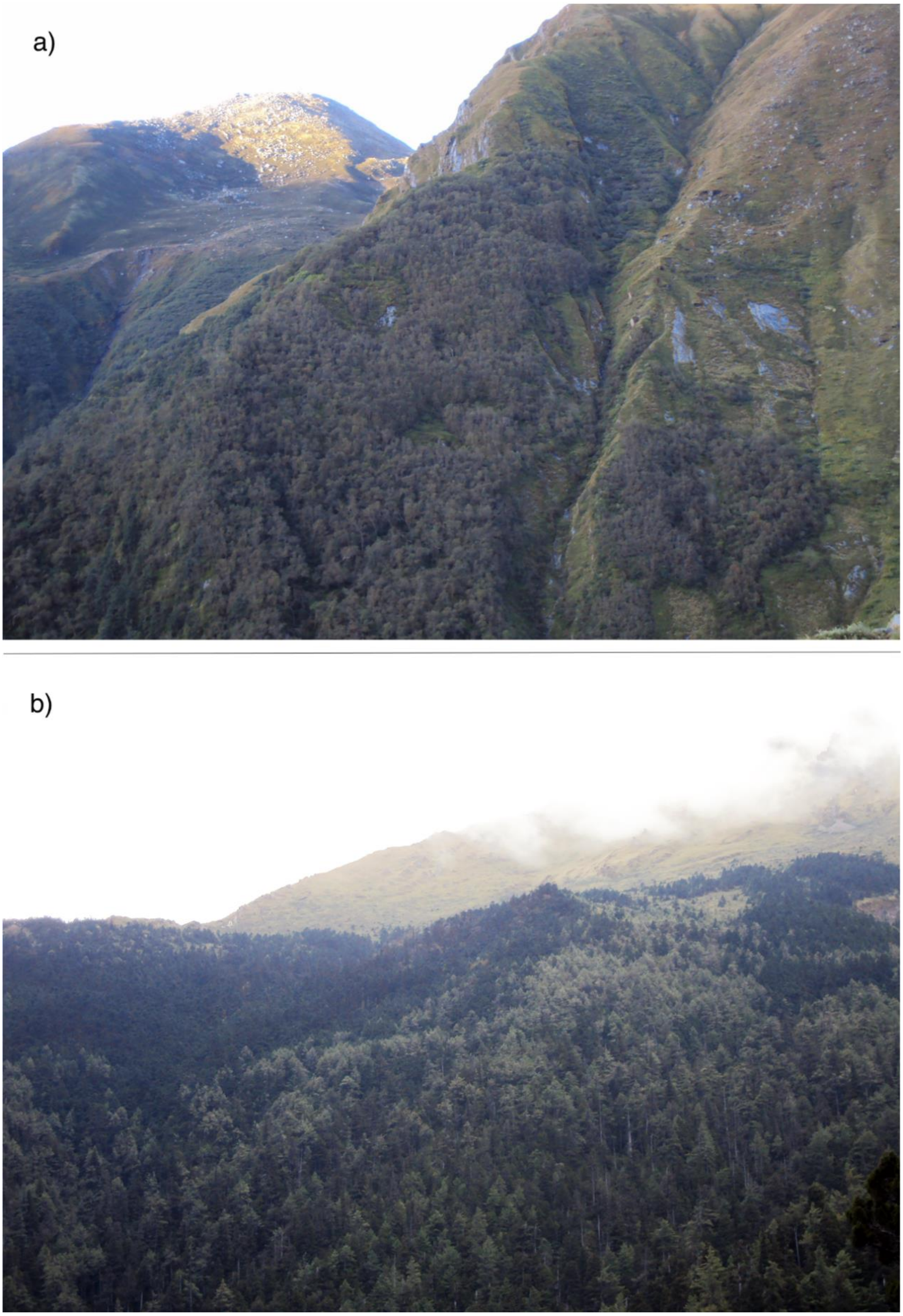

Fig. 3. Treeline ecotones in Mustang: *Betula utilis* treeline site at Kokhedhara (Lete) (a), *Abies spectabilis* treeline site at Chimang (b) (Photograph by A. Tiwari, 2014).

observed. The rising temperatures associated with increasing evapotranspiration rate and decrease of precipitation over the Himalayas likely to intensify drought stress, particularly in the pre-monsoon (early growing) season (Liang *et al.* 2014; Panthi *et al.* 2017; Tiwari *et al.* 2017b). The intensified pre-monsoon droughts may suppress tree growth and seedling recruitments.

Growth-climate relationship

Growth–climate analysis is performed by correlating annual ring width index chronologies and climate data. Climate in the preceding growing season has a strong influence on tree growth in the following year (Fritts 1976). The growth period includes previous year's growing season, intervening winter/spring and the growing season during the year of ring formation, which includes an evaluation of any effects of preconditioning by climate before the growing season (Biondi & Waikul 2004; Cook & Kairiukstis 1990).

Studies in Himalayan region indicated that the limiting factors for tree growth in the treeline are temperature as well as moisture. The observation of moisture sensitive treelines from some parts of central Himalaya indicated both topographic complexity and regional climate variation in the region (Miehe *et al.* 2015). The highly elevated maximum temperature (Tmax) in the higher elevations induces moisture stress due to evapotranspiration, and increases drought sensitivity of high mountain trees (Tiwari *et al.* 2017b). Generally, in Himalayan treelines, the snow cover lasts for more than 4 months (5–6 months also), however, it is now being affected by warming, which can have a considerable influence on seedling establishment, and overall treeline dynamics. In some cases the slightly increasing mean annual temperature has still not responded promptly to treeline shift although the higher rate of shifting has been observed after 1950 (Suwal *et al.* 2016). Responses to warming in terms of radial growth of trees have been found to differ between conifers and broadleaved species (Gaire *et al.* 2016).

Site selection constraint

Treeline studies associated with dendrochronological techniques are greatly limited by site selection. The natural and near natural treelines are often inaccessible and difficult to access due to higher field expedition costs, hence treeline studies from natural ecotones are very rare, and so called near natural treelines are often exposed to anthropogenic disturbance. The orographic treelines are highly complex in terms of growth climate relationship and population demography including seedling recruitment. Most treelines in the southern slope of entire Himalayan region are anthropogenic as stated by Schickhoff (2005).

Site-specific regeneration

Intensive studies on seedling establishment and tree recruitment intreeline ecotone are scanty, so tree recruitment patterns in the treeline ecotones are not well understood (Dutta *et al.* 2014; Schickhoff 2005; Schickhoff *et al.* 2015, 2016). Most of the studies refer to stand age structure and population demography of treeline ecotones at the given time. The regeneration studies in treelines of Nepal Himalaya show reverse J-shaped density–diameter distributions, and good regeneration, which may result in an upward movement of treeline (Gaire *et al.* 2011, 2014; Ghimire & Lekhak 2007; Ghimire *et al.* 2010; Shrestha *et al.* 2007; Sujakhu *et al.* 2013; Suwal *et al.* 2016). In some regions, however, rather bell-shaped density–diameter distributions or deviation from reverse J-shaped distributions (Lv & Zhang 2012; Sujakhu *et al.* 2013) were observed indicating poor regeneration.

Some demographic studies have not included the smallest dbh class (Ghimire & Lekhak 2007; Shrestha *et al.* 2007); they only showed smaller numbers than the subsequent larger class (Gaire *et al.* 2011, 2014; Sujakhu *et al.* 2013), which could be misleading because the smaller seedlings emerge into trees in few years time. The lower frequency of the small dbh class recorded in some investigations may indicate grazing impact. The lower numbers of the tall diameter classes or absence of classes above 50 cm dbh (Ghimire & Lekhak 2007; Gaire *et al.* 2011, 2014; Sujakhu *et al.* 2013) also indicated substantial anthropogenic impacts in high mounatins.

In Nepal Himalaya most of the treeline studies are confined to single tree species in the ecotone (Gaire *et al.* 2014; Lv & Zhang 2012; Shrestha *et al.* 2007; Sujakhu *et al.* 2013). Studies also found that some near-natural treeline ecotones can also contain codominant tree species which respond differently to climatic changes (Trant & Hermanutz 2014). Changes in tree physiognomic characters (diameter at breast height (dbh), tree height and growth form) in treeline are highly sensitive to decreasing temperature both air and soil resulting in climatically shaped growth forms (Holtmeier & Broll 2005). Thus, multispecies approach to survey all ecotone tree species to detect their sensitivity to environmental changes could be the future research issue in treeline ecotone.

Few studies from Nepal provide data on recruit densities. In Langtang valley, Gaire *et al.* (2011) found significantly low *B. utilis* recruits per ha, about the same number of *A. spectabilis* and significantly less *R. campanulatum* and *S. microphylla* recruits compared to the ecotone in Rolwaling. Schickhoff *et al.* (2015) found a comparable distribution of seedling and sapling species and slightly higher total numbers of recruits in Langtang. Recruit density of *Pinus wallichiana* was very high (c. 4500 ha^{-1} at lower altitude; c. 1000 ha^{-1} at higher altitude) in Manang (Ghimire *et al.* 2010). This is consistent with its colonizing habit. A study on *A. spectabilis* from Manang also exhibited very high recruit numbers (c. 3200 ha^{-1}). However they found a very high number of *A. spectabilis* recruits at relatively lower altitudes (3500–3900 m asl; c. 5600 N ha^{-1}) in comparison to higher altitude (3900–4200 m asl; c. 160 ha^{-1}). *Pinus wallichiana* showed a similar pattern with high numbers at lower and smaller numbers at higher altitude. The poor regeneration at the higher elevation indicated more or less stationary position of treeline in these sites. The poor regeneration was also observed for *R. campanulatum* (c. 200 ha^{-1}, Sujakhu *et al.* 2013) and for *A. spectabilis* in Barun valley (c. 200 N ha^{-1}; Chhetri *et al.* 2016).

In summary, the site and species specific regeneration and tree establishment have been found along treeline in Himalayas. Usually recruitment of birch in the closed forest canopy is lower than that of pine and fir. The recruit height class distribution of *A. spectabilis* was found to be different from *B. utilis*, *Acer caudatum* and *Sorbus microphylla*. Obviously, the last species grow faster and aggregate more individuals in taller height classes at the early life stage.

The occurrence of trees at the upper edge indicated that there is a potential to develop even further. The frequency of survivors of new recruits for *A. spectabilis* and *B. utilis* towards higher side of elevational ranges was reasonably high, indicating their upslope migration. Open canopy favors the growth of birch and pine whereas fir regenerates well in closer canopies. In many Himalayan treelines stand densification in the recent decades has been observed (Chhetri *et al.* 2016; Shrestha *et al.* 2014; Tiwari *et al.* 2017a); similar results were observed from south east Tibet (Liang *et al.* 2011). The influence of warming climate on regeneration as well as treeline shifting is evident in some regions including Himalayan region (Camarero & Gutiérrez 2004; Wang *et al.* 2006)

Treeline shifting in central Himalaya

There are a few actual field observations on treeline shift in the Himalayas, and they show that the species responses to recent climatic change vary: (i) substantial upward shifting (Gaire *et al.* 2014, 2016; Tiwari *et al.* 2017a); (ii) moderate upward shift (Chhetri *et al.* 2016); and (iii) almost stationary treeline position (Gaire *et al.*2011; Liang *et al.* 2011; Schickhoff *et al.* 2015; Shrestha *et al.* 2014); and even the possibility of retreating in case of warming induced drought stress (Liang *et al.* 2014). Several studies have revealed that there has been rapid densification of treeline ecotone in the recent decades indicating the possibility of treeline shifting to upper elevation in near future (Gaire *et al.* 2014; Shrestha *et al.* 2007; Tiwari *et al.* 2017a).

Treeline dynamics appear to be more related to changes in snow precipitation than to global warming (Negi 2012). Remote sensing investigations (Singh *et al.* 2012) indicated an upward shift of treeline up to 80 m in the Uttarakhand Himalayas, between 1962 and 2009. Similar reports were made from northwest Yunnan, with rapid glacier recession. The dramatic increase in vegetation cover, drastic reduction of snow cover and upward shifting of alpine plants have also been reported in the central Indian Himalayas (Panigrahy *et al.* 2010).

Most of the treeline ectones studied for quantifying treeline shift in Himalaya constitute younger forest stands, as observed from reconstruction of stand age structure. There has also been non-uniformity in considering treeline and calculating treeline shift. Most of the studies rely on Gamache & Payette (2005) using the following formula:

$$\text{Rate of shift (per yr)} = \frac{\text{Uppermost elevation of young tree} - \text{Uppermost elevation of oldest tree}}{\text{Age of oldest tree} - \text{Age of youngest tree}}$$

Some studies followed horizontal stretch (1.5 km) crossing the respective elevation transects to find the mean position of treeline. The average elevation of these treelines gave mean treeline of that location (Dalen & Hofgaard 2005; Shrestha *et al.* 2014). This method eliminates the influence of single outpost tree while locating the exact treeline of the given area. However, in most of the studies in Nepal Himalaya, treeline is considered as the highest

Table 2. Treeline studies from central Himalaya in Nepal.

Location	Region	Species	Elevation (m asl)	Lat/Long	Reference	Limiting factor
Rolwaling	central	fir	3900	27.86°N, 86.41°E	Schwab *et al.* (2017)	species interaction
Mustang (Dry)	central	fir	3641	28.72°N, 83.68°E	Tiwari *et al.* (2017a)	moisture
Mustang (Moist)	central	birch	3900	28.6°N, 83.58°E	Tiwari *et al.* (2017b)	moisture
Rolwaling	central	fir	3900	27.9°N, 86.36°E	Müller *et al.* (2016)	soil moisture
Manaslu	central	fir	3950	28.57°N, 84.65°E	Gaire *et al.* (2014)	temperature
Pangboche SNP	eastern	fir	≈ 4000	27.87°N, 86.78°E	Gaire *et al.* (2016)	temperature, moisture
Dole SNP	eastern	fir	≈ 4000	27.97°N, 86.65°E	Gaire *et al.* (2016)	temperature, moisture
Phorste SNP	eastern	birch	≈ 4000	27.96°N, 86.68°E	Gaire *et al.* (2016)	not specific
Ngawal Manang	central	pine	4067	28.68°N; 84.00°E	Shrestha *et al.* (2014)	season specific
Lauribinayak, Rasuwa	central	fir	3824	28.12°N; 85.35°E	Shrestha *et al.* (2014)	season specific
Samagaun (MCA)	central	fir	3701	28.56°N, 84.69°E	Suwal (2010)	temperature (recruitment)
MCA	central	fir	3858	28.57°N, 84.69°	Suwal *et al.* (2016)	land use
GCA	central	fir	3956	27.89°N, 86.37°E	Suwal *et al.* (2016)	land use
Barun valley	eastern	fir	4092	(27.81°N, 87.16°E	Chhetri *et al.* (2016)	winter temperature
Ghunsa (Kanchanjungha)	eastern	birch	4118	27.65°N, 87.92°E	Bhuju *et al.* (2016)	unknown
Chuchhemara (Rara)	western	fir	3870	29.47°N, 82.05°E	Bhuju *et al.* (2016)	unknown
Api Nampa	far-west	fir	≈ 3700	29.93°N, 80.89°E	Bhuju *et al.* (2016)	moisture

elevation at which at least a single upright tree with height greater than 2 m as mentioned by Hofgaard (1997) and Körner (2003). The following table (Table 2) summarizes the treelines explored in Nepal Himalaya.

The stand densification by young individuals in the treeline indicated that juveniles could be more benefitted by warming temperature, whereas adult trees will have more competition for water (Lv & Zhang 2012; Qi *et al.* 2015). Investigations on the differences in variables explaining adult and juvenile population densities of different life stages and their relation to abiotic and biotic conditions are required to understand regeneration dynamics in treeline ecotone. Early beginning of growth season and warmer maximum temperature have increased rate of evapotranspiration and hence moisture stress in Nepal Himalaya (Laing *et al.* 2011; Panthi *et al.* 2017; Tiwari *et al.* 2017b). Because of this, in drier areas (Trans-Himalaya, central Nepal) decline in growth of birch has been observed (Tiwari *et al.* 2017b).

While we concentrate on natural treelines, it is critically important to understand the interaction between climate change and altered land use (Vittoz *et al.* 2008) to assess the potential for treeline advance beyond the current climatically determined upper limit. It is reported that prolific regeneration, increased tree establishment and invasion into treeless areas above the anthropogenic forest limit, are directional changes readily attributed to effects of climate change. However in most cases, pastoral abandonment or other changes in human impact also influences

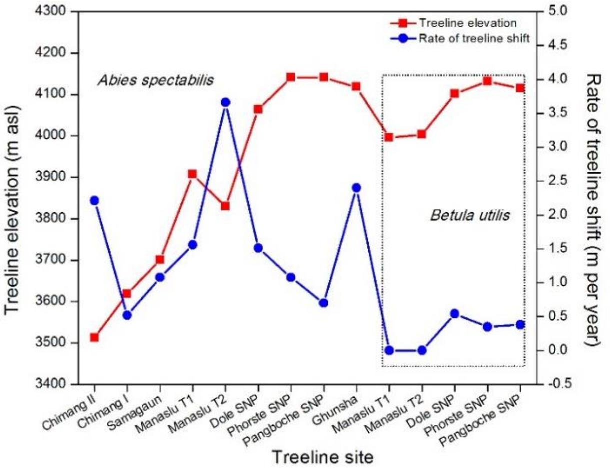

Fig. 4. Treeline elevation and rate of shifting in Nepal Himalaya (rate of shifting is expressed as zero in sites with no shifting and in the sites where shifting was not studied).

treeline dynamics (Holtmeier 2009; Schickhoff 2011); excessive grazing pressure, widespread fire (Beug & Miehe 1999), seasonal drought and poor quality of soil (Müller *et al.* 2016) were reported as the main agents for lowering treelines in Himalaya.

The observed treelines across Nepal Himalaya show that the treeline elevation is higher in the eastern sites in comparison to the western sites (Figs. 2 & 4) as mentioned by Bhuju *et al.* (2016). This spatial variation could be due to the different rainfall patterns in eastern and western sites; however there has not been investigation on it. The rate of upward shifting showed that *A. spectabilis* is shifting faster than *B. utilis* in most of the sites, and there are very few studies on growth performance of these species from the same region. The variation on rate of shifting could be due to the different regeneration behavior, seed dispersal mechanism and water utilization strategies of these species in treelines. Also *B. utilis* is distributed at higher elevation (reaching up to glaciers) in Nepal Himalaya and poor regeneration of this species at treelines could be due to the lack of soil substrate, poor soil conditions (Müller *et al.* 2016) and greater slopes above existing treelines.

Conclusion

Most findings on advancing treelines in Nepal Himalaya show considerable recruitment of seedlings and saplings in the recent decades especially after 1950s. There has not been the reporting of retreating treelines in the region, although some treelines have remained stationary (Gaire *et al.* 2016; Shrestha *et al.* 2014). Soil environment in Himalayan treelines is highly critical for tree recruitment, however as mentioned by Müller *et al.* (2016) such studies are rare in the region. Increased biotic interaction in the treeline ecotone sometimes, outweighs the climatic influence on tree establishment (Liang *et al.* 2016; Schwab *et al.* 2017). Given the rapid warming (maximum temperature trend) in the Himalayan treelines, warming induced drought stress is the most visible impact in association with prolonged early growing season (March–May) drought (Dawadi *et al.* 2013; Liang *et al.* 2014; Panthi *et al.* 2017; Tiwari *et al.* 2017a,b) with strong influence on regeneration in treeline ecotone. Changes in land use patterns, pastoral abandonment, less disturbance in high mountain forest (migration of people to lower valleys) as well as expanding protected area in Nepal Himalaya have greatly modulated treeline dynamics in region. The stand densification by younger individuals could also be the part of succession process in treeline ecotone besides environmental influence. Therefore long term monitoring of forest stands in treeline is immensely important while interpreting treeline dynamics. Further, the lack of long term environmental history (temperature, rain, cloud cover, snow) in the region has made past distribution range of high mountain forests more enigmatic. Further studies focusing on environmental factors, microtopography, soil factors, growing season shift as well as reproductive performance and seed dispersal mechanisms in the treeline are essential to scale up our existing knowledge on treeline dynamics in the Himalayan region.

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Expansion of *Rhododendron campanulatum* krummholz in the treeline ecotone in Tungnath, Garhwal Himalaya

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Abstract: Sensitivity of alpine treeline ecotone to climate change and upward shift of plants due to warming have been reported from many parts of the globe. However, such research in the climate sensitive western Himalaya is still in infancy due to paucity of past climatic and vegetation distribution data to detect the change. In this paper we determined the expansion of *Rhododendron campanulatum* krummholz using seedling population and growth characteristics along an altitudinal transect rummimg from the upper forest limit to treeline ecotone and beyond it in Tungnath (i.e., 3242 m asl), Uttarakhand. In the studied transect (altitudinal gradient of 3511–3665 m asl) in 2017, a total of 17 trees and 36 seedlings of *R. campanulatum* were found growing. Almost half of the trees were devoid of any seedlings around their canopies. Height and circumference at collar height of both the adults and seedlings were positively correlated ($P < 0.05$). Taking the mean distance of seedlings from the mother tree (2.8 m; range = 0.50–4.72 m) and mean age of the seedlings (2–9 yrs; mean = 3.9 yr; reckoned by the number of internodes) the rate of expansion of *R. campanulatum* population was computed about 1.4 m yr^{-1} Occurrence of mature individuals at the mountain top without any seedlings indicates that as no space left for upward movement of plants, the interspaces between the krummholz are being filled by the regenerating individuals. This may leave little grazing grounds for the migratory livestock and change ecosystem properties. It may be further pointed out that due to rise in atmospheric temperature (@ 0.11 °C yr^{-1} in the past two decades) and continued biotic stress of grazing and tree lopping, *R. campanulatum*, a non-palatable species of wider niche width might preponderate at the expense of herbs and other treeline species in future and may bring out compositional changes in treeline vegetation and carbon storage.

Key words: Climatic warming, krummholz expansion, *Rhododendron campanulatum*, seedling population, treeline ecotone, Western Himalaya.

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Introduction

The high altitude limit of forests and trees, commonly known as timberline, and treeline respectively represents one of the most conspicuous vegetation boundaries (Körner 1998). Natural treeline ecotones are sensitive biomonitors of past and recent climate change (CC) and variability (Kullman 1998), and are well suited for monitoring its impact (Becker *et al.* 2007; Kullman 1998). Sensitivity and response of alpine treeline ecotone to climate change (CC) is increasingly being discussed among scientists (Holtmeier 2009), and by the general public (IPCC 2007). Upward shifts of plants due to warming have already been reported from many parts of the globe (Cannone *et al.* 2007; Kelly & Goulden 2008; Schickhoff *et al.* 2015), including Himalayan region (Dubey *et al.* 2003; Gaire *et al.*

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Fig. 1. *R. campanulatum* krummholz beyond the treeline ecotone in Tungnath alpine meadow.

2011; Padma 2014; Panigrahi *et al.* 2010). In Parvati valley, Himachal Pradesh rate of upward movement of Himalayan blue pine (1.9 m yr^{-1} on south and 1.4 m yr^{-1} on north slope) was reported using dendrochronological technique (Dubey *et al.* 2003). In the central Nepal, Gaire *et al.* (2014) reported upward shifting of *Abies spectabilis* (@2.61 m yr^{-1} since 1850 AD); however, they found the upper distribution limit of *Betula utilis* to be stagnant in the past few decades. Liang *et al.* (2011) found little change in the fir (*Abies georgei* var. *smithii*) tree line position in the Tibetan plateau after 200 yrs of warming.

During the last few decades, the Himalayas have experienced approximately 2–3 times greater rise of atmospheric temperature than the global average (Liu & Chen 2000; Shrestha *et al.* 1999; Xu *et al.* 2009), and the increase is greater (0.07 °C yr^{-1}) in winter, than in summer (0.03 °C yr^{-1}) (Shrestha *et al.* 2012). Also, increasing warming rate with altitude, peaking between 4800 m and 6200 m altitudes has been reported (Singh *et al.* 2011; Wolfe 1979). It has been stated that in the face of CC, most ecosystems and landscapes will be impacted through changes in species composition, productivity and biodiversity (Leemans & Eickhout 2004). The Himalayan region presents the highest timberlines and treelines in the world diverse in tree species composition (Shi & Wu 2013). At present, the common thinking is that as a response to rise in atmospheric temperature timberlines are currently advancing to higher altitudes and moving further north (Parmesan & Yohe 2003), thus impacting the species with restricted niche widths and loss of habitats and even species extinction (Subedi 2009). However, there are also many anomalies, due to local and regional conditions (terrain type, orographic influences, herbivory, disease), and the anthropogenic influences (Cairns & Moen 2004), which have been reported as much as over 80% of treelines in Himalayas (Schickhoff 2015). Empirical data, however, based on filed observations is seriously lacking to support or defy the upward movement of plants in the western Himalayan treeline ecotone.

In this study undertaken on *R. campanulatum* krummholz in and around treeline ecotone at Tungnath, Western Himalaya, we have hypothesised that *R. campanulatum* krummholzs are expanding its population (both vertically and laterally), and occupying the space available in the alpine meadow rapidly as an impact of global warming. The specific research issues were: (i) regeneration status (density of seedlings) of *R. campanulatum* beyond the treeline ecotone, and (ii) filling of the interspaces between the krummholz patches by the regenerating *R. campanulatum* seedlings in the alpine meadow.

Fig. 2. *R. campanulatum* seedlings growing about 5 m distance from the mother bush in the Tungnath alpine meadow.

Study area

Details of the study site and vegetation are given in Pradeep Singh *et al.* 2018 (this Issue). *R. campanulatum* is a shrub or small tree or sub-tree (up to 8 m high; referred to as tree hereafter) that bears spectacular bell shaped flowers during April–May, followed by fruiting in June and seed dispersal subsequently (Bisht *et al.* 2014). It is a timberline krummholz (crooked wood) species and provides a biogeographical example of a sub-dominant taxon, which ranges from subalpine to cold temperate zones (Tiwari & Chauhan 2006). It is one of the few species of *Rhododendron* that forms dense, pure stands in the timberline zone of the Central and Western Himalaya (Vetaas 2002). In the study area its density ranges from 360 to 2840 ind./ha; Rai *et al.* 2012), signifying that this species is an important constituent of tree line ecotone. In the study site *R. campanulatum* krummhols are found in isolated patches with 50 m to 500 m gaps between them along the NW slopes (Fig. 1), up to the highest point of Tungnath alpine meadow (3665 masl). In Tungnath, none of the seedlings/saplings of other tree species were found growing in the alpine meadow beyond the treeline ecotone except for the *R. campanulatum* (Fig. 2). It has been reported that rhododendrons may survive global warming *in situ* because of high temperature tolerance, but the long-term effect on their regeneration is uncertain (Vetaas 2002). *R. campanulatum* is not grazed as it is an unpalatable species (Negi *et al.* 1993), so its regeneration status is expected to be largely determined by warming. However, cutting of its mature sticks for fuelwood is rampant due to its inflammable character by the migratory graziers leading to disturbance in its natural growth and succession. Also, heavy grazing at this site has been reported leading to dominance of less palatable herbs and grass species such as *Anemone* spp., *Poa alpina*, *Polygonum* spp., *Ranunculus hirtellus* etc. (Nautiyal *et al.* 2004), which might influence the regeneration of *R. campanulatum*.

Materials and methods

This study was initiated with literature search relating to the distribution of *R. campanulatum* in Tungnath reported by earlier workers. It revealed the highest altitude of occurrence of this species

Fig. 3. Growth mesurements on *R. campanulatum* seedlings in the Tungnath alpine meadow.

(tree species line) at 3500 m asl. June 1977 (Semwal & Gaur 1981), and mature krummholz of this species forming abrupt treeline at 3000 and 3250 m asl. in Tungnath (Sundriyal & Bisht 1988). Thus to investigate the rate of expansion of its population in the interspaces of its krummholz during the time span of past about 40 yrs (taking 1977 as base year following Semwal & Gaur 1981), we placed a vertical belt transect (20 m wide and 150 m long) along a representative slope (altitudinal gradient 3511 to 3666 m asl) representing *R. campanulatum* in NW aspect of Tungnath alpine meadow beyond the treeline ecotone in August 2017. With respect to biotic disturbance (in terms of grazing and cutting of *R. campanulatum* mature shoots) this transect was least disturbed. Census of seedlings (< 15 cm height) was carried out around each of the bushes found within this transect (Fig. 3). This method of belt transect plots (20 m wide and 250 m long), which included treeline as well as tree species limit has also been used in Central Nepal (Gaire *et al.* 2014), and also in western Himalaya using 100 m^2 plots by Dubey *et al.* (2003). Within this transect, measurements on all the trees of *R. campanulatum* and seedlings growing around them were taken for their altitude, height, circumference at collar height (Cch; 10 cm above ground), number of internodes per individual, number of leaves per seedling, etc. A metal measuring tape (0.5 mm least count) and a micrometer (0.1 mm least count) were used to measure the plant height and diameter at collar height (10 cm above ground). Number of internodes (as a proxy of one year growth to determine the age of the plants; one internode = 1 yr age) was counted for these seedlings (Fig. 4). Internode numbers and length have been used as a measure of growth and life span determination of *R. campanulatum* (Barquero 2009), and also other plants (Wills 2003; Zalamea *et al.* 2008). As *R. campanulatum* has a distinct branching pattern with circular swellings formed at the junction (node) of each annual growth increment, the nodes were visible and could be counted from the leader shoot to the base of the main stem to give an estimate of aboveground plant age (Fig. 4). In some instances bark was removed at the swelled spot to verify the presence of nodes. However, after a certain age with increase in stem diameter the internodes are fused with the nodes, thus the number of internodes could be counted only up to a maximum of 9. Counting nodes is a simple non-destructive technique to determine plant age.

Fig. 4. A seedling showing number of nodes (marked with pen 1–7 along the leader shoot).

The number of modules (e.g., internodes, leaves etc.) produced over a plant's life span provides an estimate of its age, thus has been used to determine the age of plants, and has opened the possibility to reconstruct their past growth and dynamics (Taylor & Zisheng 1993). It has been pointed out that age determination using tree ring limits is considered inappropriate for young seedlings (Durate *et al.* 1999). Data for all the measured parameters were pooled for statistical analyses following Snedecor & Cochran (1980).

Results and discussion

In the study altitudinal transect of Tungnath alpine meadow the height of the trees (17 trees recorded) ranged from 0.65 to 2.63 m, circumference from 14 to 30 cm, and number of clumps from 4 to 26 per individual (Table 1). There existed a positive relationship between tree height and circumference ($r = 0.459$; $P < 0.05$). Tree height vs. number of clumps ($r = 0.092$), and altitude vs. tree height ($r = 0.045$) were found weakly negatively correlated. Around these trees a total of 35 seedlings of varying heights (range = 1.6–10.2 cm) were found within a distance ranging from 0.45–4.72 m from the centre of these trees (Table 1). Age of these seedlings (reckoned by number of internodes) ranged from 2 to 9 yrs. Seedling height and circumference were positively correlated ($r = 0.625$; $P < 0.05$). Seedling number vs. altitude was found negatively related ($r = 0.317$; NS), indicating that with increasing altitude cold conditions limit the seed germination and seedlings survival (Tranquillini 1979). No relationship occurred between height of seedling and distance from the tree, and between altitude and age (number of internodes) of the seedlings indicating that *R. campanulatum* did not follow any definite pattern of regeneration that may owe to continued biotic interference. Seedling height and number of leaves/seedling were also found unrelated. Vetaas (2002) reported that extreme chilling temperature limits the survival of *R. campanulatum*. Climate in high altitudes of the western Himalayan region is poorly studied due to logistic difficulties in maintaining observational networks and often supplemented through tree ring studies (Yadav *et al.* 2004).

In ten of the total 17 trees growing towards the higher part (3546–3666 m asl) of the studied transect, only 3 trees were represented by one seedling each, and in the rest of the seven trees no

Table 1. Growth characteristics of mother bushes and seedlings of *R. campanulatum* along an altitudinal gradient in Tungnath alpine meadow (Cch= circumference at collar height).

R. campanulatum krummholz	Altitude (m asl)	Crown length (m)	Crown width (m)	Height (m)	Cch (cm)	No. of clumps	Seedling characteristics				
							Distance from bush (m)	Height (cm)	Diameter (mm)	No. of nodes	No. of leaves
1	3511	4.65	2.70	1.79	30.2	24	0.86	2.80	3.34	4	3
							0.92	1.60	2.45	2	3
							1.43	2.40	2.34	4	2
							1.80	8.30	3.09	9	3
							1.81	3.50	4.17	5	3
							1.83	3.00	4.25	4	3
							1.87	2.00	3.93	2	2
							0.68	10.00	7.61	7	3
2	3522	3.00	3.20	1.04	23.2	18	-	-	-	-	-
3	3534	3.64	2.45	1.35	20.5	13	-	-	-	-	-
4	3534	2.34	1.93	1.32	20.0	9	2.96	2.90	2.56	4	2
5	3539	5.02	4.05	1.45	20.1	9	0.80	1.80	2.00	2	3
							0.83	1.50	1.00	2	3
							1.00	3.60	2.63	4	3
							1.00	2.40	2.21	3	4
							2.42	4.90	3.65	4	3
							2.45	2.00	1.04	2	3
							2.20	2.90	2.49	4	2
							2.40	1.80	2.41	2	2
							3.14	2.80	2.00	2	5
							3.39	3.00	2.59	3	3
							3.15	5.13	5.03	3	4
							3.10	2.80	2.45	3	2
							2.99	2.60	4.00	4	3
							2.99	2.10	2.60	2	3
							4.72	3.40	3.22	4	3
							4.72	3.50	3.42	5	3
6	3543	1.51	1.09	1.06	14.3	9	0.50	5.00	4.87	6	3
							0.70	3.00	4.35	4	2
							0.71	3.50	4.81	5	5
							0.63	10.2	6.56	6	3
7	3546	2.30	1.70	1.14	15.2	9	0.45	2.70	3.30	3	4
							0.47	6.00	4.68	5	3
							3.92	8.60	6.21	6	3
8	3546	3.20	1.25	2.05	29.2	7	-	-	-	-	-
9	3546	2.80	1.70	2.10	23.0	6	-	-	-	-	-
10	3550	2.72	0.98	2.60	19.1	4	-	-	-	-	-
11	3574	2.74	1.36	2.08	35.2	17	-	-	-	-	-
12	3601	2.01	1.37	2.02	28.1	13	-	-	-	-	-
13	3604	2.23	1.15	0.97	18.0	7	-	-	-	-	-
14	3610	3.09	1.13	2.63	36.2	12	3.67	6.50	5.27	6	4
15	3630	1.60	1.01	1.20	25.2	18	4.64	5.50	4.86	3	5
16	3642	1.92	1.31	1.12	21.3	26	26.00	4.00	2.46	4	3
17	3666	0.93	0.65	0.65	15.0	19	-	-	-	-	-

seedlings were found under their canopy (Table 1). In contrast, some of the trees growing towards the lower altitude of the studied transect were represented by fairly high number of seedlings (max. 16) around them, and that requires to be studied to understand their reproductive success. Taking the mean distance of seedlings from the tree (2.8 m) and mean age of the seedling 3.9 yr (reckoned by the number of internodes) the rate of expansion of *R. campanulatum* population can be computed about 1.4 m yr^{-1}. This rate of expansion computed by us is comparable to the rate of upward movement of treeline for Himalayan blue pine (1.9 m yr^{-1} on south and 1.4 m yr^{-1} on north slope) reported by Dubey *et al.* (2003) in Parvati Valley, Himachal Pradesh and 2.61 m yr^{-1} for *Abies spectabilis* in Nepal Himalaya (Gaire *et al.* 2014) using dendrochronological study. For the endemic herbs of alpine region of Sikkim Himalaya, the rate of range shift has been reported 2.75 m yr^{-1} (Telwala *et al.* 2013). Considering the altitude of occurrence of this species at 3500 m asl. in June 1977 reported by Semwal & Gaur (1981), and the highest altitude of its occurrence in 2017 (i.e., 3665 m asl), it turns out that in an interval of about 40 yrs. (between 1977 and 2017) this species has moved up about 165 m @ 4.1 m yr^{-1}. However, it may be pointed out that Semwal & Gaur (1981) might have recorded only *R. campanulatum* bushes visible from a distance and ignored the seedlings/saplings, which have grown up now to a mature bush stage. In the Santa Rosa Mountains of Southern California, Kelly & Goulden (2008) reported that the average elevation of the dominant plant species rose by ~ 65 m between 1977 and 2006–07 @ 2.2 m yr^{-1} along a 2314 m elevation gradient. Dendrochronological study in the treeline of high mountains of central Nepal Himalaya for dominant trees *Abies spectabilis* and *Betula utilis* since AD 1850 show that due to species-specific responses to CC differential pattern in regeneration and population is anticipated as climate continues to change throughout the century (Gaire *et al.* 2014).

The occurrence of only one tree at the top of Tungnath (3665 m asl) without any seedling in its vicinity, points out that this quite old tree (number of clumps, 19; but height only 0.65 m) had no further space left to recruit the seedling and regenerate even if temperature rise provided favourable conditions for growth. Looking at the climatic data of 1990–97 (mean = 9.0 °C) recorded during peak growing season (July–September) at this site by Nautiyal *et al.* (2001) as compared to that recorded during July–September 2017 (mean = 11.2 °C; Joshi *et al.* this issue) indicates that substantial rise in atmospheric temperature (@ 0.11 °C yr^{-1}; about twice than reported for the Himalayan mountains, Singh *et al.* 2012) has been taken place in the past over 20 yrs and it may have promoted the regeneration and expansion of *R. campanulatum* population.

Conclusion

R. campanulatum is expanding in the interspaces of krummholzs both vertically and laterally and may occupy the alpine meadow in future under the influence of global warming. It may result in species loss as well as reduction in organic carbon layer (Speed *et al.* 2015). Preponderance and densification of this non-palatable species is expected in Tungnath at the expense of other treeline species, such as *Abies spectabilis, Betula utilis* and *Quercus semecarpifolia*, which are grazed by the migratory livestock. Therefore, long-term monitoring of treeline is important for understanding the future directions of compositional changes in the vegetation of treeline ecotone to have a clear mechanistic understanding to predict the potential impacts and changes by human activities in this fragile and eco-sensitive western Himalayan region (Negi *et al.* 2012).

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Treeline species phenology: shoot growth, leaf characteristics and nutrient dynamics

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Abstract: In this study on treeline phenology in Tungnath, Garhwal Himalaya (altitude, 2955–3334 m asl), we (i) collected data on micro-climatic conditions, timing of major phenophases, leaf and shoot growth phenology and leaf nitrogen resorption in four major tree species (*Abies spectabilis, Betula utilis, Quercus semecarpifolia, Rhododendron arboreum*) and a krummholz species (*R. campanulatum*); and (ii) compared the treeline species phenology with mid-altitude forest tree species phenology of this region. Meteorological data reported for this site revealed that the mean monthly atmospheric temperature during growing period (July–September) has increased at the rate of 0.11 °C yr^{-1} in the last two decades. Leaf bud-break occurred in all the species in May, however, the proportion of marked tree population in bud-break phase at the time of first observation in May varied considerably across the species from 10% in *Q. semecarpifolia* to 50% in *R. arboreum.* Leaf initiation and leafing in the treeline species was delayed by about two months, compared to the mid-altitude tree species. Also, the leaf expansion within one month of leafing was conspicuously slower in treeline species than mid-altitude species (43% vs. 83% in *Quercus* spp. and 49% vs. 76% in *R. arboreum*). The treeline species were characterized by short growing period (2–4 months), lower period of steady-state in peak leaf mass and rapid leaf mass loss, low nitrogen concentration in leaves (1.7% vs. 2.5%), slow shoot growth, lower shoot length (5.6 cm vs. 9.5 cm) and shoot growth period, and higher leaf density in shoots (1.2 vs. 0.8 leaves cm^{-1} shoot length) than the mid-altitude forest trees. It is expected that with the increasing rate of warming in Tungnath the phenological behaviour of treeline species would change markedly in future leading to changes in ecosystem properties.

Key words: *Betula utilis*, Garhwal Himalaya, leaf nutrients, phenology, *Rhododendron campanulatum*, treeline ecotone, tree growth forms.

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Introduction

Climatically, the Himalayas are predicted to experience a rise in temperature of 5–6 °C, and precipitation increases of 20–30% by the end of the twenty-first century (Kohler & Maselli 2009; Solomon *et al.* 2007), making them among the most threatened non-polar regions of the world. Treeline ecotones are sensitive biomonitors of past and recent climate change (CC) and variability (Kullman 1998), and are well suited for monitoring CC impact (Becker *et al.* 2007; Kullman 1998). The short growing season, snowfall, low air and soil temperature, high exposure to wind, increased exposure to frost and lower availability of nutrients are some of the common features of high altitude regions, which greatly influence plant phenophases and vegetation growth (Germino 2014; Körner 2012). Treelines are considered to be constrained primarily by heat deficiency (Holtmeier 2009; Körner & Paulsen 2004). Both winter and summer temperatures are considered as accurate predictors of occurrence of phenophases (Galan *et al.* 2005; Schwartz 1999; Spano *et al.* 1999; Sparks & Carey

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1995). For the Himalayan region, our knowledge is grossly inadequate on the relationships of the treelines to other ecological conditions and processes, such as meteorological conditions, freezing and frost, drought, soil temperature, wind, snow cover, soil quality, regeneration and other aspects (Schickhoff *et al.* 2015). In recent years, however, some progress has been made on the growth responses of plants to ongoing global warming (Gaire *et al.* 2014; Cui *et al.* 1999; Shrestha *et al.* 2012).

The alpine treeline represents not only a dramatic change in physiognomy, but also an important ecosystem with unique and rich biodiversity (Singh 2017). A few preliminary studies have shown that plant growth and phenophases here are triggered with the occurrence of favourable temperature, snow melt and consequent soil water availability (Nautiyal *et al.* 2001; Negi *et al.* 1992; Ram 1988; Sundriyal *et al.* 1987). Rai *et al.* (2013) have reported that *B. utilis* is highly sensitive to interannual climatic variations and early snowmelt. Liang *et al.* (2014) reported that Himalayan birch at its upper distribution boundary is increasingly at risk of survival. Uniyal & Uniyal (2009) reported that rising temperature during winter leads to increased activities and range expansion of pests in *Picea smithiana* in west Himalaya. In Tibetan plateau, Yu *et al.* (2010) have reported that strong winter warming could slow the fulfillment of chilling requirements, which may delay spring phenology. Phenological shifts (e.g., flowering time, its duration, and synchrony) may affect the interactions of plants with their pollinators and seed dispersers, hence reproductive success and growth of plants. In the mid-elevation forests of this region and other parts of the Himalaya there is growing evidence to show that CC has already induced changes in flowering phenology of trees (viz., *Rhododendron* spp.) (Gaira *et al.* 2014), and alpine herbs (Telwala *et al.* 2013). However, only a few such studies are available on the trees of timberline ecotone of the western Himalaya (Mir *et al.* 2016; Rai *et al.* 2012; Rawal *et al.* 1991).

Trees in seasonal climates often experience major water deficiency, and their physiology and phenology reflect the seasonality of moisture deficits. Soil moisture patterns within treeline ecotones are less frequently documented, but are supposed to be important drivers of treeline formation, and strongly influenced by moisture seasonality (González de Andrés *et al.* 2015). Tree growth may be constrained by lower water availability due to insufficient snow cover and frozen soils in spring (Balducci *et al.* 2013). Abiotic factors other than temperature, including water availability may serve as other important controls at high elevations, particularly for seedlings (*Picea engelmannii*) (Gill *et al.* 2015). Flower bud expansion and shoot growth involving cell expansion are known to be inhibited by even moderate water deficit. Soil temperature has been found to be the factor with similar importance for tree growth, both at a global and a local scale (Muller *et al.* 2016). It is known to impede photosynthesis (Dong *et al.* 2011), and biological activity in soil (< 5 °C), hence the nutrient supply (Holtmeier 2009; Körner 2012). Examination of soil and foliar nutrients is thus essential as trees are assumed to not being able to use obviously sufficient nutrients for growth as a result of low soil temperature. Several studies have assessed lower N cycling rates and contents in treeline soils, as well as lower foliar N in treeline trees compared to soil at lower altitude (Müller *et al.* 2016). In the nutrient-poor environment, protection against leaching, effective nutrient resorption from senescing plant organs, and high nutrient-use efficiency through long leaf life-span are regarded as important nutrient conservation strategies (Freschet *et al.* 2010). Thus measurements of soil temperature and moisture and related climatic and vegetation variables at high altitudes are required to understand the complexity and adaptations of the alpine ecosystems to CC (Liu & Luo 2011).

Objectives of the study were to: (i) collect first-hand data on various micro-climatic, phenological and leaf nitrogen aspects of treeline ecotone species varying in growth forms; (ii) determine phenological differences of treeline species with those of the mid-altitude (2000–2200 m asl) forest trees; (iii) find out phenological response of treeline species to global warming; and (iv) compare western Himalayan treeline ecotone with the alpine treelines of other parts of the world.

Study area description

Here, we have documented phenology of treeline ecotone species of Garhwal Himalaya in relation to treeline environment and compared its features with mid-elevation tree species phenology. The treeline species were highly diverse in growth forms ranging from *Abies spectabilis* (evergreen conifer with multi-year leaf life-span), *Betula utilis* (winter deciduous broadleaf), *Quercus semecarpifolia* (semi-evergreen broadleaf), *Rhododendron arboreum* (evergreen broadleaf) and *R. campanu-*

Table 1. Study species in Chopta-Tungnath treeline ecotone. All occurred on North-West aspect, except *B. utilis* which occupied N-E aspect.

Species	Altitudinal range (m asl)	Physiognomy
Q. semecarpifolia	2955–3085	Brown Oak; Evergreen with 1 year leaf life-span
R. arboreum	2965–3233	Tree Rhododendron; Evergreen with leaf life-span between 1 and 2 years
A. spectabilis	2990–3276	Himalayan Fir; Evergreen with multi-year leaves
B. utilis	3250–3280	Himalayan Birch; Winter deciduous
R. campanulatum	3250–3334	Simru; Evergreen shrub (krummholz) with leaf life-span between 1 and 2 years

Fig. 1. Trees marked (1–100 nos.) in each five forest types for phenological observations (Above), and micro-climatic measurements under each forest stands (Below).

latum (evergreen krummholz species) (details given in Table 1), and phenological features considered were vegetative bud-break and shoot extension, leafing and leaf population dynamics, leaf expansion, leaf mass changes, flowering, fruiting and leaf drop. Leaf nitrogen dynamics and nitrogen resorption by leaves were also investigated.

The study was carried out at Chopta-Tungnath (Lat. 30.49', Long. 79.21', Alt. 2955–3334 m asl), located in Uttarakhand Himalaya (Fig. 1; Table 1). Mean monthly temperature at this site during the study year (2017) was 6.2 °C (mean max. = 10.1 °C and mean min. = 3.4 °C), and the annual rainfall in 2017 was 3800 mm, of which ~ 94% was recorded during June-September, the typical monsoon months (Joshi *et al.* 2018). Generally, the mean annual rainfall at this site is 2411 mm (mean value of 2008–2010) (Rai *et al.* 2012). However, 2017 was an unusually wet year. December onwards the site remains under snow for varying periods with mean duration being 85 ± 22.7 days yr^{-1} (Rai *et al.* 2012). At Tungnath, the mean highest sunlight intensity has been reported 79,200 Lux at 12 noon in May, and the least, 2,500 Lux at 12 noon in September (Nautiyal *et al.* 2001). The sunshine is often limiting at this site during monsoon period. In Tungnath, the weathering bedrocks, that provide the bulk of the loose material to soil pool, are crystalline and

Table 2. Mean values of microclimatic parameters during the study period (June to November, 2017).

Forest stand	Mean altitude (masl)	Air temperature (°C)	Soil temperature (°C)	Soil moisture (%)	Atmospheric humidity (%)
Q. semecarpifolia	3020	14.60 ± 1.23	10.30 ± 0.74	20.24 ± 1.40	79.30 ± 3.20
R. arboreum	3099	13.85 ± 2.01	10.10 ± 0.92	17.40 ± 1.97	76.72 ± 3.04
A. sepctabilis	3133	14.30 ± 1.20	10.10 ± 0.73	20.48 ± 1.93	76.58 ± 3.23
B. utilis	3265	12.03 ± 1.21	8.25 ± 0.720	20.23 ± 1.61	77.72 ± 2.72
R. campanulatum	3292	14.40 ± 1.20	10.10 ± 1.00	20.23 ± 1.97	74.60 ± 2.74

metamorphic, with sedimentary deposits of Paleozoic age (Gansser 1964). Soil is sandy loam in texture and acidic with pH between 4.9 and 5.6 (Nautiyal *et al.* 2001).

In the study area forests of *Abies spectabilis* and *Betula utilis* occur on north facing slopes and *Quercus semecarpifolia* and *Rhododendron arboreum* on south facing slopes, with tree associates viz., *Acer caesium, Prunus cornuta, R. barbatum, Sorbus foliolosa* and *Taxus wallichiana* (Adhikari *et al.* 2011). The *R. campanulatum* krummholz formation is common at the site; its seedlings/ saplings grow up to 3,666 m asl (Tungnath peak). None of the other tree species had recruited seedlings/saplings beyond the treeline at 3280 m asl. at this site except for *R. campanulatum* (Rai *et al.* 2012 and our observations).

The alpine meadow beyond the treeline in Tungnath is rich in herbs with 171 species of 5 different growth forms (Nautiyal *et al.* 2001). Tungnath is under varying levels of anthropogenic disturbance with regard to lopping of trees for fuelwood (used in local shops near Tungnath temple during tourist season) and fodder and grazing / browsing, especially by cattle almost during the entire snow-free period that has brought out negative effect on the meadow plants and tree regeneration and growth of under canopy species (Nautiyal *et al.* 2004).

Methods

Mature stands of four tree line ecotone tree species viz., *A. spectabilis* (Himalayan fir; evergreen conifer with multi-year leaf life-span), *B. utilis* (Himalayan birch; winter deciduous), *Q. semecarpifolia* (brown oak; semi-evergreen), *R. arboreum* (tree rhododendron, evergreen) and *R. campanulatum* (evergreen krummholz species) distributed between 2,955 and 3,334 m asl (the upper limit of distribution of these species) were selected for the study (Table 1). Forest stand-specific *in-situ* micro-climatic data (air tempe-rature, atmospheric humidity, soil temperature and soil moisture) were recorded at a monthly interval amidst the marked stands for each of these five species from May to December 2017. Data on air temperature, humidity and soil temperature (30 cm depth) were recorded three times a day (10 AM–5 PM) with three replications each time. Soil moisture was measured gravimetrically by oven drying the soil samples collected from each of the forest stands at monthly interval from 30 cm depth. To determine soil organic carbon and total nitrogen (N), composite soil samples collected from 30 cm depth were analyzed using CHNS analyzer (Elementar Co.).

Phenological observations on various phenophases (viz., vegetative bud-break and shoot emergence, leafing, flowering, fruiting and leaf drop) were made on the above mentioned five species at monthly interval starting from June–December 2017. We wanted to sample more frequently, but the remoteness of the site and logistics was a problem. We compensated for this by keeping sample size large. For phenological records a representative forest stand of 1 ha for each of the five species was selected and 100 mature individuals of each species were marked (for *B. utilis* only 70 trees were available) (Fig. 1). Shoot extension and radial growth were measured at monthly interval on 25 marked current year shoots for each of the tree species. Leaf characters (leaf area and leaf mass) were based on 100 randomly plucked current year leaves from the marked forest stands. Leaf area was recorded using a portable leaf area meter (Biovis LeafAv). These leaves were then oven dried at 60 °C till constant weight and ground in a Wiley Mill and the leaf material was stored in airtight glass vials and subsequently analyzed for total N in CHNS Analyzer (Elementar Co.). Leaf mass loss (an indicator of senescence) was computed as: mature leaf mass − senescent leaf mass, and expressed in terms of percentage to mature leaf mass. Nutrient resorption efficiency (RE, %) was calculated as the ratio of the difference in N mass between mature leaf and senescent leaf stage. In the N resorption study, leaf N leaching

Table 3. Organic carbon, total nitrogen and C:N ratio in soil of Tungnath treeline forests.

Species	Soil organic carbon (%)	Soil Nitrogen (%)	C:N ratio
R. arboreum	6.4 ± 0.7	0.55 ± 0.06	11.7
Q. semecarpifolia	7.4 ± 0.9	0.60 ± 0.08	12.3
A. spectabilis	6.7 ± 0.8	0.53 ± 0.05	12.6
R. campanulatum	5.4 ± 0.5	0.44 ± 0.04	12.3
B. utilis	5.4 ± 0.3	0.37 ± 0.02	14.6

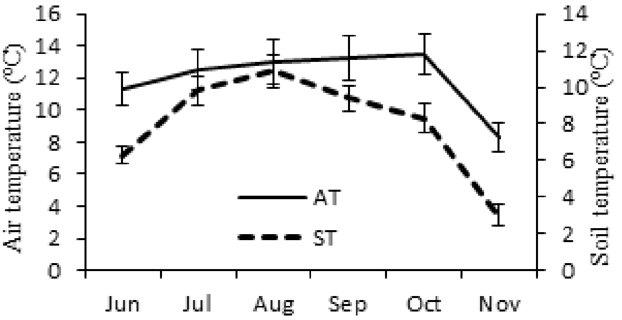

Fig. 2. Air and soil temperature across the study period in *B. utilis* forest stands in 2017.

could not be considered, that makes a negligible part compared to resorption (Freschet *et al.* 2010).

Results

Microclimatic variations among the forests

Mean values of various micro-climatic parameters across the study period varied only marginally among the five study sites (Table 2). The mean air temperature and soil temperature in forests decreased with elevation; being the highest in *Q. semecarpifolia* forest and lowest in *B. utilis* forest, and soil on average was nearly 4 °C cooler than air (Table 2). Among the study sites, *B. utilis* forest site was distinctly cooler (both air and soil temperature) than others. The soil of *R. arboreum* site was relatively drier. During rainy season the difference between soil and air temperatures tended to narrow down as soil warmed up more than the air, where after it widened in autumn because of the rapid cooling-off of soil than air (illustration of this trend for *B. utilis* is given in Fig. 2).

The peak air temperature was recorded in August for two species, and in September for the rest three species, and peak soil temperature was recorded in August for all the five species. Peak soil moisture was recorded in July for all the species except for *R. campanulatum* (August) and it declined in the following months. Peak values of relative humidity were recorded in August for all the species. The air and soil temperatures were positively correlated (r = 0.789; $P < 0.01$) and the atmospheric temperature and relative humidity were inversely related (non-significant).

Soil nutrients

Mean annual total soil nitrogen in the treeline forests of Tungnath varied from 0.37% to 0.60%, soil organic carbon from 5.4% to 7.4% and C:N ratio from 11.7 to 14.6 (Table 3). In general, soil carbon and soil N tended to decrease with elevation, while C:N ratio tended to increase with elevation, being the highest (14.6) in *B. utilis* forest.

Major phenophases

The occurrence of different phenophases in the five species during the study period is shown in Fig. 3. Leaf bud-break occurred in all the species in May, however, the proportion of total bud break (out of 100 marked trees) that occurred in May varied widely from 10% in *Q. semecarpifolia* to 50% in *R. arboreum*. Leafing was a rapid activity in *R. arboreum* (2 months) and extended activity in *Q. semecarpifolia* (4 months). Leaf drop started earlier in *B. utilis* and *Q. semecarpifolia* in September and October, and by November *B. utilis* trees become leafless. In all the other three species (*A. spectabilis*; an evergreen species with multi-year leaf life-span, and the two *Rhododendron* species with leaf life-span more than one year) previous year (2016) leaves dropped continuously throughout the growing season of 2017, that stopped in August 2017. Again, leaf drop of previous year leaf population started from November onward and continued until next spring (March–April). Flowering occurred in all the species during April-May, except for *B. utilis* (October). It was soon followed by fruiting and fruit maturation in all the species that continued for 3–4 months (Fig. 3).

Phenology of leaf and shoot growth

In all the species leafing and shoot elongation continued from bud-break until September (Fig. 4),

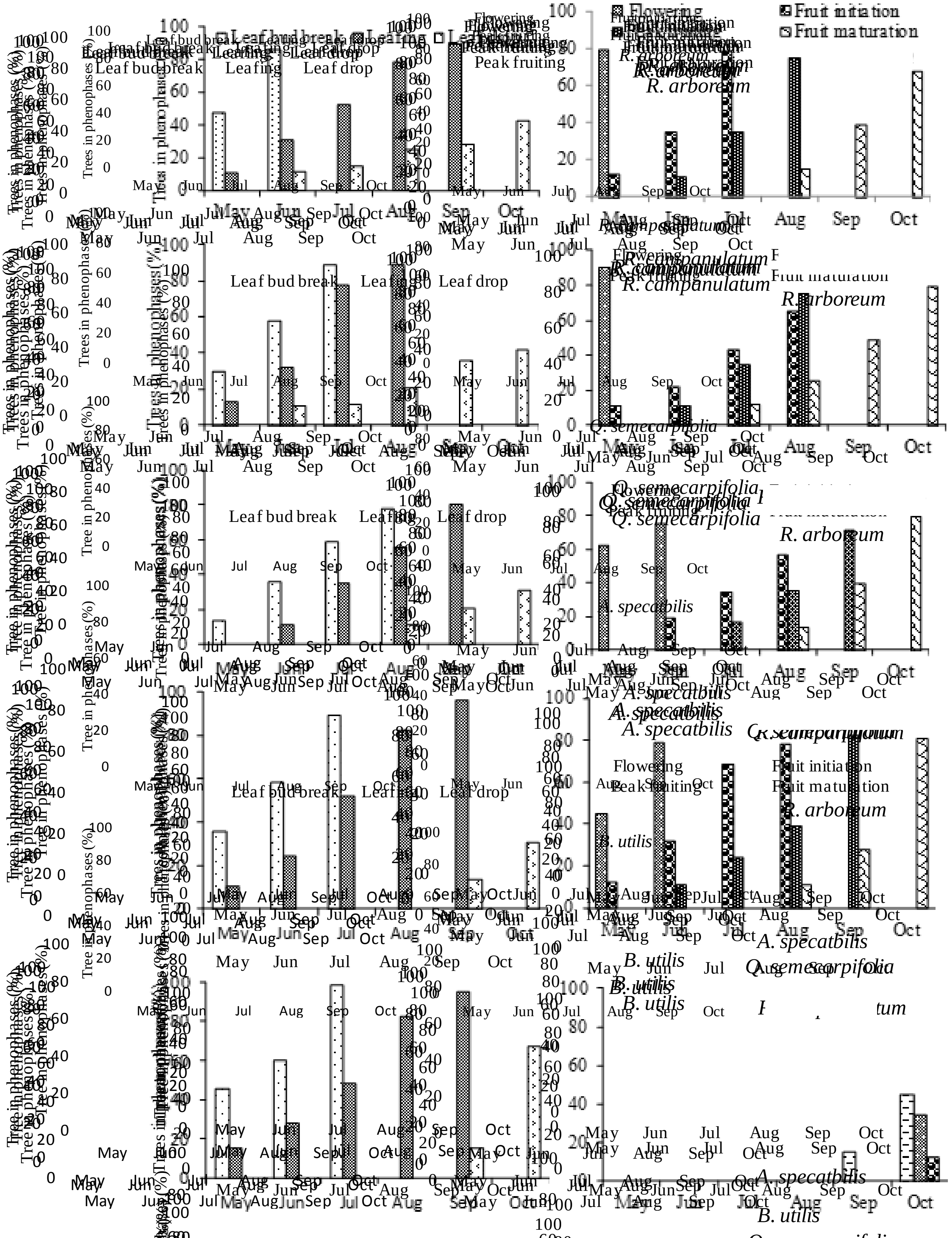

Fig. 3. Phenological events in different forest trees species expressed as % of 100 marked individuals of each species in 20[illegible].

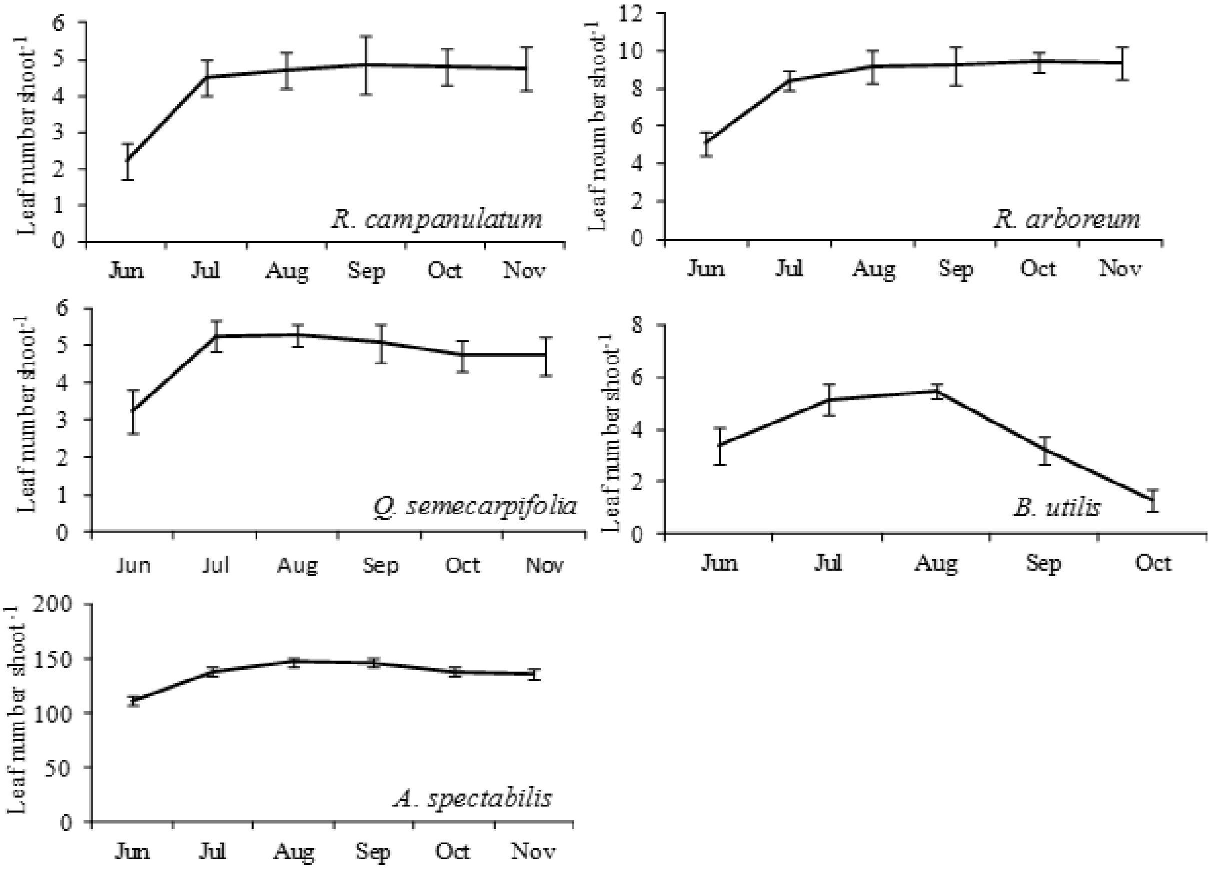

Fig. 4. Number of leaves per shoot in different species in 2017.

however, > 80% shoot extension was attained by July in all the species. Thus much of the canopy was restored by the commencement of monsoon. At the full extension, the shoot length ranged between 4.6 cm in *R. campanulatum* and 13.5 cm in *B. utilis*. The radial growth at full extension of shoot was found ranging from 2.5 mm (*B. utilis*) to 7.5 mm (*R. arboreum*). Leaf number per shoot (current year leaf crop) at mature stage ranged from 4.9 (*R. campanulatum*) to a maximum of 9.4 (*Q. semecarpifolia*). In *A. spectabilis* it was 147.3 needles/shoot. Leaf density (no. of leaves cm^{-1} shoot length) ranged from 0.37 (*B. utilis*) to 13.3 (*A. spectabilis*).

Leaf expansion took place rapidly in the initial months of leaf formation and attained peak in August in all the species except for *R. campanulatum* in which it continued until September (Fig. 5). Here, it can be stated that as the leaf area measurements were based on 100 leaves (randomly collected at monthly interval from the marked population of current year leaf crop), full expansion of leaves could be considered when the leaves had attained ~90% of the leaf area on a leaf population basis. Peak leaf area (cm^2 leaf^{-1}) ranged from 0.29 cm^2 (*A. spectabilis*; a conifer) to 64.8 cm^2 (*R. campanulatum*). Time taken to attain peak leaf area was three-four months (except for two months in *B. utilis*). Corresponding to leaf area, gain in leaf mass was rapid in the initial months of leaf formation (Fig. 5). The time when full leaf mass was attained ranged from August in *Q. semecarpifolia* to October in *R. campanulatum*. At the mature leaf stage the leaf dry weight (g leaf^{-1}) was measured lowest for *A. spectabilis* (0.008 g) and highest for *R. campanulatum* (1.37 g). In most of the species leaf mass loss started as early as in August-September except for *R. campanulatum*. Leaf mass loss ranged from 25.3% (*R. arboreum*) to 42.0% (*B. utilis*) (Fig. 5).

Leaf N dynamics

Mean values of leaf N concentration and leaf N mass are depicted in Fig. 6. At the bud-break stage leaf N concentration was maximum in all the species, which declined with the expansion and gain

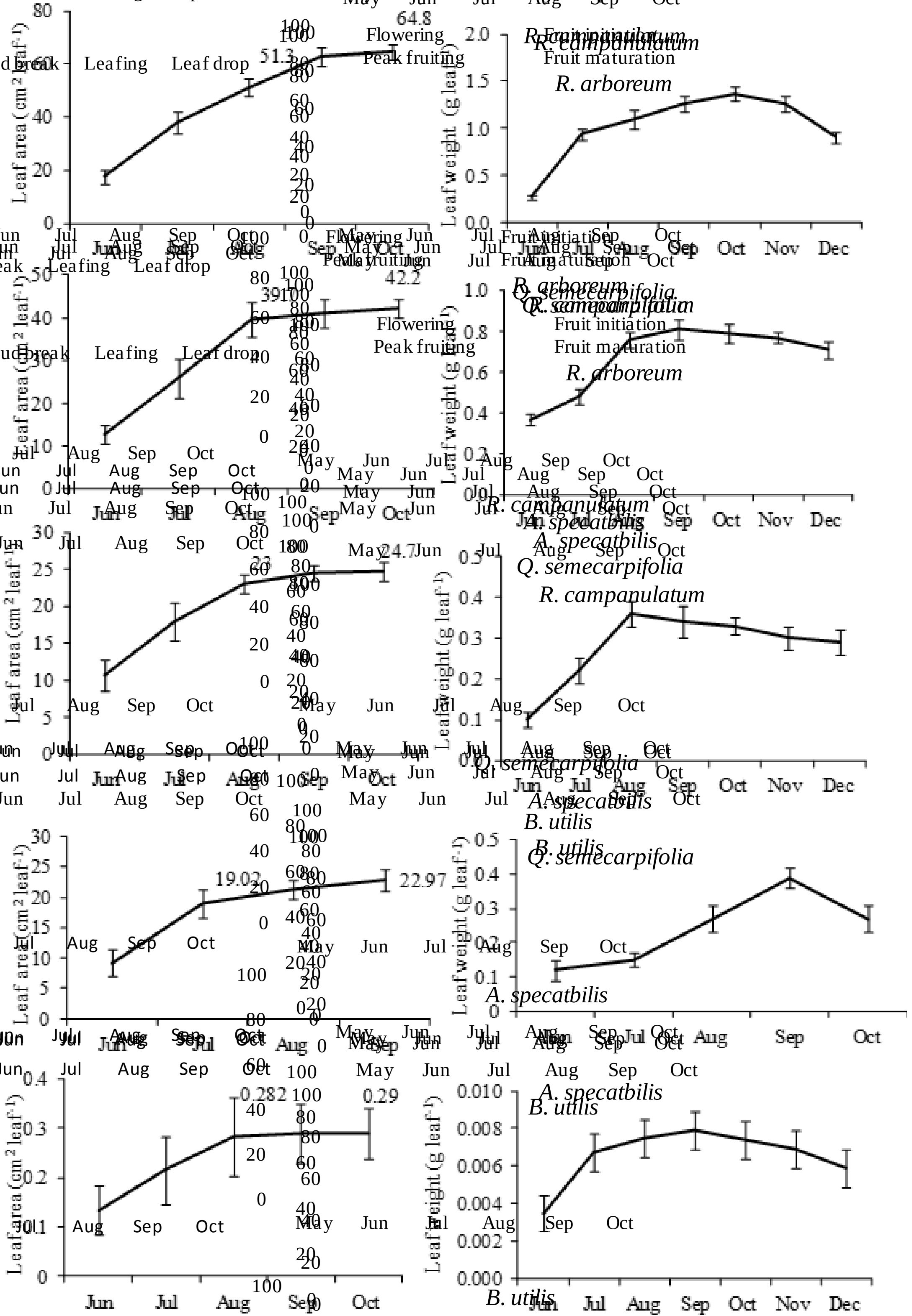

Fig. 5. Leaf area (cm² leaf⁻¹) and leaf weight (g leaf⁻¹) in relation to growing period for different species in 2017. Mean leaf area at fullest expansion (~90%) in August and at the end of the observation in October is given in figures over the line diagram (Left side).

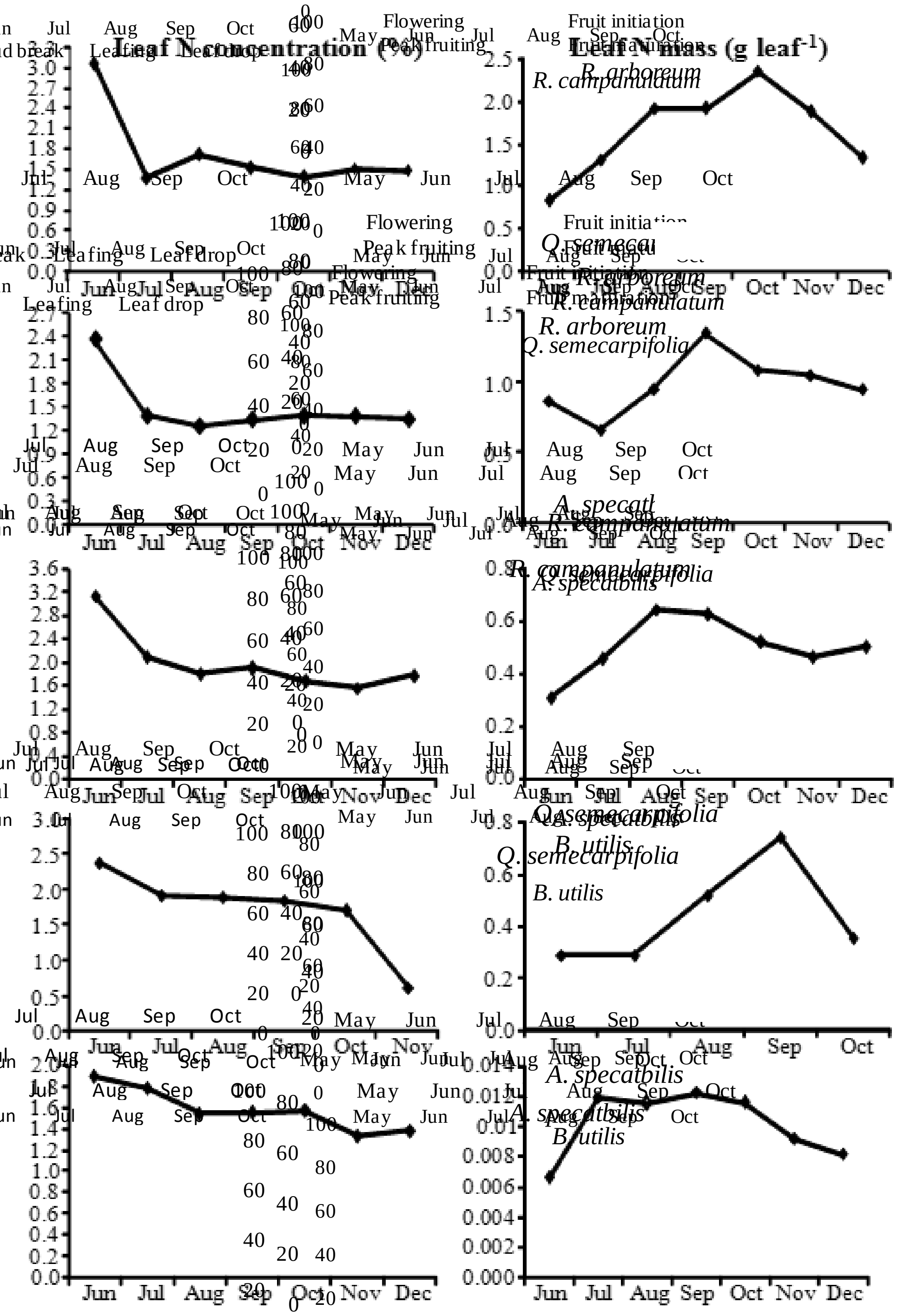

Fig. 6. Leaf nitrogen dynamics of different studied species (Left: leaf N concentration, %; Right: leaf N mass, g leaf^{-1}).

in mass of leaves. At mature leaf stage (steady-state in leaf mass) leaf N concentration varied from 1.53% (*R. campanulatum*) to 1.89% (*Q. semecarpifolia*). The phase of peak leaf N concentration was followed by a gradual decline until the leaf drop. At the senescent stage leaf N concentration varied from 0.63% (*B. utilis*) to 1.3% (*A. spectabilis* and *Q. semecarpifolia*). In terms of leaf N mass all the species attained peak leaf N mass by September, except for August in *Q. semecarpifolia* (Fig. 6). Across the species peak leaf N mass varied from 0.012 g leaf^{-1} in *A. spectabilis* to

Table 4. Atmospheric temperature recorded for Tungnath by various workers. (-) Data not available.

Year of measurement	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Growing season mean (Jul –Sept.)	Reference
1985–86	6.3	11.1	15.9	14.4	12.9	7.4	5.6	-	-	11.6	Ram *et al.* (1989)
1985–86	-	-	-	12.3	12.0	9.0	7.2	-	-	11.1	Sundriyal *et al.* (1987)
1990–97	-	10.0	12.0	10.0	9.0	8.0	7.0	-	-	9.0	Nautiyal *et al.* (2001)
2008–10	7.0	8.0	11.0	12.0	11.5	9.0	7.0	4.0	1.0	10.8	Rai *et al.* (2012)
2017	6.7	8.09	10.2	11.7	11.7	10.1	6.4	2.6	-	11.2	Joshi *et al.* (2018)
2017 (Day time)	-	-	12.8	13.9	16.0	15.8	13.2	-	-	15.2	Present study

1.93 g leaf^{-1} in *R. campanulatum*. N mass resorption efficiency at the stage of leaf senescence was computed ranging from 34% in *A. spectabilis* to 63% in *R. arboreum*. Leaf N mass was steady for only a short period, except in *A. spectabilis*, *R. arboreum* and *R. campanulatum*.

Discussion

This study on phenology, leaf and nitrogen dynamics in forests of varying growth forms in a treeline ecotone of western Himalaya has generated some first-hand data in this least investigated and “data-deficient” system of the Himalayan region. In all the five species studied the onset of growth (vegetative bud-break and leafing) occurred in the first week of May, however, the number of trees (out of 100 marked trees of each species) in the bud-break phase varied from one species to other. In tree stands of *R. arboreum* occupying the lower limit of the ecotone (2965–3233 m asl) about 50% marked tree individuals exhibited bud-break in May compared to 25% in *R. campanulatum* growing at the higher altitudes (3250–3334 m asl) in Tungnath. However, it was quite possible that bud-break in some species might have initiated before May when the site was inaccessible because of snow cover. For this study site, Rai *et al.* (2013) have reported 102 ± 11.5 Julian day (April first week), the average date of bud-break, and appearance of first leaf on 111 ± 14 JD (mid-April) in *B. utilis*. In the dominant trees (both evergreen and deciduous species including *Quercus* spp. and *Rhododendron arboreum*) of mid-altitude (2000–2200 m asl) zone of this region peak leafing (~90% new leaf crop in trees) is accomplished by the end of April–early May (Negi 2006). The mid-altitude tree species are also characterized by concentrated leafdrop during March–April. Thus, in the treeline ecotone species leafing and accomplishment of full leaf canopy were delayed by about two months as compared to the mid-altitude tree species. A similar delay in treeline ecotone occurred in the time of the highest temperature that occurs in August in Tungnath, and during June in mid-altitude forests. Also, in the evergreen treeline species peak leaf drop occurred during May–June. However, during October-November due to heavy frost and cold winds some leaf drop was recorded in these species. In the Tibetan Plateau, Yu *et al.* (2010) reported that winter and spring warming has resulted in delayed spring phenology. In our study site mean atmospheric temperature for growing period (July–September) has increased by about 1 °C (@ 0.11 °C yr^{-1}) during the last two decades (between 1990–97 and 2017; Table 4). The excessive wet conditions of the year 2017 (annual rainfall= 3800 mm vs. 2410 mm in 2009–10; Adhikari *et al.* 2011) may have prolonged the active growth period.

R. campanulatum krummholzs differ from other treeline species with respect to a slower rate of leafing and simultaneous and prolonged drop of previous year leaves that occurred from June to December. In respect to leafing and leaf drop, it resembled more with *R. arboreum*; a species of tree rhododendron also found in the mid-altitude forests in this region (Negi 1989). Leaf area and leaf mass of *R. campanulatum* were highest among all the species, and its lower specific leaf area indicated that the leaves were thicker than other species possibly to escape from the stressful conditions of high altitudes (Körner 2012). The krummholz stands were particularly characterized by relatively lower relative humidity and more atmospheric temperature during day time as the stands occurred in open meadows with abundant wind flow.

A comparison of leaf and shoot growth characteristics with the *Quercus* spp. and *R. arboreum* of the mid-altitude forests of this region reveals that the bud-break and leafing takes place about four-six weeks earlier than in conspecifics at Tungnath site (Negi 2006). Also, the leaf expansion within one month of leafing was conspicuously greater in these species of mid-altitudes (83% vs. 43% in *Quercus* spp. and 76% vs. 49% in *R. arboreum*). These observations quantify the limiting effect of heat deficiency in treelines. Leaf area of *R. arboreum* at these sites was almost equal indicating that the difference of temperature in this species results in delay in phenophases, but not in leaf size. Leaf size depends on several other factors, particularly sunlight (James & Bell 2000). A lower shoot extension period (2–5 months vs. 4–6 months) and lower shoot extension growth at the treeline ecotone for *Quercus* spp. and *R. arboreum* than at the mid-altitude site (mean shoot length= 5.6 cm vs. 9.5 cm) was the other striking feature of shoot growth phenology. In terms of leaf number per cm shoot length, leaves were distantly placed in mid-altitude species as compared to densely packed leaves along shoot length in treeline species (0.8 vs.1.2 leaves/cm shoot length). It implies temperature control over the growth of plants in alpine environment (Tranquillini 1979) and warming is expected to increase growth in treeline ecotone.

Phenological events are constrained at high altitudes by the short growing season delimited by cold temperatures and snow cover. The time of snowmelt appears to have an almost universal effect on high-altitude phenology (Inouye & Wielgolaski 2003), and variations in phenology has been usually linked to variations in the accumulation and melting of snow (Holway & Ward 1965; Mark 1970). In the alpine sites of this region it has been reported that because of early availability of snowmelt water, ca majority of the species initiate growth (Negi *et al.* 1992; Ram *et al.* 1989) and do not wait for the onset of the monsoon as required for herbaceous plants of the low altitude of this region (Singh & Singh 1992). At Tungnath, Rai *et al.* (2012) reported that the development of leaves in a shoot and leaf fall at the end of the growth period were highly correlated with soil and air temperature, precipitation and relative humidity. They found that leaf fall was delayed in years with a higher temperature and vice versa, and higher temperatures and delayed monsoon extended the overall growth period of trees.

When considered the growing period between 1990–97 and 2017 (the period using modern meteorological instrumentation) rise in atmospheric temperature has been quite conspicuous (i.e., 2.2 °C in the last two decades @ 0.11 °C yr^{-1}) (Table 4). This rate of warming is in conformity with those reported by several workers for the Himalayan mountains (Schickhoff *et al.* 2015; Shrestha *et al.* 2012; Singh *et al.* 2011; Xu *et al.* 2009). Of particular interest is growing season mean of air and soil temperatures that vary across forests and influence growth of plants. In our study site, considering the wet and warm months (July–September) as active growing season when the foliage is fully developed, the mean air temperature in 2017 (i.e., 11.2 °C) was much higher than seasonal mean ground temperature of 6.7 °C (± 0.8 SD; 2.2 K amplitude of means for different climatic zones of the world), reported by Körner & Paulsen (2004). Thus, it may be pointed out that growing season length at Tungnath is much longer than the climatic treelines, which may have several eco-physiological implications on the treeline vegetation and warrant further studies.

The annual mean of soil temperatures across the five forest sites (range = 8.3 °C to 10.3 °C; mean= 9.8 °C at 30 cm depth) recorded by us was higher than other reports for alpine treelines (Körner 2012) that may have favoured nutrient mineralization. At a global scale, an average growing season soil temperature below 6.4 ± 0.7 °C in 10 cm soil depth is supposed to limit alpine tree growth (Körner 2012), whereas growing season mean soil temperature at a local scale exhibit a large range from 5 °C to 12 °C (Müller *et al.* 2016). In a year (2010) with high air and soil temperatures in Tungnath, Rai *et al.* (2012) found a short growing period that was related with slow rate of leaf expansion, lower leaf area and leaf number in *B. utilis.* Also, low soil temperature led to a slow rate of leaf expansion, shoot growth and fewer leaves in a shoot in Tungnath (Rai *et al.* 2012). Further, higher temperature and delayed monsoon extended the overall growth period, resulting in a delayed and slower leaf fall which is advantageous in terms of longer leaf life-span and photosynthetic gain. A longer leaf life-span is associated with potentially higher carbon gain by the plant and more efficient nutrient use (Richardson *et al.* 2006).

Plants have developed two main strategies to grow and persist under regimes of nutrient limitations: optimizing nutrient acquisition and reducing nutrient loss. These adaptations are part of a well-known trade-off in and among plants between resource acquisition and conservation (Reich *et al.* 1997; Wright *et al.* 2004). We found that in the *R. arboreum* and *R. campanulatum* krummholz poor in soil nutrients and leaf N, resorption efficiency of leaf N (mean= 60%) was markedly greater than other species growing at similar site conditions. Treeline species at Tungnath were relatively poor in leaf N at mature stage than the mid-altitude forest trees (2.5 vs. 1.7%; Negi 1989). Freschet *et al.* (2010) found inter-specific variation in organ nutrient resorption and leaf leaching in 40 subarctic vascular plants and linked it with "nutrient acquisitive-conservative strategies", and resorption process as a potential importance for the plant nutrient budget. Some studies have found resorption efficiency and leaching resistance decreases with increasing leaf nutrients (e.g., Kobe *et al.* 2005; Pastor *et al.* 1987). Studies elsewhere (e.g., Drollinger *et al.* (2017) have shown that nutrient concentration in soil and trees decreases with increasing elevation in treeline ecotone that might explain why treeline shift and global warming are decoupled (Müller *et al.* 2016). Our data also show that both soil nutrients (total N, $R^2 = 0.30$; and OC, $R^2 = 0.22$) and foliar N decreased with increasing elevation though the relation was weak, indicating nutrient conservation strategy of *R. campanulatum* in poor site conditions. Our values of soil OC were much higher than that reported for mid-altitude forests of this region (range= 0.8–3.3%) but the soil total N was quite comparable (range= 0.25–0.70%; Joshi & Negi 2015). Garkoti & Singh (1994) have reported mean value of soil organic carbon (3.04–3.13%) and N (0.40–0.41%) in *B. utilis* and *R. campanulatum* forests of this region (up to 30 cm depth). Soil organic carbon stock has been reported highest for *B. utilis* across a variety of temperate forests of Kashmir Himalaya (Dar & Somaiah 2015). Decreasing soil C with increasing elevation, however insignificantly (Speed *et al.* 2015), whereas significantly decreasing soil N concentration (Muller *et al.* 2016), thus significantly increasing C/N ratio (Thebault *et al.* 2014) has been reported. Since, leaching of organic acids and organomineral compounds is part of the podzolization process as a whole, N limitation might be a typical factor for treeline ecotones (Müller *et al.* 2016) that requires further research.

To conclude: (i) the treeline species are characterized by a delayed bud-break and leafing, a slow leaf expansion, a short steady-state period in leaf mass, lower shoot growth, higher leaf density per shoot and lower leaf N concentration compared to the mid-altitude forest tree species of the western Himalayan region; (ii) treeline of our study site is characterized by a longer growing season owing to markedly higher mean growing season temperature than the climatic treelines of the world (11.2 °C vs. 6.7 °C). Treeline ecotone vegetation of western Himalayan region may face several eco-physiological implications with the ongoing pace of global warming.

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Treeline species in Western Himalaya are not water stressed: a comparison with low elevation species

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Abstract: Water potential (predawn {Ψ_{pd}} and midday {Ψ_{md}}), osmotic potential at full turgor (OP_f) and zero turgor (OP_z) turgor, relative water content at zero turgor (RWC_z) and leaf conductance were measured for four species, *Quercus semecarpifolia* Sm., *Abies spectabilis* D. Don., *Betula utilis* D. Don and *Rhododendron campanulatum* D. Don in the Tungnath treeline ecotone, located between 3200 and 3450 m elevation. Similar parameters were studied in four species, *Pinus roxburghii* Sarg., *Myrica esculenta* Thumb., *Quercus leucotrichophora* A. camus and *Rhododendron arboreum* Wall. of low elevations located between 1720 m and 2100 m to compare the degree and timing of stress and adaptational features. The treeline ecotone soils were moister than low elevation forest soil in all seasons and years. In all the four treeline ecotone species Ψ_{pd} remained above −1.1 MPa indicating the potential absence of severe water stress. The low elevation species (LES) had lower daily change in water potential in comparison to treeline species (TLS). Daily change was significantly correlated with Ψ_{pd}. The Ψ_{pd} water potential during the summer season in undercanopy evergreen species *M. esculenta* was close to −2.2 ± 0.05 MPa and −1.93 ± 0.02 MPa in Yr_1 and Yr_2. The winter to spring/ summer time rise in Ψ_{pd} was a more pronounced in the LES than the in TLS and coincided with the lowering of osmotic potential. The morning leaf conductance in all seasons of TLS ranged between 28.75 ± 1.45 and 329.2 ± 8.98 m mol m^{-2} sec^{-1}. The TLS maintained a high rate of leaf conductance during spring and summer season.

Key words: Leaf conductance, osmotic potential, relative water content, water potential.

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Introduction

Drought is amongst the most important climatic events which can severely impact natural ecosystems. The Himalayas are warming at a faster rate than the global average due to global warming (Yao & Zhang 2012). The treeline of the Himalayan region are highest in the northern hemisphere (Miehe *et al.* 2007; Shi & Wu 2013), therefore, trees occurring there experience a different physical environment than treelines of other mountains. Due to monsoonal pattern of rainfall, Himalayan tree species experience drought of several months (Zobel & Singh 1997). Trees growing in the treeline ecotone are exposed to various environmental stresses like short growing season and adverse climatic conditions which influence the tree water relations (Körner 2003; Mayr *et al.* 2006; Tranquillini 1979). During winters, water uptake is low due to frozen soil but comparatively high atmospheric temperature enhances evaporation resulting in drier soils (Larcher 1972; Mayr *et al.* 2006; Pisek & Larcher 1954; Tranquillini 1976, 1980;)

Water moves across a gradient from the soil through the plants to the atmosphere, water potential being the highest in the soil and lowest at the leaf surface (Lambers *et al.* 1998). Stem predawn water potentials Ψ_{pd} give an indication of

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the soil water availability and is a useful measure of plant water status (Reich & Hinckley 1989).

There is some evidence that water deficit in treeline ecotone can reach lethal level in the north hemisphere during winters (Tranquillini 1976). For example, in *Picea abies*, water potentials can fall below −4.0 MPa (Mayr *et al.* 2002). However, during the growing season tree water potential of treeline does not reach critical levels to affect the normal plant function (Anfodillo *et al.* 1998). Enhanced evapo-transpiration rate with rising global temperature and uncertainty associated with precipitation, earlier snow melt and more rain than snow may combine to create a more drought stressed condition for plants in a warming climate. Extended period of water stress would eventually lead to death of young individuals of some tree species at the drier sites (leeward sites) as already shown for white bark pine (Miller *et al.* 2012).

Low soil temperature can impair water uptake in alpine treeline species particularly during the winter season. In *Picea glauca* growing at treeline at Alaska water uptake reduction occurs when soil temperature is close to 9 °C (Goldstein *et al.* 1985). During winters water uptake is usually blocked in stands with limited snow (Tranquillini 1979). Embolism in root xylem may occur specially during the spring and autumn season in the top soil layer due to repeated freezing and thawing effect. The fine roots are more vulnerable to embolism (Hacke *et al.* 2000; Kavanagh *et al.* 1999; Sperry & Ikeda 1997).

The conductivity of leaf surface to water vapour is an important integrator of the plant water condition (Hinckley *et al.* 1983; Schulze 1986; Smith & Hollinger 1991). Leaf conductance during the growing season in treeline species is generally not restricted. *Larix deciduas* can maintain a high stomatal conductance than the species of lower altitudes, as it requires an increased leaf conductance to compensate for the short growth period (Benecke 1981).

Osmotic adjustment is an effective adaptation that the tree species employ to overcome drought, as it can contribute in the maintenance of turgor during periods of drought and therefore can enhance the chances of competing with other species in treeline areas (Badalotti 2000).

The Himalayan treeline species have generally not been studied for the impact of drought and its possible repercussions on tree phenology and physiology. Most eco-physiological data for treeline species has been collected from European temperate region where drought conditions are very different from those of Himalayas.

In the present paper we have tried to assess (I) the level of stress that is encountered by the treeline species (TLS) of western Himalayan region in comparison with lower elevation species (LES) and to find out whether it becomes low enough to affect their physiological functions. (II) How these tree species react to droughts and the drought adaptation mechanisms they employ is another issue that we have addressed here.

We hypothesize that TLS will be less affected by water stress than LES because of relatively lower evapotranspiration losses in tree line area (Körner 2012). However, loss of snow with climatic warming in future may intensify tree line drought during pre-monsoon period. This study is the first attempt on developing understanding of tree water relations in treeline ecotone of Himalayas and provides data which would be used to determine the impact of changes like loss of snow and accelerated upward migration of fast growing species of lower elevations.

Material and methods

Study Area & Climate

Study Site: The studied treeline site (Tungnath) 30°49′22″N latitude and of 79°21′47″E longitude occurs between 3200 and 3560 m asl elevation. The tree species selected for the present study in the treeline site were *Quercus semecarpifolia*, *Abies spectabilis*, *Betula utilis*, *Rhododendron campanulatum*. The data in the treeline site was collected during the year 2016 and 2017 (Two years) (Table 1).

The low elevation sites were located between 29°23′21″ and 29°24′40″N and 79°29′34″ and 79°28′14″E along an elevation transect between 1720 and 2100 m asl. The LES includes *Pinus roxburghii, Myrica esculenta, Quercus leucotrichophora* and *Rhododendron arboreum* and they belong to subtropical to warm temperate forest zones. The data in the low elevation site was collected during the year 2014 and 2015 (Two years) (Table 1).

Climate: The climate of treeline site is characterized by severe frosts, and hail storms for almost eight months in the year (September–April). Snow fall is from December to March and snow melt occurs during April and May which helps in keeping the soil moist prior to the monsoon period. Maximum rainfall is in July-August (Nautiyal *et al.* 2001). In the study site the mean annual temperature varies between −8.91 °C to 25.6 °C. The average annual precipitation was about 2410

Table 1. A list of study sites.

Location	Site	Species	Latitude & Longitude	Elevation (m)	Aspect
Treeline	Tungnath	*Q. semecarpifolia* Sm. *A. spectabilis* D.Don. *B. utilis* D.Don. *R. campanulatum* D.Don	30°49′22″N 79°21′47″E	3200–3450	Southern
Low elevation	Mangoli chirpine	*P. roxburghii* Sarg. *M. esculenta* Thumb.	29°23′21″N 79°29′34″E	1720–1750	Southern
	Kilburry oak	*Q. leucotrichophora* A. camus *R. arboreum* Wall	29°24′40″N 79°28′14″E	2000–2100	Southern

mm of which 90% was received during June to September (Rai *et al.* 2012). According to Joshi *et al.* (unpublished data) 3800 mm of rainfall occurred during the year 2017, which is exceptionally high for the sites.

In the low elevation site average annual precipitation was 2258 mm of which two third occurred during rainy season. Mean annual temperature was 15.2 °C with mean minimum temperature of coldest month 4.6 °C (January) and mean maximum temperature of warmest month 25.9 °C (June) during the study period.

Soil Moisture: Soil samples were collected from five representative locations from 0–10 cm (surface layer), 10–20 cm (middle layer) and 20–30 cm (deeper layer) depth from each site. Soils from different depths were packed in polythene bags and brought to the laboratory for soil analysis. For soil moisture content estimation, five replicates of 50 g soil were dried at 100 °C till constant weight. The moisture content was determined on dry weight basis following Jackson (1958).

Tree water potential (Ψ), Pressure volume curves and leaf conductance were measured on five representative trees of each of the selected species across the seasons. Sample trees were 15–25 m tall and measurements were made on twigs located 2 to 3 m from the ground. However *R. campanulatum* plants were 1–2 m tall.

Twig Water Potential**:** Pressure chamber (PMS Instrument Co. model 1000, range 70 bars) was used for the determination of water potential and the development of Pressure-Volume Curves (P-V curves). In this study water potential measurements were made for two years on selected sites and species in different seasons. The water potential (Ψ) was measured at predawn (Ψ_{PD}) (5.30–6.30 am) and in the midday (1.30–2.30 pm) (Ψ_{MD}) following Tewari (1999) and Zobel *et al.* (2001).

Pressure volume curves (PV curves) and Components of water potential: PV curves were prepared to develop a relationship between components of water potential and Relative water content (RWC %). PV curves were prepared following the bench drying method from overnight saturated twigs. From PV curves, the osmotic potential at full turgor (OP_f), the osmotic potential at zero turgor (OP_z) and RWC% at turgor loss point (RWC_z) were determined following Pallardy *et al.* (1991) and Tewari (1998).

Osmotic adjustment is generally calculated as the decline in osmotic potential over the drought period (difference between the value at the beginning of drought and that at the peak of drought). We calculated decline in osmotic potential (zero and full turgor) separately for different seasons rainy, autumn, winter, late spring and summer, as environmental and phenological factors unrelated to drought also affects change in osmotic adjustment (Abrams 1988). Here we have applied the term osmotic adjustment for an obvious decline in osmotic potential over a period falling between two sampling dates of drought irrespective of its intensity.

Leaf Conductance: Leaf conductance measurements were made seasonally, using AP_4 porometer (Delta-T Devices). The porometer was calibrated against a perforated plastic plate of known conductance (Poudyal *et al.* 2004; Webb 1991). Data were collected from 03 leaves/ individual on the sunny sides of tree and from approximately similar height, in the morning and afternoon (10.30–11.30 AM & 1.30–2.30 PM) following Tewari (1998) and Garkoti *et al.* (2000).

Statistical analysis: The data were subjected to analysis of variance with a 95% confidence level using SPSS version 2016. Species, seasons and year were the factors used for ANOVA. Correlation coefficient was used for expressing relationship between different variables.

Table 2. Depth wise variation in soil moisture content (%) across different sites seasons and years.

Site	Soil depth (cm)	Yr_1				Yr_2				
		Summer	Rainy	Autumn	Winter	Spring	Summer	Rainy	Autumn	Winter
Treeline site										
Tungnath	00–10	39.4 ± 2.96	59.9 ± 2.1	74.2 ± 2.53	44.4 ± 2.56	49.6 ± 0.38	36.2 ± 1.92	66.13 ± 1.01	42.9 ± 1.25	53.6 ± 1.02
	10–20	38.4 ± 1.14	56.4 ± 1.9	48.7 ± 2.05	47.3 ± 0.81	53.3 ± 0.82	39.9 ± 1.17	71.23 ± 1.24	32.7 ± 0.36	47.8 ± 1.90
	20–30	36.3 ± 3.24	57.9 ± 1.39	34.9 ± 1.41	32.15 ± 2.52	55.8 ± 0.99	44.0 ± 1.63	82.2 ± 1.38	33.28 ± 0.37	35.5 ± 0.13
Low elevation site										
Mangoli (chirpine)	00–10	21.4 ± 1.56	45.6 ± 3.04	21.2 ± 0.74	19.9 ± 0.71	15.4 ± 3.94	19.9 ± 1.80	40.81 ± 1.00	21.0 ± 0.83	20.8 ± 0.90
	10–20	23.8 ± 4.03	44.7 ± 1.92	27.1 ± 0.67	23.5 ± 1.29	14.2 ± 2.80	22.4 ± 4.31	43.6 ± 4.56	23.7 ± 0.72	24.9 ± 1.58
	20–30	23.7 ± 4.96	47.9 ± 2.08	28.2 ± 0.31	25.2 ± 1.40	15.5 ± 2.98	22.3 ± 4.99	45.2 ± 0.70	25.8 ± 0.69	25.7 ± 1.00
Kilburry (oak)	00–10	20.4 ± 1.05	32.8 ± 0.88	19.8 ± 0.10	6.4 ± 0.61	24.0 ± 0.97	18.6 ± 0.41	32.1 ± 1.00	20.5 ± 0.38	6.83 ± 0.64
	10–20	20.2 ± 1.24	36.3 ± 0.23	20.2 ± 0.72	7.2 ± 0.67	23.6 ± 0.87	17.7 ± 0.47	35.3 ± 0.32	23.7 ± 0.50	7.6 ± 0.62
	20–30	21.3 ± 0.9	36.3 ± 0.98	23.0 ± 0.66	7.4 ± 0.46	23.4 ± 1.18	16.2 ± 1.06	34.7 ± 1.00	26.3 ± 0.71	8.45 ± 0.71

Result

Soil Moisture: Soil moisture was highly variable across the sampling dates and differed significantly ($P < 0.01$). The treeline forest soils were moister than soils of LES. At the TLS across all soil depths and seasons the soil moisture ranged between 32.7 ± 0.36 and 74.2 ± 2.53% (Table 2). At the LES in chir pine forest in the top soil layer moisture content ranged between 19.9 ± 0.71 and 45.6 ± 3.04% and in banj oak site between 6.4 ± 0.61 and 32.8 ± 0.88% (Table 2). Comparison of soil moisture during the winter seasons indicates that the chir pine forest soil was moister than the banj oak forest soil in all depths. ANOVA showed soil moisture varied significantly across sites and years ($P < 0.01$). Interestingly, soils tended to be drier in surface layer than deeper layer in low elevation forest sites, while at treeline, soils tended to be drier in deeper layers particularly during autumn and winter season.

Tree Water Potential (Ψ): In the TLS the tree water potential (Ψ) varied significantly across species and seasons ($P < 0.01$). Across all seasons and the two study years, the Ψ_{pd} of all species remained above 1.0 MPa indicating the absence of severe stress. The lowest predawn tree water potential values indicate that LES suffered roughly twice as much water stress as did treeline species. It was only in the summer season of Yr_2 the Ψ_{pd} in *Q. semecarpifolia* and *A. spectabilis* had declined below −1.0 MPa. Minimum values of Ψ_{pd} for all species were observed during the summer season followed by the comparatively dry autumn season. Maximum Ψ_{pd} was during the rainy season the period during which more than 80% of annual rainfall occurs. Tree Ψ_{md} varied significantly among species and seasons ($P < 0.01$) (Fig. 1).

The lowest Ψ_{md} were generally encountered by treeline species during summer and winter seasons with values ranging between −0.88 ± 0.02 MPa (*B. utilis*) and −1.95 ± 0.04 MPa (*A. spectabilis*) (Fig. 1).

Water potentials in LES varied significantly across seasons and species ($P < 0.01$). *P. roxburghii* had the minimal Ψ_{pd} during the summer season (−1.7 ± 0.02 MPa and –1.81 ± 0.01 MPa, Fig. 2). The under canopy species *M. esculenta* had Ψ_{pd} values –2.2 ± 0.05 MPa and –1.93 ± 0.02 MPa during the summer season of Yr_1 and Yr_2. The species encountered another drought of slightly less magnitude during the winter season. *Q. leucotrichophora* and *P. roxburghii* during the summer

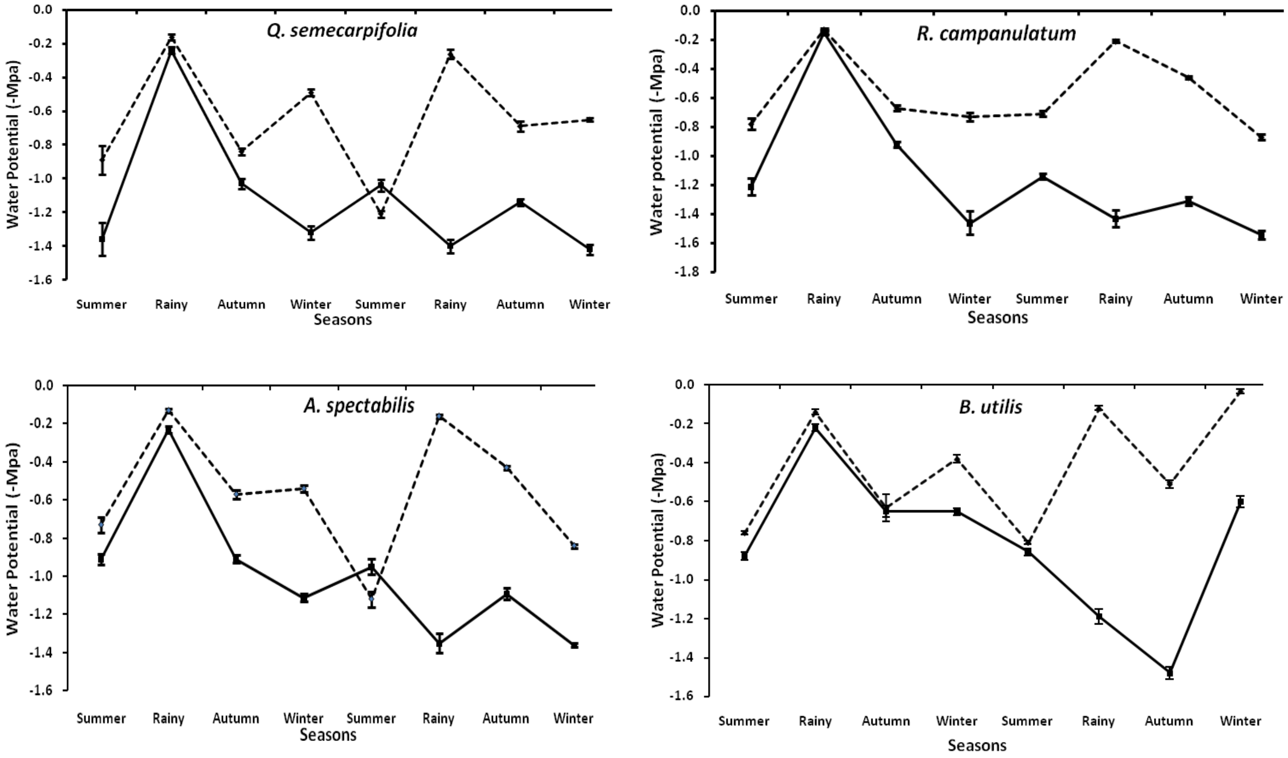

Fig. 1. Variation in predawn (Ψ_{PD}, dotted line) and midday (Ψ_{MD}, Solid line) Water potential (MPa) in treeline species (TLS).

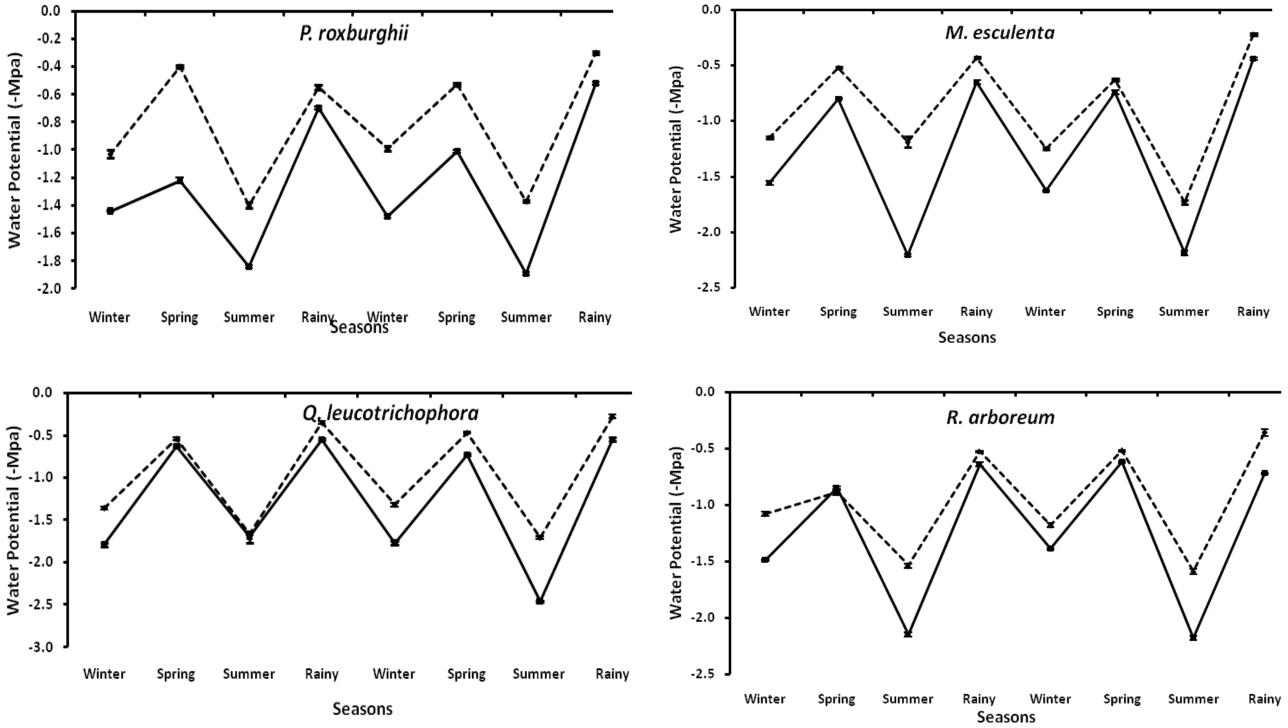

Fig. 2. Variation in predawn (Ψ_{PD}, Dotted line) and midday (Ψ_{MD}, Solid line) Water potential (MPa) in lower elevation species (LES).

Table 3. Seasonal changes in Osmotic Potential at full turgor (OP_f), and at zero turgor (OP_z) and Relative water content at zero turgor (RWC_z) % in treeline and low elevation species.

Ψ Components	Rainy	Autumn	Winter	Spring	Summer
Treeline Species					
Q. semecarpifolia					
OP Full	−1.24 ± 0.08	−1.74 ± 0.18	−1.94 ± 0.69	−2.5 ± 0.09	−1.04 ± 0.20
OP Zero	−1.78 ± 0.42	−2.30 ± 0.07	−3.10 ± 0.47	−3.8 ± 0.20	−1.45 ± 0.20
RWC%	78.63 ± 4.12	58.89 ± 5.99	72.34 ± 5.25	69 ±1.53	54.63 ± 1.46
R. campanulatum					
OP Full	−1.24 ± 0.29	−1.76 ± 0.2	−1.40 ± 0.31	−1.7 ± 0.06	−0.74 ± 0.02
OP Zero	−1.6 ± 0.58	−2.15 ± 0.34	−2.24 ± 0.02	−2.7 ± 0.12	−1.54 ± 0.11
RWC%	91.66 ± 1.74	88.23 ± 0.97	89.73 ± 2.97	75.3 ± 1.20	73.20 ± 4.01
A. spectabilis					
OP Full	−1.04 ± 0.62	−1.76 ± 0.12	−1.05 ± 0.17	−1.6 ± 0.12	−0.72 ± 0.19
OP Zero	−1.52 ± 0.58	−2.10 ± 0.06	−1.48 ± .01	−2.7 ± 0.26	−1.54 ± 0.42
RWC%	90.16 ± 4.09	91.02 ± 1.21	79.02 ± 4.82	75.3 ± 2.03	52.18 ± 5.77
B.utilis					
OP Full	−0.94 ± 0.14	−1.51 ± 0.14	−1.32 ± 0.12	−2.6 ± 0.09	−1.38 ± 0.15
OP Zero	−1.43 ± 0.37	−2.50 ± 0.12	−2.16 ± 0.23	−3.4 ± 0.15	−2.07 ± 0.14
RWC%	88.14 ± 1.90	78.86 ± 6.14	78.28 ± 4.3	65.7 ± 1.20	88.76 ± 2.6
Low Elevation Species					
P. roxburghii					
OP Full	−1.3 ± 0.02	−0.83 ± 0.03	−1.69 ± 0.03	−1.41 ± 0.01	−1.18 ± 0.02
OP Zero	−1.6 ± 0.06	−1.46 ± 0.06	−2.24 ± 0.03	−2.47 ± .02	−1.83 ± 0.01
RWC%	84.0 ± 1.58	78.5 ± 1.58	79.36 ± 0.66	82.24 ± 0.76	84.94 ± 0.84
M. esculenta					
OP Full	−0.88 ± 0.03	−1.27 ± 0.04	−1.38 ± 0.01	−1.92 ± 0.01	−2.46 ± 0.02
OP Zero	−1.36 ± 0.03	−1.47 ± 0.03	−1.97 ± 0.03	−2.45 ± 0.02	−2.88 ± 0.01
RWC%	90.96 ± 1.45	81.38 ± 1.5	90.94 ± 0.55	86.14 ± 0.71	82.6 ± 1.02
Q. leucotrichophora					
OP Full	−1.27 ± 0.01	−1.43 ± 0.02	−2.2 ± 0.01	−2.40 ± 0.01	−2.08 ± 0.01
OP Zero	−1.67 ± 0.02	−1.79 ± 0.01	−2.35 ± 0.02	−2.82 ± 0.02	−2.81 ± 0.01
RWC%	85.12 ± 0.84	83.68 ± 0.81	74.32 ± 1.13	71.88 ± 0.41	82.66 ± 0.87
R. arboreum					
OP Full	−0.74 ± 0.01	−1.9 ± 0.01	−1.94 ± 0.02	−2.16 ± 0.02	−1.8 ± 0.01
OP Zero	−1.47 ± 0.02	−1.65 ± 0.02	−2.44 ± 0.02	−2.38 ± 0.11	−2.36 ± 0.02
RWC%	84.12 ± 0.99	85.46 ± 0.54	84.1 ± 1.36	94.14 ± 0.22	74.34 ± 0.84

season had relatively low Ψ_{pd} values. This species also encountered a moderate stress during the winter season with values close to −1.3 MPa (Fig. 1). The under canopy species R. arboreum had the lowest Ψ_{pd} values during the summer season followed by the winter season with Ψ_{pd} values marginally lower than the dominant *Q. leucotrichophora.* At the lower altitude the most negative Ψ_{md} were during the summer and winter season across all species. The values in these seasons ranged between −1.39 ± 0.01 and −2.46 ± 0.01 MPa.

The daily change ($\Delta\Psi = \Psi_{md} - \Psi_{pd}$) differed significantly among species and seasons ($P < 0.01$). The magnitude of diurnal change across all TLS was maximum during the growing season from spring to autumn. The species varied in seasons and magnitude of diurnal change. *B. utilis*, the only

Table 4. The lowest pre-dawn water potential Ψ_{pd} (−MPa) and maximum daily change $\Delta\Psi$ among all seasons and years in the treeline species (TLS) and low elevation species (LES).

Species	Lowest Ψ_{pd} (-MPa)	$\Delta\Psi$ (MPa)
Q. semecarpifolia	−1.21(Summer, Yr_2)	1.13 (Rainy Yr_2)
R. campanulatum	−0.87 (Winter, Yr_2)	1.22 (Rainy Yr_2)
A. spectabilis	−1.12 (Summer, Yr_2)	1.19 (Rainy Yr_2)
B. utilis	−0.81 (Summer, Yr_2)	1.07 (Rainy Yr_2)
P. roxburghii	−1.81 (Summer, Yr_2)	0.64 (Autumn Yr_2)
M. esculenta	−1.93 (Summer, Yr_2)	0.41 (Winter Yr_1)
Q. leucotrichophora	−1.71 (Summer, Yr_2)	0.75 (Summer Yr_2)
R. arboreum	−1.84 (Summer, Yr_1)	0.31 (Autumn Yr_1)

deciduous species had the highest daily change during the rainy and autumn season of Yr_2 (1.07 and 0.97 MPa respectively). In LES the magnitude of daily change was lower than in TLS and varied between 0.41 MPa and 0.75 MPa compared to 1.07 to 1.22 MPa in TLS (Table 4). This indirectly represents the ability of the TLS to keep the stomata open and conduct water freely and carry on leaf conductance. There was a significant correlation between the $\Delta\Psi$ and Ψ_{pd} ($P < 0.01$, r = 0.80).

Water Potential Components: The water potential parameters (Osmotic Potential at full turgor (OP_f) and zero turgor (OP_z) and Relative Water Content (RWC_z) %) differed significantly across species and seasons ($P < 0.01$). *Q. semecarpifolia* at the treeline showed osmotic adjustment persistently from rainy to the late spring season (−1.26 MPa at full turgor and −2.02 MPa at zero turgor). The RWC at turgor loss point for the species was the lowest during autumn season 58.89 ± 5.99% and maximum at winter season 72.34 ± 5.25%. *R. campanulatum* showed an osmotic adjustment between rainy to autumn season of −0.52 MPa at full turgor and a smaller adjustment from winter to late spring. However, OP_z for the species showed a continuous decline from the rainy to late spring time (−1.1 MPa). This species could maintain a high RWC_z at turgor loss point across all seasons. *A. spectabilis* showed a decline in osmotic adjustment at zero and full turgor between rainy to autumn season and a larger adjustment between winters to late spring. *B. utilis* the only deciduous species reduced its osmotic potential at full and zero turgor between rainy to autumn and from winters to late spring. The adjustment was more than −1.0 MPa both at full and zero turgor between the winters and late spring (Table 3).

All the LES except *M. esculenta* showed a decline in osmotic potential at full and zero turgor during winter and spring season. In *P. roxburghii* the decline in osmotic potential was from autumn to winter season. *M. esculenta* reduced its osmotic potential from rainy to summer season and adjusted by −1.58 MPa at full turgor. In *Q. leucotrichophora* the decline was from rainy to spring season, the osmotic adjustment at full turgor being −1.13 MPa. *R. arboreum* behaved similarly as did *Q. leucotrichophora*, but the adjustment was more pronounced than *Q. leucotrichophora.* All the species could maintain a high RWC at turgor loss point which generally remained above 71.8% (Table 3). There was a significant correlation between the $\Delta\Psi$ and Ψ_{pd} at low elevation site ($P < 0.01$, r = 0.94). The two oaks, *Q. semecarpifolia* and *Q. leucotrichophora* did not differ in the timing of osmotic adjustment which was between rainy to spring season, however, the degree of adjustment was more in the high altitude oak, −1.26 MPa at full turgor and –2.02 MPa at zero turgor compared to –1.13 MPa at full and –1.15 at zero turgor in *Q. leucotrichophora.* In *R. campanulatum* the adjustment at full and zero turgor was much lower than in *R. arboreum*.

Leaf Conductance: The instrument AP_4 type diffusion porometer could not measure the leaf conductance of conifers hence the conductance of only broad leaved species was measured. As the deciduous *B. utilis* was leafless during autumn and winter season leaf conductance in these two seasons were not estimated. Leaf conductance was measured over four seasons summer, autumn, winter and late spring over a two year period. Morning conductance varied significantly across seasons ($P < 0.01$) but there was no significant variation across species. The afternoon conductance varied significantly across species as well as seasons ($P < 0.01$). The TLS maintained a high rate of leaf conductance during late spring and summer season. The morning leaf conductance across all seasons and species of the treeline areas ranged

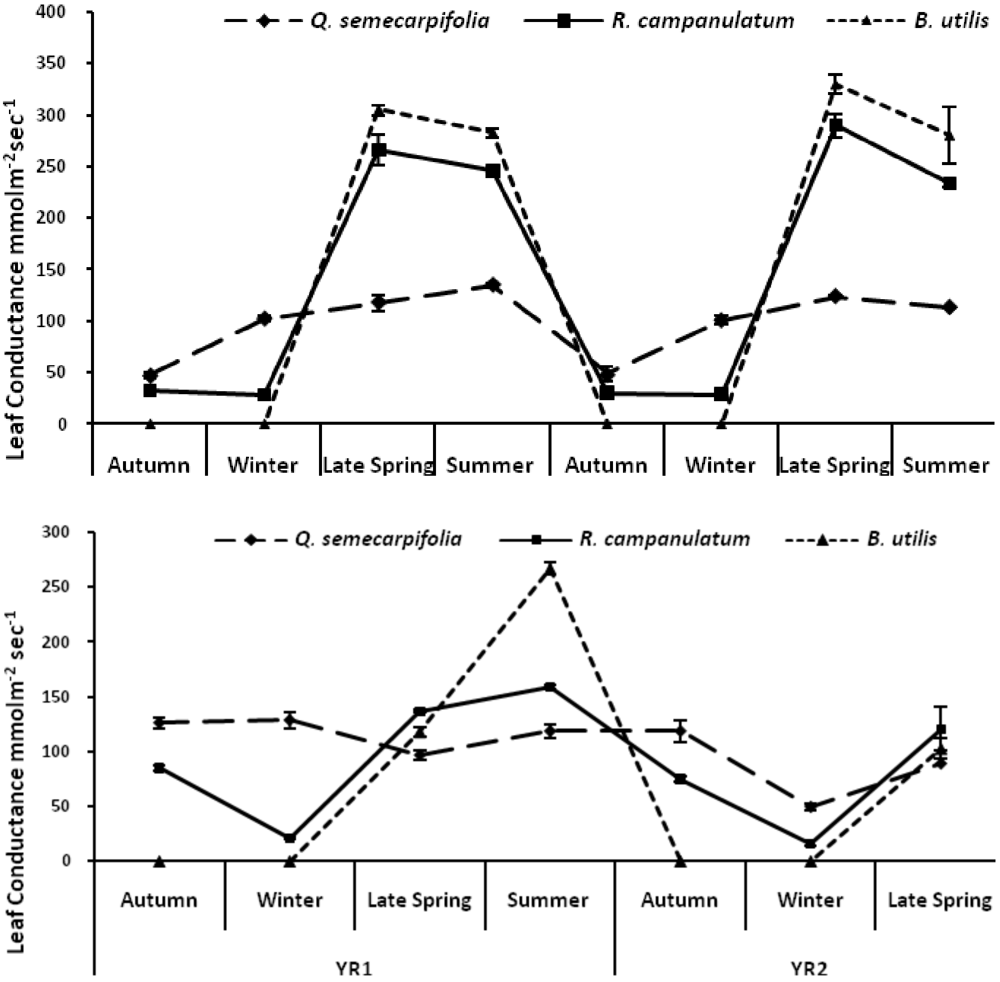

Fig. 3. Seasonal pattern of leaf conductance (m mol m^{-2} sec^{-1}) in the treeline species (TLS). Upper graph is of morning leaf conductance and lower graph is of afternoon leaf conductance.

between 28.75 ± 1.45 and 329.2 ± 8.98 m mol m^{-2} sec^{-1}. *R. campanulatum* had the lowest leaf conductance during the autumn and winter season. The afternoon leaf conductance was generally lower for all species than the morning conductance (Fig. 3).

The morning leaf conductance for LES ranged between 44.43 ± 1.15 and 234.20 ± 4.78 m mol m^{-2} sec^{-1} across all species and seasons. The low altitude oak *Q. leucotrichophora* had relatively lower leaf conductance during the summer season compared to high altitude oak *Q. semecarpifolia.* The conductance of almost all species was lowest during the summer season when Ψ_{pd} was most negative. All the species generally showed one peak in conductance during the winter season and a small peak during the autumn season. The afternoon conductance was 50 to 60% lower than the morning conductance during the summer time and in *M. esculenta* during the autumn season (Fig. 4). Significant correlation existed between Ψ_{pd} and morning leaf conductance ($P < 0.01$, r = 0.45) and afternoon conductance ($P < 0.01$, r = 0.58) at low elevation sites.

Discussion

The TLS were much less water stressed than LES across all seasons. There is a marked difference in temperature and soil water availability of the two study areas. In treeline areas the snow melt from winter snowfall keeps the soil moist during spring and summer season, prior to monsoon rains. The low elevation sites are characterized by an approximately three months of heavy rainfall from mid June to mid September and the remaining 9 months with little rainfall or no rain. The severity of drought can be assessed by the minimum level of Ψ and the best indicators can be the lowest Ψ_{pd} on a particular site and sampling date.

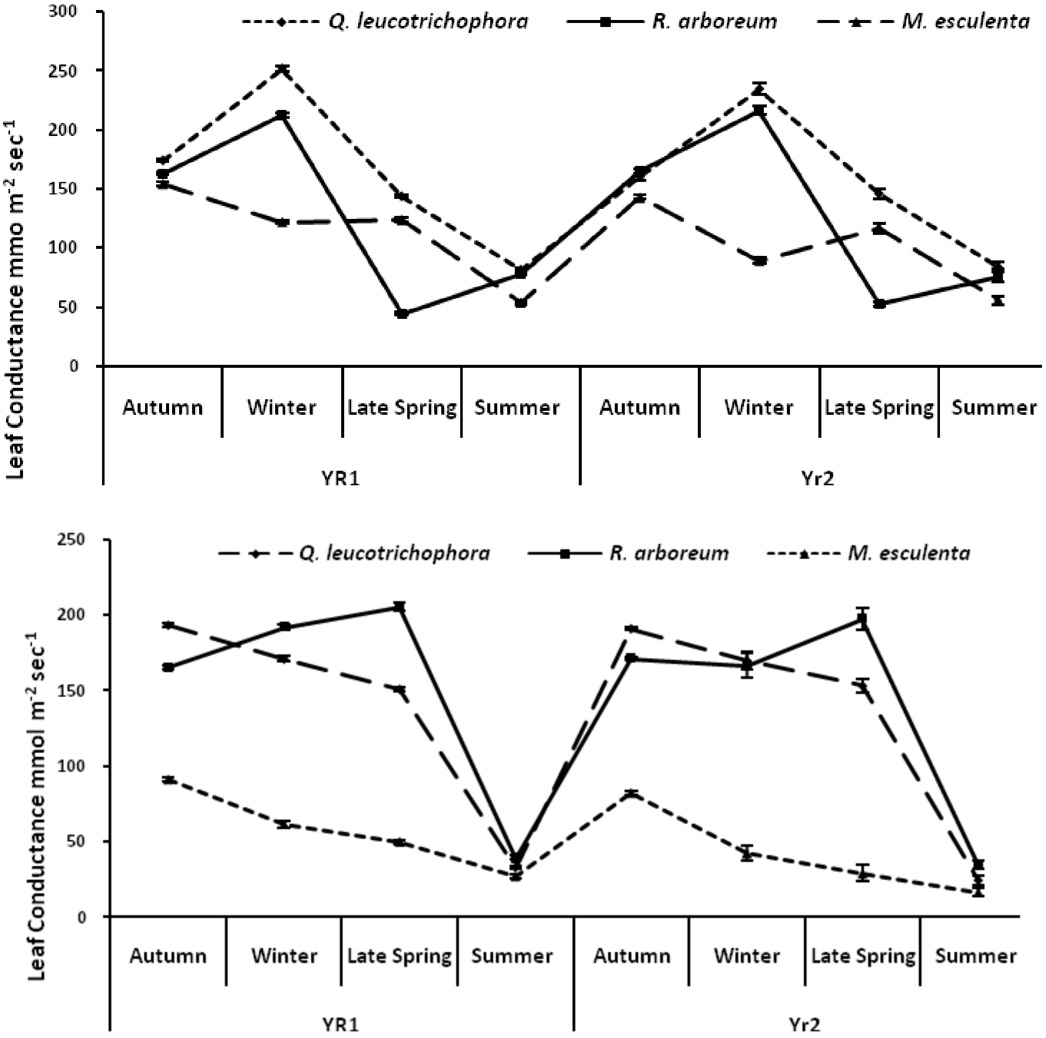

Fig. 4. Seasonal pattern of leaf conductance (m mol m^{-2} sec^{-1}) in the low elevation species (LES). Upper graph is of morning leaf conductance and lower graph is of afternoon leaf conductance.

The studied forest forming evergreen species generally have one year leaf life and the new leaves that the trees put forth during March–April seems to induce leaf drop (Ralhan *et al.* 1985). In the LES the winter to spring time rise (0.19–0.82 MPa) or stability of tree water potential was a pronounced feature which coincided with the timing of maximum phenological activities. In TLS the rise in Ψ_{pd} occurred, but was from winter to late spring season (April–May). The rise amongst all species ranged between 0.2 MPa to 0.42 MPa and was of a lower magnitude than LES. The wet soils from the melting snow possibly keeps the water potential higher above the threshold required for the commencement of phenological activities. This spring/ summer time rise could also be due to thinning of the canopy (about 25% in oaks and 40–50% in other species) and resultant reduction in transpiration rate (Tewari 1998). This data and those of Williams *et al.* (1997) on Savanna trees support the Reich-Borchert hypothesis that leaf flushing is determined by change in internal water status of the whole plant. However this Ψ_{pd} rise in Himalayan trees is generally lower than the woody species of drier climate such as Australian savannah (Williams *et al.* 1997). In Australian savannah the leaflessness is suggested to be an adaptation that species employ to raise Ψ_{pd} between −1.0 and −0.5 MPa (William *et al.* 1997) for producing leaves during dry season.

The values of Ψ_{pd} in *Q. leucotrichophora* and *Q. semecarpifolia* ranged between −0.16 and −1.71 MPa. These are on the higher side when compared with the range of values reported for oaks in literature −1.98 MPa and −2.26 MPa to 0.39 MPa for *Q. rubra* and *Q. velutina* (Bahari *et al.* 1985). For

Q. rubra in mesic and xeric sites the reported values were −1.5 MPa and −2.39 MPa, respectively (Kubliske & Abrams 1992). The Ψ_{pd} of some other Himalayan species of mid altitude varied between -0.49 (*Pinus roxburghii*) and −0.86 MPa (*Cornus macrophylla*) (Singh *et al.* 2006).

The pre-dawn water potentials in all studied TLS remained above −1.0 MPa. Ψ in TLS of different parts of world has not been found to reach critically low level of Ψ to affect the normal plant function (below −2.0 MPa) during the growing season (Anfodillo *et al.* 1998; Körner 2012). Anfodillo *et al.* (1998) have reported Ψ_{pd} close to −1.0 MPa during exceptionally dry period and peak mid day value between −1.5 and −1.9 MPa. The most negative water potential (value) is reported for *Larix decidua*, but in *Pinus cembra* and *Picea abies* remained above −1.5 MPa (Körner 2012). However, Mayor *et al.* (2002) have reported low water potential (−4 MPa) in tall trees of *Picea abies*. Richard & Bliss (1986) observed water potential as low as −5.3 MPa in *Larix lyallii* in the Rocky Mountains. Except for a few such studies, the trees of tree line experience only small periods of mild constraints of water which are much less than the tree growing at lower elevations. Problems in water supply can occur during winter months in TLS when the ground is frozen, hampering water uptake required for foliar maturation and induced winter desiccation in young individuals without snow protection above the tree line (Mayor 2007). However, in the Tungnath TLS such low water potentials were not found during winter season.

The TLS species differed from LES also seasonal patterns of water potential. In all TLS species the ΔΨ was maximum during the rainy season. However, in Yr1 the ΔΨ was negligible in all species due to overcast conditions in this season. The magnitude of ΔΨ particularly in growing season was higher in TLS in comparison to LES. The ΔΨ generally peaked when Ψpd was generally above −0.5 MPa and tended to decline with increasing stress. However, *A. spectabilis* could maintain a ΔΨ of 0.83 MPa when the Ψ_{pd} was −1.12 MPa in Yr_2. In a study by Poudyal *et al.* 2004 Q. semecarpifolia had a daily change of 0.77 MPa when Ψ_{pd} was −0.40 MPa. Fotelli *et al.* (2000) reported ΔΨ values up to 1.5 MPa in Mediterranean oaks during drought.

At the low altitude during the summer season *P. roxburghii* closed its stomata when Ψ_{pd} had declined to −1.7 MPa and below as evident from the ΔΨ; 0.14 MPa in Yr_1 and 0.8 MPa in Yr_2. *Q. leucotrichophora* could maintain a daily change of 0.53 MPa when Ψ_{pd} was −1.67 in Yr_1 and 0.75 MPa when Ψ_{pd} was −1.71 MPa. *Q. leucotrichophora* tends to keep its stomata open and conduct water freely as evident from the ΔΨ value even at low Ψ_{pd}. In LES the spring time ΔΨ was amongst the lowest in all the evergreen broad leaved species. This could be attributed to new leaf flush in these species with under developed stomata resulting in less water loss through transpiration (Poudiyal 2013). In the under canopy species of low elevation *M. esculenta* and *R. arboreum* during the peak summer time when Ψ_{pd} has declined to −2.0 MPa the ΔΨ in both the species had become negligible (0.1 to 0.8 MPa) signifying their ability to avoid drought by closing their stomata. Singh *et al.* (2006) have reported ΔΨ values ranging between 0.06 and 0.90 MPa, for *P. roxburghii*, *R. arboreum* and *Q. leucotrichophora*.

Osmotic potential at full and zero turgor varied significantly across species and season ($P < 0.01$). As drought intensifies cells adjust their internal water status by accumulating osmotic active compounds resulting in lowering of osmotic potential which is helpful in maintaining turgor pressure. The studied species differed in degree of osmotic adjustment both at zero and full turgor. The high altitude treeline forming oak *Q. semecarpifolia* and deciduous *B. utilis* had lower osmotic potential during late spring both at zero and full turgor in comparison to *A. spectabilis* and *R. campanulatum*.

The TLS behaved differently in the extent and intensity of osmotic adjustment. In *Q. semecarpifolia* osmotic adjustment was from rainy to late spring. In *R. campanulatum*, *A. spectabilis* and *B. utilis* the adjustment occurred at two times in a year between rainy and autumn and winter to late spring. The adjustment was maximum in *Q. semecarpifolia.* In *B. utilis* the adjustment was above 1.1 MPa between rainy to autumn and winter to late spring. *A. spectabilis* and *P. roxburghii* differed in seasonality and extend of osmotic adjustment. In *P. roxburghii* the adjustment was from autumn to winter season whereas in *A. spectabilis* a smaller adjustment between rainy and autumn and a larger adjustment between winter and late spring. The magnitude of adjustment at zero and full turgor was greater in *A. spectabilis* than *P. roxburghii. Q. semecarpifolia* behaved similarly to LES oak, *Q. leucotrichophora* both in the season and extent of adjustment.

The under canopy species of low altitude *M. esculenta* and *R. arboreum* showed maximum osmotic adjustment which was comparable with the osmotic adjustment of *Q. leucotrichophora*. Singh *et. al.* (2006) for *P. roxburghii, Q. leucotrichophora* and *R. arboreum* have reported wider range of values of osmotic potential at full and zero turgor across seasons, the minimum osmotic potential values being more negative. According to Tewari (1998) the two Himalayan oaks *Q. leucotrichophora* and *Q. floribunda* showed osmotic adjustment from autumn to winter ranging between −0.5 and −1.8 MPa at full turgor and −1.47 to −2.0 MPa at zero turgor. These values are marginally lower than the reported values of oaks of the present study RWC_z which is a indirect measure of a plant capacity to maintain its turgor with declining Ψ was always high for all TLS except *Q. semecarpifolia* and *A. spectabilis* in which it had declined to 54.63 ± 1.43 and 52.18 ± 5.77% during the summer season. In the remaining two TLS the RWC_z was relatively high during the summer season when Ψ was most negative. All LES species could also maintain a high RWC_z ranging from 74.34 ± 0.84 and 82.66 ± 0.87% during the peak summer drought. The capacity of trees to maintain a high RWC under drought was also observed by Zlatev (2005) and Gorai *et al.* (2010).

The pronounced lowering of osmotic potential in the TLS during the autumn season and early summer indicate that their main strategy is to ensure water availability to maintain high rate of photosynthesis when days are warm and sunny with optimal humidity, soil is not significantly dry and leaves are fully mature. *Q. leucotrichophora, M. esculenta* and *R. arboreum* at the low elevation keep on gradually declining their osmotic potential across the drought seasons after the rainy season in autumn, winter, late spring and upto summer in *M. esculenta*, so that the phenological activities of the spring and summer season are not affected. This may be referred as slow osmotic adjustment strategy.

All broad leaved evergreen species kept their stomata open throughout the year however species differed in degree of fall in leaf conductance in response to adverse climatic conditions. Keeping stomata open as drought intensifies, allows a plant to continue photosynthesis and provide more dry matter for eventual use and growth. Maximum conductance for the *Q. semecarpifolia* was lower than reported for *Q. leucotrichophora* and *Q. floribunda* (Garkoti *et al.* 2000; Tewari 2000) and much lower than for the deciduous oak *Q. rubra* 400 mmol m^{-2} sec^{-1} (Kubiske & Abrams 1992). Other oaks maintain high conductance with low water potential. For example *Q. dumosa* (L.) has a conductance of 80 mmol m^{-2} sec^{-1} at −3.34 MPa (Hastings *et al.* 1989), *Q. coccifera* (L.) has a conductance of 150 mmol m^{-2} sec^{-1} at −3 MPa and *Q. douglasii* has a conductance of > 200 m mol m^{-2} sec^{-1} at −3.6 MPa (Xu & Baldocchi 2003). Leaf conductance declined as drought intensified in the LES however, in the TLS maximum conductance occurred during the late spring and summer time. *B. utilis* maintained high morning conductance during late spring and summer time. *B. utilis* appears to make maximum use of the late spring and summer season and maintained high morning leaf conductance. In *R. arboreum* the morning conductance ranged between 44.43 ± 1.15 and 216.0 ± 3.79 mmol m^{-2} sec^{-1} which are comparable with the range 28 to 219 mmol m^{-2} sec^{-1} reported by Poudyal *et al.* (2004) and Tewari (1998).

To conclude, it is apparent from the study that water potential does not reach lethal level to curtail phenological and physiological activities in TLS. All the species could reduce their osmotic potential and maintain a favorable water potential gradient from the soil to the tree which assists in absorption of water particularly during the growing season. Among TLS, *R. campanulatum* has a weaker osmotic adjusting capacity and deciduous *B. utilis* makes maximum use of the period during which it has leaves as evident from its higher leaf conductance. At the low altitudinal sites the species faced relatively more severe water deficit than the treeline species with Ψ_{pd} declining up to −1.8 MPa in the canopy species and −2.2 MPa in undercanopy species. In the majority of species osmotic adjustment was between winters and late spring when soil moisture had started to decline and warming had commenced, with the initiation of phenological activities. The shallow rooted undercanopy species showed larger osmotic adjustment than the canopy species. All the species kept their Ψ_{pd} well above the critical level (−1.0 MPa) at the time of leaf production. Several factors contribute to maintain high turgor at the time of leaf production such as osmotic adjustment, brief spell of rain storms and reduction in leaf foliage mass. With rising temperature due to global warming and enhanced evapo-transpiration rate the LES may face severe water deficit over the next few years. The young individuals would be more severely affected as they grow in the harsh micro environment affecting regeneration of the species.

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Diversifying livelihood options of timberline resource dependent communities in Uttarakhand Himalayas: Conservation and development implications

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Abstract: The Timberline ecotones and their nearby areas in Central Himalayas remain under pressure due to the resource use by people, often resulting in ecosystem degradation. In the study Chopta-Tungnath treeline ecotone area, livelihood options for local communities are limited, and largely based on vegetation and biodiversity. The consumption of firewood is very high in the study area, accounting to an average of 7–8 ton fuel wood per household annually. In case of shops/restaurants, serving tourists and local people consumption goes up-to 10–14 ton fuel wood per year. The frequent extreme weather events in a warming climate have further worsened the situation for the communities. In this study, we have analyzed (i) the socio-ecological condition of local communities connected with a timberline ecotone of central Himalayas (Tungnath) and (ii) the impact of a few development interventions on them. Traditional forest resource-based subsistence, agriculture continues to be the primary occupation in this remote area, but people heavily depend on the income generation from summer time religious tourism. It accounts for about 47% of income of studied households (882 households) of timberline linked villages. In regard to the income generated by all livelihood options, contribution of the non-farm activities was nearly 97%. Among the non-farm sources the second major share was of business/self employment (an income of about 33.8% with an engagement of 31.25% households) connected to tourism. On the basis of the need assessment, willingness of the community and timberline connectivity, for the first time some livelihood interventions were carried in two villages. They dealt with off-season vegetable cultivation, mushroom cultivation, floriculture, vermin composting and rainwater harvesting. Among them off season vegetable cultivation in polyhouses was most favoured (adopted by 120 families) followed by mushroom cultivation. About 1600 kg vegetables and 60 kg of *Pleurotus* mushroom worth INR 35,000 and INR 42,000 respectively were produced. Cultivation in polyhouses gives protection against climate extremes, which are on increase in high and remote Himalayas.

Key words: Appropriate technologies, community, household well being, livelihood, technical interventions, timberline, tourism.

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Introduction

In the Himalayan region, the high altitude areas have remained marginalized in the context of larger development process. The people of these areas face harsh climatic conditions, difficult terrains and infrastructural deficiencies, due to which they remain away from the mainstream development (Mohinder 2013). Invariably forest resources and agriculture provide the major livelihood for such communities, and forests are also used extensively for grazing, fuelwood and fodder collection by them (Rahmani 2003). However, degradation of forests due to

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indiscriminate biomass harvesting and reduction in agricultural production has considerably affected livelihoods of these communities. Presently, social and economic stagnation is the major concern in Indian Himalayan Region (IHR), as elsewhere in Himalayas. In this region 30–40% population lies below poverty line and over 45% people are unemployed resulting in a poor physical development, weak immune system of inhabitants, and high maternal and infant mortality (Anonymous 2010). In addition, over last few decades, climate change has emerged as an overriding factor, impacting upon very sustenance of people.

In the above context, the conservationists and the development practitioners equally agree that livelihood improvement and diversification hold a key to promote poor people's livelihood and encourage them to minimize exploitation, thereby reduce degradation of natural resources (IMM 2008). Despite this understanding, the attempts supporting livelihood enhancement and diversification have remained supply-driven and more focused on single 'blueprint' solution with limited market appeal and poor reflection for fast changing people's aspirations for future.

Within IHR, people in high altitude areas (i.e., 2000 m asl) still heavily depend on neighbouring forests, including those of timberline ecotones. Because of the inherent vulnerability to climate change, timberline ecotones are particularly stressed by pressure of diverse subsistence uses by local populations. Furthermore, widely recognized aesthetic, cultural and spiritual attributes of these high mountain areas have historically made them attractive to people, resulting in an additional pressure due to the continuous growth of religious, spiritual and adventure tourism.

The high elevation residents also remain disadvantaged and marginalized from mainstream economic processes due to general lack of economic enablers for marketing, institutional credits, energy, technologies and information, etc. All these have resulted in (i) a poor life quality of inhabitants, and (ii) an increased rate of forest degradation and loss of other natural resources. Considering the long term consequences of this situation, there is a need for an immediate attention from all concerns. Keeping this in view, the present study attempts to promote bio-resource based diversification of livelihood options as one of the potential solutions for maintaining ecological integrity of timberline ecotones and improving life quality of inhabitants in high altitude areas.

This paper analyses a case study of villages nearby timberline in the central part of IHR with focus on some livelihood interventions as a possible way-out to reduce pressure on valuable biodiversity components and ecosystem services of this important zone. The available studies on this theme have mostly focused on figuring out the factors that enable households to diversify livelihoods options (Adhikari 2008b; Blaikie & Coppard 1998; Ghimire *et al.* 2014; Rahut *et al.* 2014). Such studies have definitely provided inputs for policies and programmes that would foster enabling environments for livelihoods diversification. However, a larger question has broadly remained under-attended- to what extent and in what socio-economic condition livelihood status of the community residing nearby timberlines can be enhanced? The present study, to a large extent, attempts to fill this gap by measuring the impact of existing on-farm and non-farm livelihood options on household well-being and identifying the socio-economic conditions that favour a particular option for livelihood improvement. This has been achieved by way of: (i) developing a composite well-being index and identifying 'high' and 'low' return livelihood activities in terms of contribution to community well-being, (ii) analyzing economic, social and demographic characteristics of households that determine their involvement into different on-farm and off-farm sectors, and (iii) demonstrating appropriate livelihood interventions and strengthening capacities of communities for adopting and expanding such interventions. Needless to say, developmental activities take a long time to achieve targets, hence our inferences are likely to be premature, and should be taken with caution.

Methods

The study targeted four high altitude villages of Chopta-Tungnath area in Rudraprayag district (30°28′56.3″ to 30°30′57″ N and 79°08′3.79″ to 79°09′44.9″ E, a border district), Uttarakhand. Being located in a high altitude zone, study area faces topographic and climatic constraints that limit agricultural production. Traditional climate regulated agro-pastoral transhumance is a common practice in this area. Owing to remoteness and harsh climatic conditions, the market and the trade options are limited. Only 2.2% of total cultivated land of the studied villages is irrigated (Census of India 2011); therefore, agriculture, by and large relies on natural precipitation, and is highly vulnerable to vagaries of weather. In general, as

Table 1. Socio-economic profile and energy consumption in four timberline (Tungnath, Uttarakhand) connected study villages.

Socio-economic profile	Sari	Huddu	Tala	Makkumath
Mean Altitude (m asl)	1963	1788	1872	2096
Total Households (HHs)	230	106	96	450
Total Population (nos.)	995 (784*)	550 (361*)	544 (544*)	1500 (950*)
Number of HH surveyed	115	53	48	225
Average family size (Ind./HH)	4.33	5.19	5.67	3.33
Average land holding/family (ha)	0.13	0.28	0.35	0.26
Average annual income per family (INR)	9248	14183	13386	35683
Livestock				
Households having livestock (%)	97	94	89	97
Livestock density per HH	3.91	5.58	5.72	3.61
Average fodder consumed HH/year (ton)	9	8	6.5	11
Distance covered for fodder collection (km)	2.5±1.0	2.5±0.5	2.8±0.25	3.0±0.5
Number of days when fodder is collected in a year	200	175	150	250
Energy consumption by villagers				
Average Fuelwood consumption/HH/year (ton)	6.5±1.0	7±0.5	7.5±1.5	8.5±0.5
Distance travelled for Fuelwood consumption (km)	2.0±0.5	1.5±1.0	1.5±1.0	2.5±1.0
LPG using families (%)	94.6	94	100	95.2

Source: Survey under the project study, 2016; * Census of India 2011.

Table 2. Study villages with social construct.

Study Village	Households	Male	Female	Literacy rate (%)*	Brahmins (%)	Rajputs or Thakurs (%)	Schedule Caste (%)
Sari	230	488	507	69.85	10.0	80. 1	9.91
Huddu	106	282	268	70.0	5.0	71.0	24.0
Tala	96	269	275	70.03	-	100.0	-
Makkumath	450	702	798	75.67	45.0	30.2	24.8

Source: Survey under the project study, 2016; * Census of India 2011.

elsewhere in Himalayas, the agriculture production in study area remains grossly inadequate to meet the food demand (Adhikari 2008a).

To understand the pressure on timberline ecotone, the village people were interviewed at a household level about their requirement of fodder and fuelwood the use of alternative fuel like LPG. Various methods were applied for collecting precise and quantitative data for income generation and livelihood resources i.e., questionnaires, Focus Group Discussion (FGDs), general observation, individual interviews, meetings and discussion with village representatives i.e. Villlage head, Sarpanch, etc. The data collected also include information on family size, education level, land holding size, number of livestock, livelihood resources, income and income sources, energy, dependency on forests for fuelwood/fodder/NTFP, enrollment of females in livelihood and agriculture activities and others. These exercises helped us to develop an idea about socio-economic status of people. The information on distance travelled to collect fuelwood and fodder and the time consumed was also gathered (Table 1).

Traditionally, there are three prominent social groups (i.e., caste/ethnic groups), namely Brahmins, Rajputs and Dalits (Schedule Caste). Of these, nearly 80% belonged to upper caste (i.e., Brahimins and Rajputs) and remaining 20% to Schedule Caste. Details of studied villages and their social construct are given in Table 2.

The data from selected villages were collected

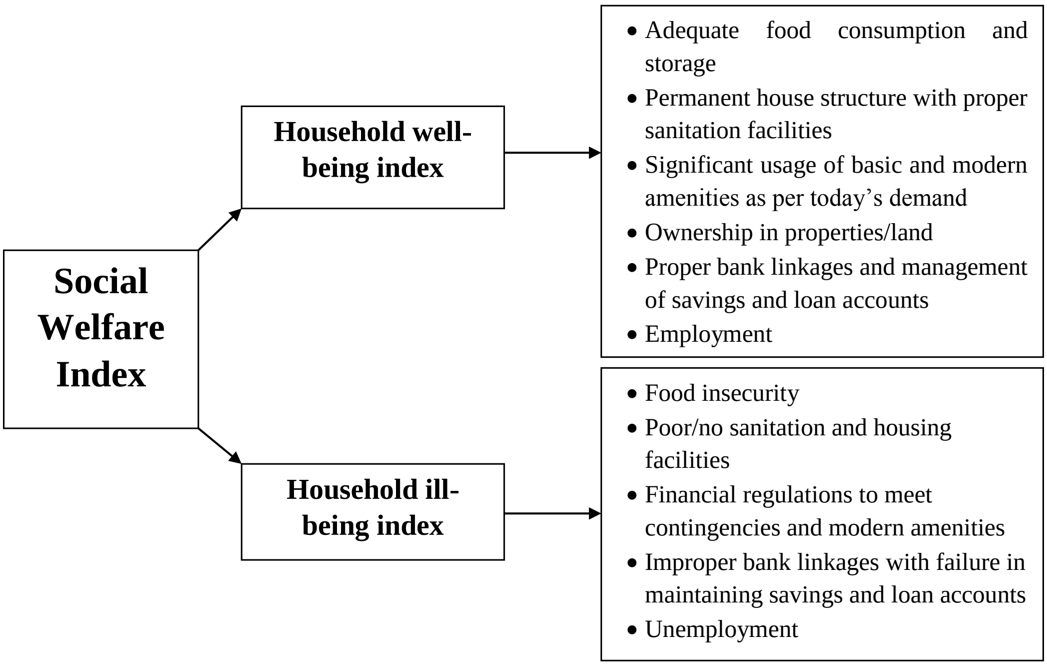

Fig. 1. Derived social well-being index and associated household characteristics.

Table 3. Participation of social groups and gender in group discussions across the studied villages.

Social Groups	Male	Female
Brahmin	30	25
Rajput	140	85
Scheduled Cast	65	45

during 2016 following household surveys, focus group discussion and Participatory Rural Appraisal (PRA). The design and administration of the survey questionnaire were based on rapid and extensive preliminary qualitative inquiries. At the beginning, a series of informal discussions and several in-depth interviews with villagers were conducted. This was followed by a total of 10 village level group discussions to generate information on various aspects of the local livelihoods.

In addition, a local wealth classification, employing locally valued asset criteria for household well-being, was also attempted. The assets/ components considering household well-being was elicited by discussing with the community members to figure out the major differences between the wealthy and poor households (Fig. 1). In the contextof assets, selected variables for composite well being index included: food consumption, housing/logistics, connectivity and dependency on banks, land holding, infrastructure, livestock and employment. While conducting group discussions, recognizing that social groups (i.e., caste) and gender form the major factors in shaping local power relation, the groups were composed in such a way to maintain homogeneity within groups and heterogeneity between groups (Bedford & Burgess 2001). The total number of group discussions was based on the concept of 'theoretical saturation' (Agar 1996; Bryman 2004). Therefore, inclusiveness of social groups and gender in participation across group discussions was ensured (Table 3).

Before the household surveys, a structured questionnaire was developed to gather the baseline information, and administered to 450 households (>50% of the targeted households) which represented statistically sizable population of all the major castes/ethnic groups. Considering that well-being of the residents is the major desirable outcome of assessment of existing livelihood options, the indicators of well-being remained central to the analysis. Better livelihood is associated with having things or resources of 'prudential values' (Griffin 1986) that enables meeting various elementary needs of life. The idea of a better lifestyle, therefore, makes well-being a relative concept, defined according to material circumstances as well as individual preferences and social and cultural contexts. The group discussants were asked to (i) inventorize the key components/assets characterizing a 'quality of life' or household 'well-being'; and (ii)to classify and categorize of the components which would represent households livelihood status.

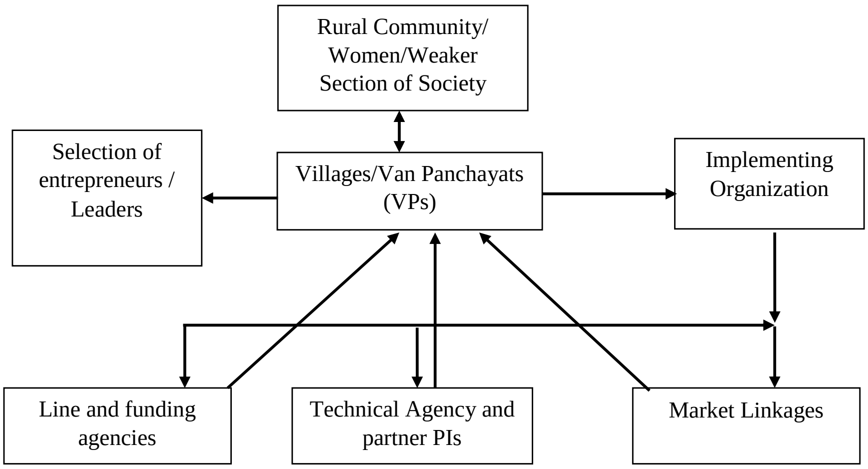

Fig. 2. Implementation mechanism following participatory approach.

Table 4. Composite Household Well-being Index in context to different social groups in all studied villages.

	Brahmins (%)	Rajputs (%)	SCs (%)
Food consumption	100	100	70
Housing/ Logistics	95	90	12
Connectivity and Dependence on Banks	90	85	50
Ownership of land	100	100	20
Infrastructure	100	100	100
Livestock	100	100	70
Employment	98	95	60

Source: Survey under the project study, 2016.

While linkages of inhabitants with timberline ecotone were major consideration for village selection, it also considered the willingness of the community and resources availability for the implementation of technical interventions. Compact Area Approach was adopted for implementation of the livelihood interventions, and to gear up activities for entrepreneur development and ensuring market access (Singh & Rawal 2017) (Fig. 2). Our assumption was that the positive results, if any are likely to be adopted by other beneficiaries and there is every livelihood that they also get replicated in nearby villages. Based on the engagement of households for livelihood generation and contribution of different livelihood activities in income generation, the existing options were analyzed. Based on PRA, FGDs and discussion with allied stakeholders, the main options were categorized based on certain criteria (i.e., economic viability, availability of local inputs, post produce analysis (market), risk assessment, sustainability and willingness of inhabitants for adoption of activity, etc.).

The cost-benefit analysis of each intervention (at a demonstration scale) was worked out and mainly depends on the nature of intervention, materials/items required for infrastructure development, land area treated/covered and other monetary inputs, yield of the products (agro and others) and their monetary equivalent. The major monetary inputs for the technologies tested/demonstrated included materials/items such as UV polythene, bamboo poles, vegetable seeds, mushroom spawns, etc. The monetary output included yield of the produce/products and their monetary equivalent based on the current market rates. The manpower required for different activities/operations under each technology was calculated based on the existing daily wage labor rates.

Results

Household characteristics and well being

In the study area there was no food deficit, though food production was inadequate to meet people's food requirement for whole year, because people could get food from Public Distribution System and purchase from market. Dependency of SC households was high on government supply through PDS in comparison of other groups. At least one individual from each household was engaged in one or the other income generating activity (other than farming). On the basis of food security criteria, which considered elements of adequacy, access and food preference, >90% households were food secure (Table 4).

Table 5. Percentage of household engagement in different livelihood activities at village level.

Village	On farm activities		Off farm activities			
	Agriculture (%)	Horticulture (%)	Business (%)	Labour (%)	Tourism (%)	Service (%)
Sari	94	65	15	80	70	10
Huddu	90	61	10	70	20	5
Tala	100	47	20	60	32	7
Makkumath	95	85	80	20	80	10

Source: Survey under the project study, 2016

As for basic household facilities and goods, the households falling in upper caste/ethnic groups had access to toilets, safe drinking water, LPG and improved stoves. They also had TV, radio, telephone, etc. In contrast, only 10–12% of the SC households had access to such amenities. Nearly all households had bank linkages. About, 50% of SC households (80 households) had bank and private loans, but 30% of them (24 households) were not able to repay the loans. The poorer households revealed that their subsistence living often got affected, due to the unforeseen events, such as loss of crops, diseases, and marriage, etc. which put an additional financial burden on them. On an average across all villages the cultivable land was 0.21 ha per household, and it was relatively smaller for SCs. In general SCs were found to be the most disadvantaged also in terms of other socio-economic indicators. Compared to state level literacy of 78.8%, entire population level literacy was 71.4%. Almost all households cultivated agricultural and horticultural crops (viz. wheat, paddy, finger millet, barley, jhangura, kidney bean, garlic, onion, cucurbits, cauliflower, cabbage, tomato, soyabean, brinjal, malta (citrus fruit), walnut, etc.) most for self consumption. However, some of the households treat malta (a citrus) and walnut as cash crops. Of the total livestock (3,470), cows were about 40%, buffaloes 4.6%, sheep and goats 21.3%, horses and ponies 4.1% and poultry 30.2%. The villagers reported an increase in the population of buffaloes and decrease in sheep and goats population in recent years. However, PRA indicated a decrease of 5–7% in buffaloes and sheep and goat population in last one decade. Cows and buffaloes were generally stall-fed, while sheep and goats were left for grazing in nearby forests and for about 6 months (April–September) in alpine meadows. With the increase in stall-feeding for a decade, the demands for fodder and workload on women have increased. Fuelwood and fodder collection is a major household activity, forcing women to travel considerable distances and spend a lot of time on fuelwood and fodder collection from the adjacent forests. On an average fodder and fuelwood were collected on194 days during a year and women spent about 3–4 hours and travel on an average 2.75 km per day to collect 40–45 kg fodder or 30–35 kg fuelwood as their backload in the studied villages. Days for fodder collection varied in studied villages. Demand for fodder is uniform round the year, though scarcity of green forage during winters is common feature (Dhyani & Maikhuri 2012). Fuelwood consumption varied in different villages. People's dependence on forests for collection of fuel wood, and fodder is considerable viz. 7–10 ton fuel wood and 8–12 ton fodder per household per annum. The consumption goes up-to 10–14 ton fuel wood per year in restaurants of Chopta-Tungnath area. In general, the fuel wood consumption was comparatively higher among 15% of households, most of which belonged to SC families as they could not afford buying cooking gas and enough warm clothes.

Existing livelihood status

Most households are engaged in agriculture, but it does not produce enough food to meet their needs. That is why households are engaged in other activities, such as horticulture (64.5%) (vegetable and fruit cultivation); business (31.25%) which included running restaurants, shops, lodges, camps, etc.; labour work (57.5%) which included employment at restaurants, shops, and under different government schemes such as MNREGA etc.; tourism and allied jobs (50.5%) and government jobs (8%) (Table 5). Farming was common to most of 94.75% households. It may be pointed out that in many cases, households were involved in more than one income generating activity, that is why sum of all percentages exceeds 100%. The long winter period is generally a lean period for agriculture, which offers a window of opportunity to attempt non-farm income sources beyond local settings. Employment as laborer was the second most important income resource in the studied villages. Many youth migrate to foothills or other regions seasonally for wage labor (wage migrants ~ 50% households). They return before the beginning of the next farming season with small amounts of cash and consumer goods.

About 50% households and 75% youth population were directly engaged in tourism sector and its allied jobs such as local porter, guides, and bird watcher etc. As tourist flow is seasonal, the tourism based livelihood is not a continuous income source. However, individuals involved in tourism related activities (TRAs) earned ₹ 1500–3000/day, but only during tourist season. Tungnath and Deoriatal are the most favourite tourist destinations of the study area. On an average approximately 30,000–35,000 tourists visit Deoriatal annually in a season; while 20,000–25,000 tourists visit Tungnath during the tourist season. The total income generation through tourism activities like local porting, guiding etc. in a season is approx. INR 80,00,000 and at household level it accounts for INR 23,000 for Makkumath while for Sari it is approx. INR 15,00,000 and INR 10,000 at household level. The record of Rudraprayag district shows that 68,60,306 tourists visited Rudraprayag district during 17 years (2000–2016); of which 18,143 (more than one fourth) were foreigners and the rest were domestic tourists (Tourist Statistical Handbook, Rudraprayag district). As per the information available with Uttarakhand Tourism Development Board (UTDB) in Rudraprayag about 58% of the international tourists visited for holidaying, 22% for enjoying nature and adventure, and 19.4% for pilgrimage/religious functions. However, for domestic tourists main purpose was pilgrimage/religious (44.2%), followed by 43.6% for holiday/trekking/bird-watching, etc.

Business (trade) largely connected with tourism engaged about 31% of households. Among others, ringal (hill bamboo) weaving and handicraft making are also important income sources mostly for SC households. NTFP collection was reported by about 12% households. Among NTFPS, collection of medicinal plants such as *Picrorhiza kurroa* (Kutiki), *Aconitum heterophyllum* (Atees), *Rheum australe* (Archa), *Datcylorrhiza hatageiria* (Hatajari), *Bergenia legulata* (Pakhanbed), *Morina longifolia* (Biskandara), *Aconitum balfourii* (Meetabis), *Polygonatum verticillatum* (Kanthalu), *Zanthoxylum armatum* (Timur) and *Delphinum denudatum* (Nirbisi), *Angelica glauca* (Chora), *Allium consanguineum* (Faran), *Tinaospora cordifolia* (Geloi), *Phyllanthus embilica* (Anwala), *Terminalia chebula* are major species. In general, these medicinal plants are collected by the local residents for self-use in traditional health care system.

To summarize, while agricultural involvement continues in this timberline area, tourism, both religious and non-religious contributed significantly to economy and has kept out migration in check. On an average tourism accounted for 47.3% of the total income generated in studied villages, followed by business (33.8%), labour (12.8%), government job (3.2%), and horticultural cash crops (2.6%) and agricultural cash crops (0.16%). The income has kept most people rooted in their villages, but is not enough to have health security and quality education. Poverty still is a major issue.

Interventions for livelihood diversification

Following the results of rapid field surveys and the review of secondary data, five most viable additional interventions were considered for promotion and demonstration keeping in view discussion with stakeholders, and resources and time period available. They were off-season vegetable cultivation, mushroom cultivation, floriculture, vermin-composting and rainwater harvesting tanks.

The two villages, Makkumath and Sari were selected for demonstration of the appropriate livelihood options based on willingness of communities, timberline connection and potential resource availability. A total of 15 training sessions (each of 2–3 days) on appropriate rural technologies were organized in selected villages. During 2016–2017, a total of 595 participants from different social groups were trained. The target group for training and demonstration were rural and marginal farmers (50%), youths (16%), marginal shopkeepers (3%) and restaurant owners (5%) while 19% of the targeted population was female. Exposure-cum-training events were organized for students of high school to post-graduate level so as to inculcate professional and scientific spirit, and popularize knowledge and approaches of simple rural technologies. As a direct result of these efforts, there are now a number of households which have adopted such technologies and enhanced their income significantly. Among all the livelihood

Table 6. Introduction, adoption and cost-benefit (C-B) analysis of innovative livelihood options.

Name of technology	Adopted families (nos.)	Total monetary input (INR±SE)	Net monetary return (INR±SE) I year	Net monetary return (INR±SE) II year
Vegetable Cultivation				
Low cost bamboo Polyhouse	24	14500±1000	5800±250	9700±350
Open conditions	120	750±150	1850±175	2000±200
Organic composting				
Movable composting bed	12	1170±200	850±100	900±100
Open conditions	120	00	150±30	150±30
Mushroom cultivation				
Pleurotus spp.	8	1000±350	3500±250	3500±250
Non farm income generating technologies				
Floriculture	12	5000±250	900±150	1400±200
Ringal weaving	5	1200±100	3000±200	5000±300

interventions, off-season vegetable cultivation was most favored (adopted by 120 households), followed by organic composting (24 households) and mushroom cultivation (8 households). Some important vegetables viz. *Lycopersicon esculentum* (tomato), *Brassica capitata* (cabbage), *Brassica oleracea* (cauliflower), *Capsicum annuum* (capsicum), *Pisum sativum* (pea), *Coriandrum sativum* (coriander) etc. were selected for cultivation trial using high value seeds. The net monetary return was higher under mushroom cultivation followed by off-season vegetable cultivation, vermi-composting, and floriculture. The participatory action research and demonstrations on rural technologies created awareness among and acceptability the people. Performances of important vegetable crops under poly houses and open field condition were evaluated. Observations recorded for two successive growth seasons indicated that the yields of that several vegetables increased significantly by 25% in poly houses as compared to open conditions (Table 6). Thus off-season vegetable cultivation under polyhouses can be used as a strategy to deal with climate change and to create favorable conditions for production in adverse climatic conditions.

Discussion

Our findings are broadly in agreement with the understanding that a household can enhance its well-being by pulling into its livelihood portfolio in a high return sector(s) among various non-farm opportunities available. The asset-poor households, often fail to overcome the entry barriers and are confined to low return sectors that make insignificant contribution to well-being. There is also a positive feedback effect in this nexus that reinforces the well-being conditions: already rich households accumulate assets that form the basis for further lucrative diversification. The poorer households, on the other hand, are trapped in the same low return sectors resulting in overall widening of inequality (Barrett *et al.* 2001; Canagarajah *et al.* 2001; Reardon *et al.* 2000). This can be better explained using a schematic framework (Fig. 3) which recognizes that the ecosystem services and livelihoods issues are interdependent. The equilibrium between the two is the solution to achieve wellbeing in the region. However, it may be pointed out that in these remote mountain villages, most of the households are asset-poor, and rich households are not rich in the sense the term is used in mainstream economics. It is too early to assess the impact of developmental interventions we introduced in the project, however, their easy adoption at household level is quite encouraging. Our household level interventions played a role in generating cash, which has been scarce in the region historically.

Production is comparatively high under polyhouses and it can be managed round the year. Thus it can be treated as a useful climate change adaptation. Rural people are now able to grow vegetables for their own consumption, and market some amounts to the nearby market places. In our present study area, tourism seems to have emerged as a viable non-farm economic activity. The holy shrines located at mountain peaks in nearby alpine grasslands have great cultural and aesthetic values. Further, considering that the Tungnath-Chopta area is rich in biodiversity and provides

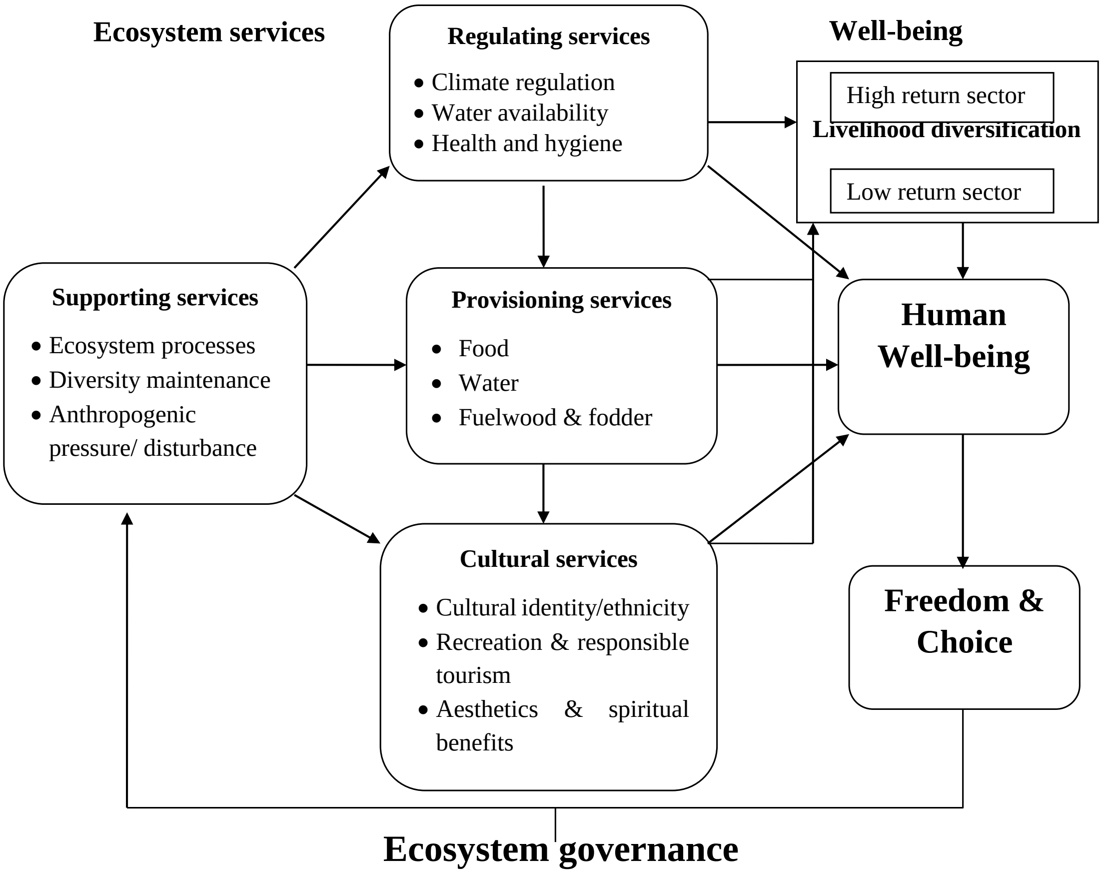

Fig. 3. Schematic framework of ecosystem governance for well being of human.

wonderful opportunities for socio-cultural and natural interactions, there exists a vast scope for promotion of livelihoods activities in this sector. In many parts of the Himalayas, nature and biodiversity based tourism activities have succeeded in improving livelihoods of local inhabitants and conservation of biodiversity (Bhalla *et al.* 2016; Huyett 2013; Lama 2016; Rai & Sundriyal 1997), but due to the lack of awareness, training, entrepreneurship approach and capital, this sector could not grow enough to bring about a major economic change. There is huge potential and scope to develop it by promoting home-stays, capacity building of porter and guides, bird watching, nature interpretation, wilderness trekking, herb based health tourism, handicrafts, etc.

As the data at state and local levels indicate, the income from tourism does not correspond to the number of tourists. Some of the reasons include: tourists' stay period is short and getting shorter; locals are poorly trained in managing nature tourism, and the share of money distributed locally is low in overall economy. Neither local workers have enough knowledge about vegetation, animals and overall natural assets to make tourists interested, nor tourists are interested in them on their own. Some centres are needed to train local bodies and individuals, and tourists. However, involvement in this sector is determined by education, good social networks and financial investment capacities. The social groups (i.e., caste and ethnicity) most notably reflect distribution patterns of these assets and therefore the resultant patterns of livelihood diversification in Chopta-Tungnath area. The rich biodiversity (flora and fauna) embedded with religious sentiments of people along with the natural scenic beauty of this area marks the origin and sustenance of tourism. We tried to make people to cultivate flowering plants and connect flowers with religious tourism.

In spite of some non-farm activities, the local people connected with Tungnath treeline ecotone still heavily depends on natural ecosystem services and goods. About 62% of the total fodder need is met from the forests (tree, shrub, leaves and herbaceous ground flora), the remaining 38% fodder materials come from agroforests, low-altitude grasslands, degraded lands, high-altitude grasslands and crop residues (Malik *et al.* 2014). During the rainy season, although the fodder is available abundantly, it is not managed efficiently due to the lack of awareness and practices to store them for feeding during lean periods. Despite abundant resources with immense potential for producing quality and quantity fodder, the issue remains unsolved (Dhyani & Maikhuri 2012).The increase in tourist flow results in increased demand for energy for cooking, heating and campfires by lodges as well as trekking and mountaineering expeditions. Although, the initiatives have been taken to promote alternative sources of energy for reducing dependency on natural resources, at present they are still very limited and uncertain. Initiatives like installation of solar panels, solar water heaters in lodges/restaurants and bio-gas units at village level can play significant role in promoting clean and alternative energy.

Presently, it is estimated that more than 15,000 sheep and goats, 2000 buffaloes and about 8000 mules graze in temperate and subalpine region of Kedarnath Wildlife Sanctuary (Singh 2008). The unregulated grazing by domestic livestock around summer cattle camps has led to the loss of about 8% of forest cover around the outer fringes of KWLS during the last three decades (Thakur *et al.* 2011) and such current levels of pastoral practices in and around this protected area are clearly unsustainable. Dhyani & Maikhuri (2012) advocated for the establishment of fodder banks across high-altitude village clusters of Western Himalaya.

It is evident from the PRA conducted and the interest shown by the communities towards new interventions that households with limited livelihood options are more likely to invest in appropriate modern technologies or ideas aiming at economic diversification. In addition, the collective approach of farming and production through groups could be strengthened. The floriculture specifically marigold cultivation can be up scaled in consultation with temple committees. The nonfarm sector is also vital to have livelihood options and mushroom cultivation is one of them. To upscale the activity, master trainers will be developed in the project area with focus on production of spawn for mass scale promotion. The all above activities will result in developing Rural Resource Persons (RRPs) who can further upscale and support the interventions in the region.

The Brahmins have served the region as priests of the Tungnath Temple in the higher altitudinal areas for several years, whereas the Maithanis and Rajputs occupy more productive land in the valley-bottoms that offers better food self-sufficiency. SC population originally comprised landless laborers and artisans. They are traditionally engaged in a wide range of activities (Bishop 1990). Arguably, this variation in land ownership in the study area can explain why SC households are more likely to be involved in wage labour.

The determinants of business sector, another high return non-farm activity, are also related to human and social capitals. The prospects for business are meager for the majority of people with poor education, social networks and capital investment, and the opportunity skews heavily toward households having educated members, social networks and investment. The poor subsection of the population, unable to get involved in non-farm livelihood generating activities, is often forced to adopt activities that do not require high investment capacities.

The individuals from SC community are involved in various occupations, such as making of a wide range of traditional agricultural tools and handicrafts (*ringal* weaving) through which they serve upper caste who offer a certain amount in exchange (Adhikari 2008a). Handicraft and tool making reflects a need as a strategy to meet or maintain survival which does not contribute substantially towards better livelihood due to inadequate land by majority of SCs (Ellis 2000).

Conclusion

Although it is too early to conclude, yet two main indications have emerged from this study. First, responsible tourism can play a role in promoting inhabitants income as well as in contributing to biodiversity conservation; our study clearly reflects that the tourism in the study area is dependent on biodiversity, natural beauty and religious sentiments, therefore, a strategy which considers all these factors would be required to promote this sector. Second, diversification, as such does not contribute to wellbeing; rather a household's ability to pull high return sectors into its livelihood portfolio is more instrumental in enhancing well-being. A household's ability to diversify into a high return sector is dependent on antecedent level of resources and assets: both tangible and intangible assets. Therefore, a prospective look at future livelihoods is needed. This highlights the need for small-scale rural poverty reduction interventions that directly target creating opportunities for most under-privileged ones. The functioning of system is complex; hence consequences of interventions can be unpredictable. Increased income can help conserving forests by replacing firewood with cooking gas. On the other hand a tourist restaurant can increase pressure on forests by cutting trees for firewood. So it is important to link income generation to conservation.

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Over-representation of some taxa in surface pollen analysis misleads the interpretation of fossil pollen spectra in terms of extant vegetation

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Abstract: Pollen grains of 21 surface samples (moss cushions) from two forest types, chirpine (*Pinus roxburghii*) dominated mixed forest at Mahidanda (MAD) and oak (*Quercus* spp.) dominated broadleaved forest at Nachiketa (NAT) (Uttarakhand, Western Himalaya) were analyzed for the pollen-vegetation relationship. At both sites samples consisted of pollen of local species (species occurring within the study forest, referred to as autochthonous pollen) and those of extra-local species (occurring outside the study forest, referred to as allochthonous pollen). The study reveals that pine pollen were highly represented at both the sites due to its profuse pollen production and long distance transport by valley winds. However, in the oak forest, there was a good representation of pollen from diverse broadleaved taxa like, *Alnus, Quercus* and *Rhododendron.* It has been noted that the proportion of oak pollen in surface samples is lower in comparison to earlier analysis from the same site. This might indicate the decline of oak and increase of fire resistant pine over time. The presence of pollen of species belonging to timberline and subalpine forests viz., *Abies, Picea, Cedrus* and *Betula* in both sites might indicate the role of valley wind in transporting the pollen grains from far off areas. It shows that the interpretation of past vegetation based on surface pollen analysis should be done with caution, as it may include pollen of species which do not occur there and species with a greater production and dispersal of pollen are over represented.

Key words: Conifer and broadleaved forests, modern pollen-vegetation relationship, Uttarkashi, Uttarakhand, Western Himalaya.

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Introduction

Recent global warming has had much impact on the vegetation pattern in terms of changing limit of the forest zonation in the Himalayas. To understand the temporal vegetation changes pollen studies are quite useful, but for that it is necessary to have modern pollen database. Chirpine (*P. roxburghii*) and banj oak (*Q. leucotrichophora*) are two major forest species of mid-elevational belt in the central Himalayan region. One of the major forestry issues in the region for quite some time has been the changes in the relative importance of these forests forming species (Singh & Singh 1992). Often chirpine is said to be expanding at the expense of banj oak because of frequent fires and lopping of oak branches for various purpose by local people. Modern pollen dispersal studies have been used to interpret changes in vegetation on the basis of fossil pollen spectra and climate (Bush & Rivera 1998; Crowley *et al.* 1994; Herzschuh *et al.* 2010; Li *et al.* 2005; Rull 2006; Yang *et al.* 2016), to find out the

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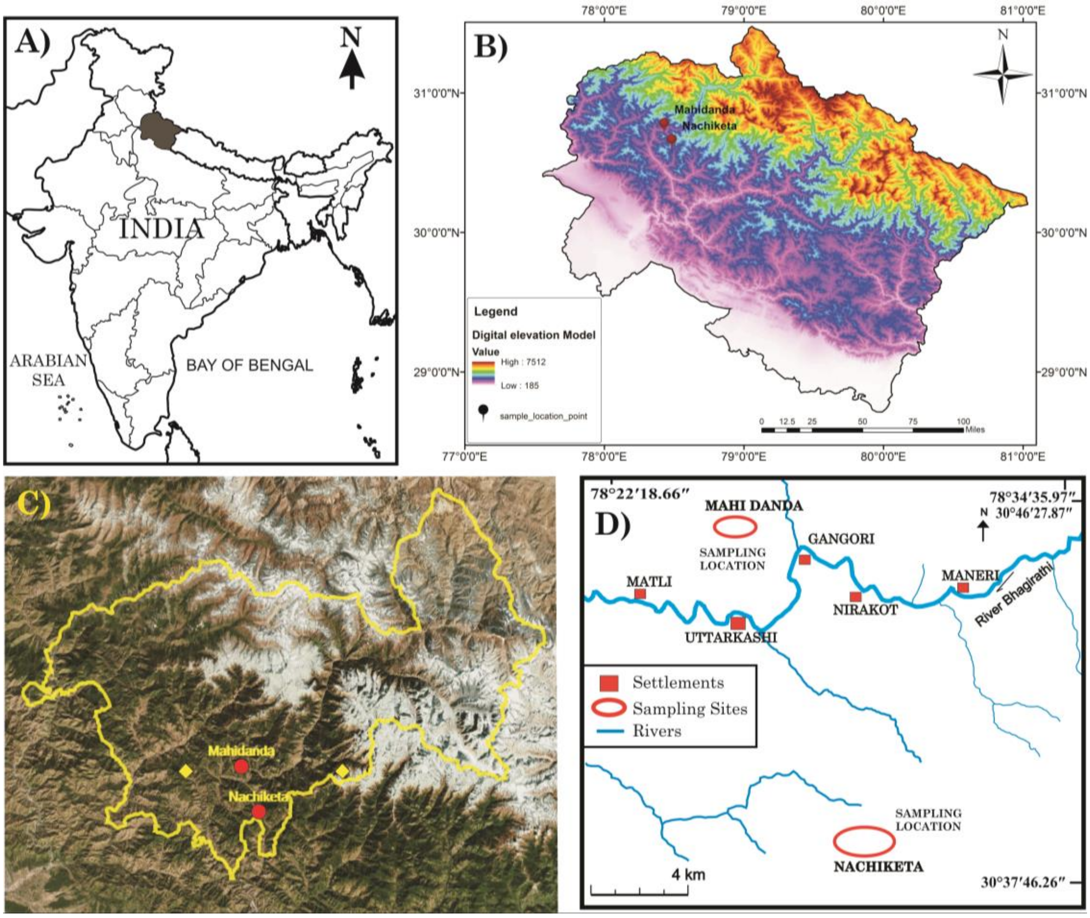

Fig. 1. (A) Map of India showing the Uttarakhand province, (B) Digital elevation map (DEM) of Uttarakhand showing the two study area Nachiketa and Mahidanda, (C) DEM of Uttarkashi district with the location of study sites (solid red circles) and the nearest CRU data grid points (yellow diamonds) for climate, (D) Sketch map of the area showing the locations of the two study sites, Uttarkashi town, surrounding settlements and other features.

relationship between pollen source area and plant abundance (Bunting *et al*. 2004; Sugita 1993), and to reconstruct the past land-cover and land-use changes (Gaillard *et al*. 2008, 2010; Mazier *et al*. 2015). There are a good number of modern pollen dispersal studies from different parts of Himalayas: moist, Indian summer monsoon (ISM) dominated eastern Himalayan and adjoining parts (Bera 2000); from the intense ISM - weak Westerly (ISM-W) dominant regions of western Himalaya (Chauhan & Sharma 1993; Gupta & Yadav 1992; Sharma 1985), Pindari Glacier area (Bera *et al*. 2011), Gangotri Glacier valley (Ranhotra & Bhattacharyya 2013), Chaurabari glacial area (Kar *et al*. 2016); Chota Shigri Glacier area (Bera & Gupta 1989), Rohtang area (Bhattacharyya 1989a), Lahaul-Spiti (Bhattacharyya 1989b; Kar *et al*. 2015) of Himachal Pradesh and primarily the Westerly dominant North-west region viz. Kashmir (Vishnu-Mittre 1966; Vishnu-Mittre & Robert 1971; Vishnu-Mittre & Sharma 1966). These studies provide modern pollen analogues from diverse environments of moist to dry vegetation/forest types on regional scale from east to the north-west Himalaya. Strong localized valley winds due to the steep pressure and temperature gradient within the short latitudinal distance play a major role in the transportation and influx of the pollen from one vegetation and climate regime to the other (Oliver & Fairbridge 2005). Thus, the modern pollen datasets from the Himalayan region need much attention for development of a good quality proxy for the reconstruction of past vegetation. For a better understanding of the regional pollen dispersal scenario and its relationship with the existing vegetation and climate, there is a need to

Table 1. The temperature (°C) and precipitation (mm) data of Uttarkashi town from the year 2009 to 2016.

Mean annual temperature (MAT)	21.8
Average temperature of summer months (JJAS)*	27
Average temperature of winter months (DJF)**	13.5
Mean temperature of hottest month (June)	30–31
Mean temperature of coldest month (January)	12
Mean Annual precipitation (MAP)	~1,500
Precipitation during summer months (JJAS)	~1,300
Precipitation during winter months (DJF)	~80

*June, July, August, September; **December, January, February
(Source: www.worldweatheronline.com)

gather more modern pollen datasets on the close spatial and altitudinal scale from the various climatic zones and forest types of the Himalaya.

This paper aims to understand pollen vegetation relationship in chirpine - banj oak forest zone of Bhagirathi valley. It sheds light on the factors which influence pollen assemblages and temporal changes in the importance of chirpine and banj oak. This work will also add to the database in the catalogue of modern pollen-vegetation relationships in the Western Himalaya, which could be used to interpret spatio-temporal fossil pollen spectra in terms of extant vegetation and climate.

Study sites

For understanding the scenario of pollen diversity in pine - oak zone, two sites, Nachiketa (NAT) and Mahidanda (MAD) near Uttarkashi Township in the Bhagirathi valley of the Garhwal Himalaya were selected (Fig. 1). NAT site (30°38'N; 78°28'E), is presently characterized by a small lake, named Nachiketa Tal, and evergreen oak forest (~2,200–2,500 m asl) consisting of *Quercus floribunda, Q. leucotrichophora, Rhododendron arboreum, Alnus nepalensis, Juglans regia,* and *Carpinus viminea* (Fig. 2). Chirpine (*Pinus roxburghii*), dominates on the comparatively drier open slopes, at relatively lower elevations around the NAT site (Fig. 2d).

The other study site, MAD (30°45'N; 78°25'E) is situated at ~2,000–2,100 m altitudes (Fig. 3). It is dominated by chirpine forest interspersed with trees of bluepine (*P. wallichiana*), *Quercus* and *Alnus*. Moist areas at both the sites support the growth of ferns and members of few Cyperaceae. The surrounding area is anthropogenically affected by the localized cultivation, cattle-grazing, and deforestation at some places.

Table 2. The temperature (°C) and precipitation (mm) data from the Climatic Research Unit (CRU-TS 3.22) of the University of East Anglia for Nachiketa and Mahidanda from the year 1901 to 2014.

	Nachiketa (NAT)	Mahidanda (MAD)
Mean Annual Temperature (MAT)	13.5	19.5
Highest temperature (June)	19.6	26.4
Lowest temperature (January)	5.2	10.1
Mean Annual Precipitation (MAP)	~1,100	~900

The last eight years' (2009 to 2016) temperature and precipitation data from Uttarkashi town (source: https://www.worldweatheronline.com/uttarkashi-weather-averages/uttarakhand/in.aspx) provide an idea of the climate of both sites (Table 1). Further, the temperature and precipitation data have also been obtained from the Climatic Research Unit (CRU) of the University of East Anglia [CRU TS v.3.22; (05 × 05 degree) grid; available at http://www.cru.uea.ac.uk/cru/data/hrg/)] for the period 1901–2014 CE (Harris & Jones 2015, Table 2). The variations in the temperature and precipitation amongst the NAT, MAD and Uttarkashi area might be due to differences in their altitudes as well as valley orientation controlling the monsoonal precipitation.

Method

Amongst the available natural pollen and spore traps viz., moss cushions, surface sediment, spider webs, cracks/hollows in tree stem and boulders etc., the moss cushions are the best natural pollen traps for the modern pollen dispersal studies. In total, 21 samples of moss cushions growing on the boulders were collected from the NAT and MAD localities and analyzed for the pollen dispersal. Of these 16 samples were from the NAT (Table 3) site (from ~2,200 to 2,500 m altitudes) (Fig. 2a,b) and five from MAD site (from 2,030 to 2,070 m altitude) (Table 4).

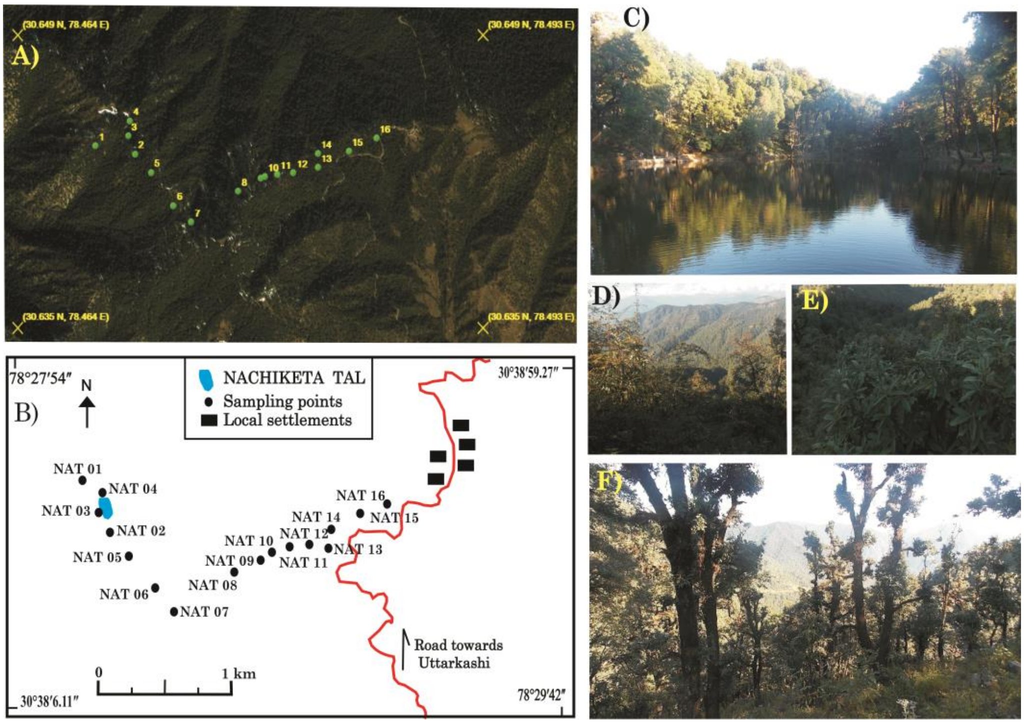

Fig. 2. (A) Google earth view of Nachiketa area showing the sampling points, (B) Sketch of Nachiketa area showing the location of Nachiketa Tal, sampling points and surrounding settlements, (C) View of Nachiketa Tal surrounded by broadleaved vegetation, (D) View of distant slopes with the pine growth, the source of *Pinus* pollen to the source area, (E-F) View of forest with growth of *Rhododendron* (E) and *Quercus* (F).

Table 3. Details of the surface samples collected from the Nachiketa (NAT) area near Uttarkashi, Western Himalaya.

Code	Lat. (N)	Long. (E)	Altitude (m asl)
NAT 06	30°38' 27.0"	78° 28' 25.4"	2492
NAT 07	30°38' 24.1"	78° 28' 29.4"	2478
NAT 05	30°38' 32.1"	78° 28' 20.4"	2477
NAT 01	30°38' 37.3"	78° 28' 07.9"	2444
NAT 04	30°38' 41.6"	78° 28' 15.7"	2442
NAT 02	30°38' 35.9"	78° 28' 16.8"	2440
NAT 03	30°38' 39.0"	78° 28' 15.3"	2439
NAT 08	30°38' 29.5"	78° 28' 39.9"	2420
NAT 10	30°38' 32.0"	78° 28' 45.9"	2419
NAT 09	30°38' 31.8"	78° 28' 45.0"	2416
NAT 11	30°38' 32.4"	78° 28' 48.7"	2388
NAT 12	30°38' 24.0"	78° 28' 48.0"	2385
NAT 16	30°38' 40.7"	78° 29' 44.5"	2306
NAT 15	30°38' 37.8"	78° 29' 10.5"	2295
NAT 14	30°38' 36.0"	78° 28' 57.8"	2294
NAT 13	30°38' 33.6"	78° 28' 57.8"	2255

Table 4. Details of the surface samples collected from the Mahidanda (MAD) area near Uttarkashi, Western Himalaya.

Code	Lat. (N)	Long. (E)	Altitude (m asl)
MAD 01	30°45' 37.37"	78° 25' 35.08"	2070
MAD 02	30°45' 36.22"	78° 25' 36.15"	2060
MAD 03	30°45' 35.12"	78° 25' 37.12"	2050
MAD 04	30°45' 36.2"	78° 25' 37.92"	2040
MAD 05	30°45' 38.22"	78° 25' 38.45"	2034

Forests of NAT site are dominated by broadleaved forest with *Quercus leucotricophora* and *Q. floribunda* as main constituents mixed with *Rhododendron arboreum, Alnus, Juglans, Corylus, Carpinus* etc. At MAD site, *Pinus roxburghii* (Conifer) grows on valley slopes with few broadleaved taxa.

For the extraction of pollen and spores the moss samples were processed (acid-base treatment) as per the standard technique (Erdtman 1943). 10 g dry mass of the moss cushions was treated with 10% potassium hydroxide solution to remove the extraneous organic matter, followed by the digestion of

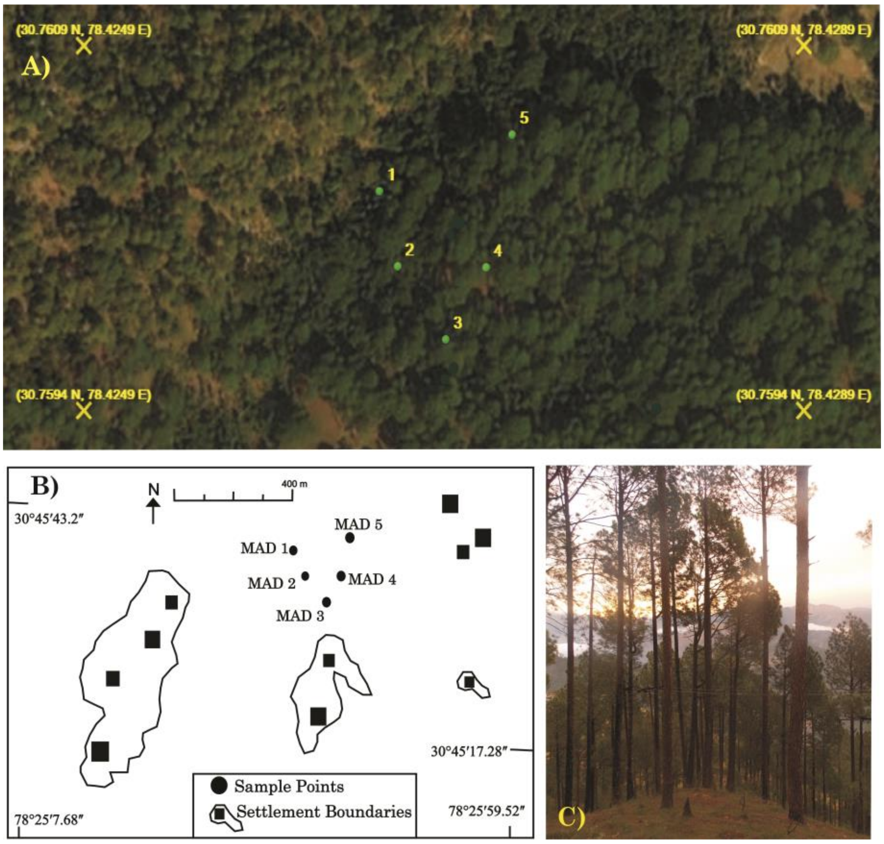

Fig. 3. (A) Google earth view of Mahidanda forest showing the location of sampling points, (B) Sketch map of Mahidanda showing the location of sampling points and surrounding settlements, (C) View of forest slopes with the growth of *Pinus roxburghii*.

silica using 40% hydrofluoric acid. The cellulose content was removed by acetolysis process (treatment with acetic anhydride and conc. sulphuric acid in 9:1 ratio). The samples were finally washed four times with distilled water to make clear of acid content by centrifugation process (2000 rpm for 10 minutes). The extracted samples were stored in glycerol and phenol to prevent them from drying and inhibit the growth of microbes.

The macerals were studied with light compound microscope (Leica DM 2500) under 20× and 40× magnification for the identification, counting and micrography of the recovered pollen and spores. For pollen and spores identification, the available pollen keys (Faegri & Iverson 1989; Gupta & Sharma 1986; Moore *et al.* 1991) and pollen reference slides available at Birbal Sahni Institute of Palaeosciences, Lucknow, were used. Between 350 and 800 pollen and spores per sample were counted, and they were taken as Total Pollen Counts (TPC). Pollen diagrams (Figs. 4, 5) representing the pollen frequency spectra of the samples were prepared using Tilia software version TILIA 1.7 (Grimm 2011). Two pollen diagrams were plotted; the first one represented the pollen frequency of individual taxa for each sample, arranged according to their altitudinal distribution (Fig. 4). The calculation of pollen frequency of each pollen taxon is based on the Pollen Sum (PS) which excludes the count of fern spores (monoletes and triletes) from the TPC. This was done to avoid the under representation of ground or herbaceaous pollen taxa in the frequency calculation, as some samples collected near the ferns represent very high counts of the fern spores which may overshadow the actual representation of other non-arboreal taxa in the frequency. The frequency of fern spores, shown in the pollen diagrams, has been calculated on the TPC. In the altitudinal pollen diagram (Fig. 4), the variations in pollen frequency throughout the diagram were demarcated as per altitude for which determination was done by cluster analysis using constrained incremental sum of squares (CONISS) method available in Tilia 1.7 software (Grimm 1987, 2011). For assessing the ecological similarities of the

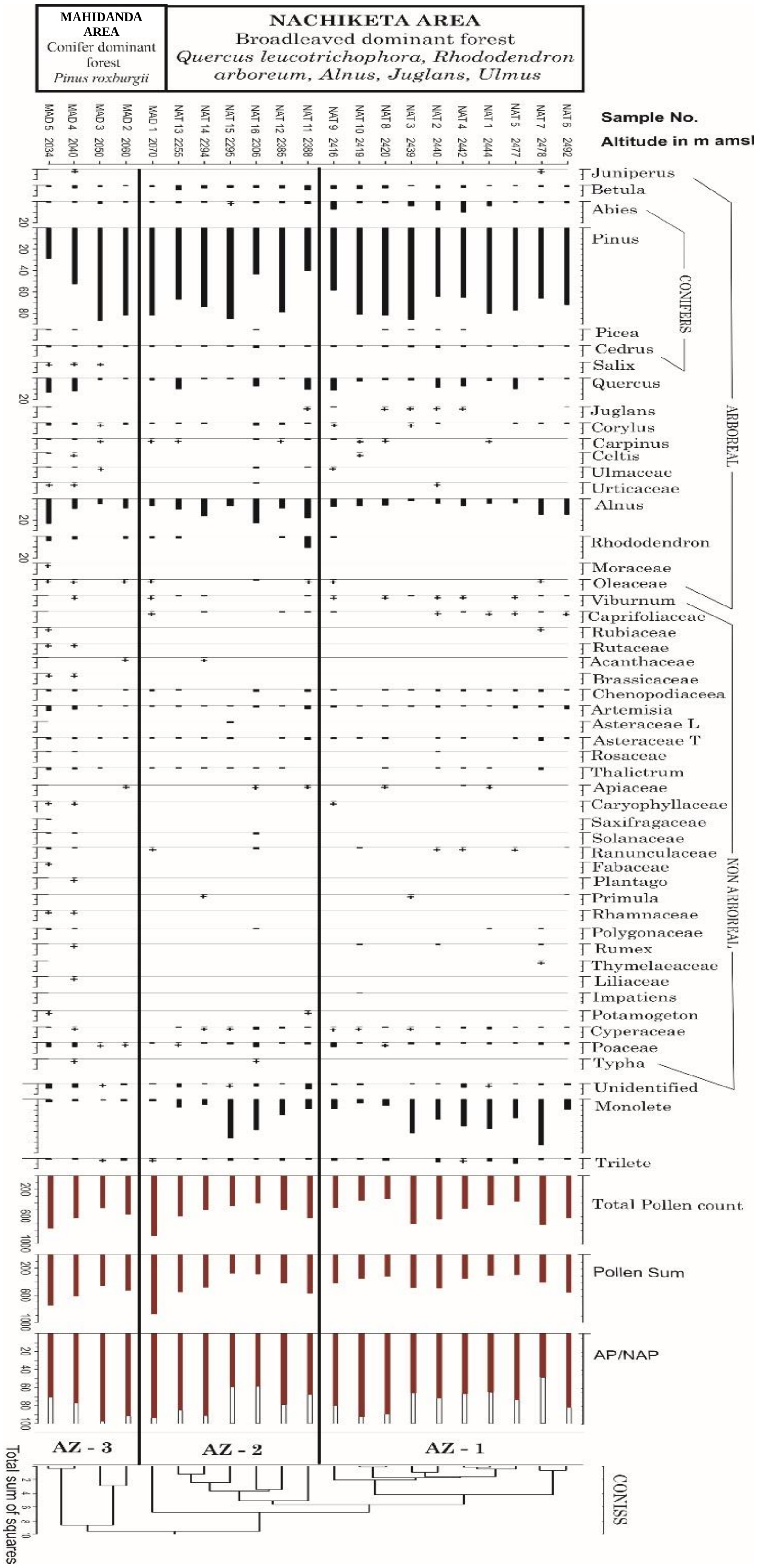

Fig. 4. Modern altitudinal pollen spectra. Each sample pollen spectrum is arranged according to the altitude. NAT represents samples of Nachiketa and MAD represents samples of Mahidanda.

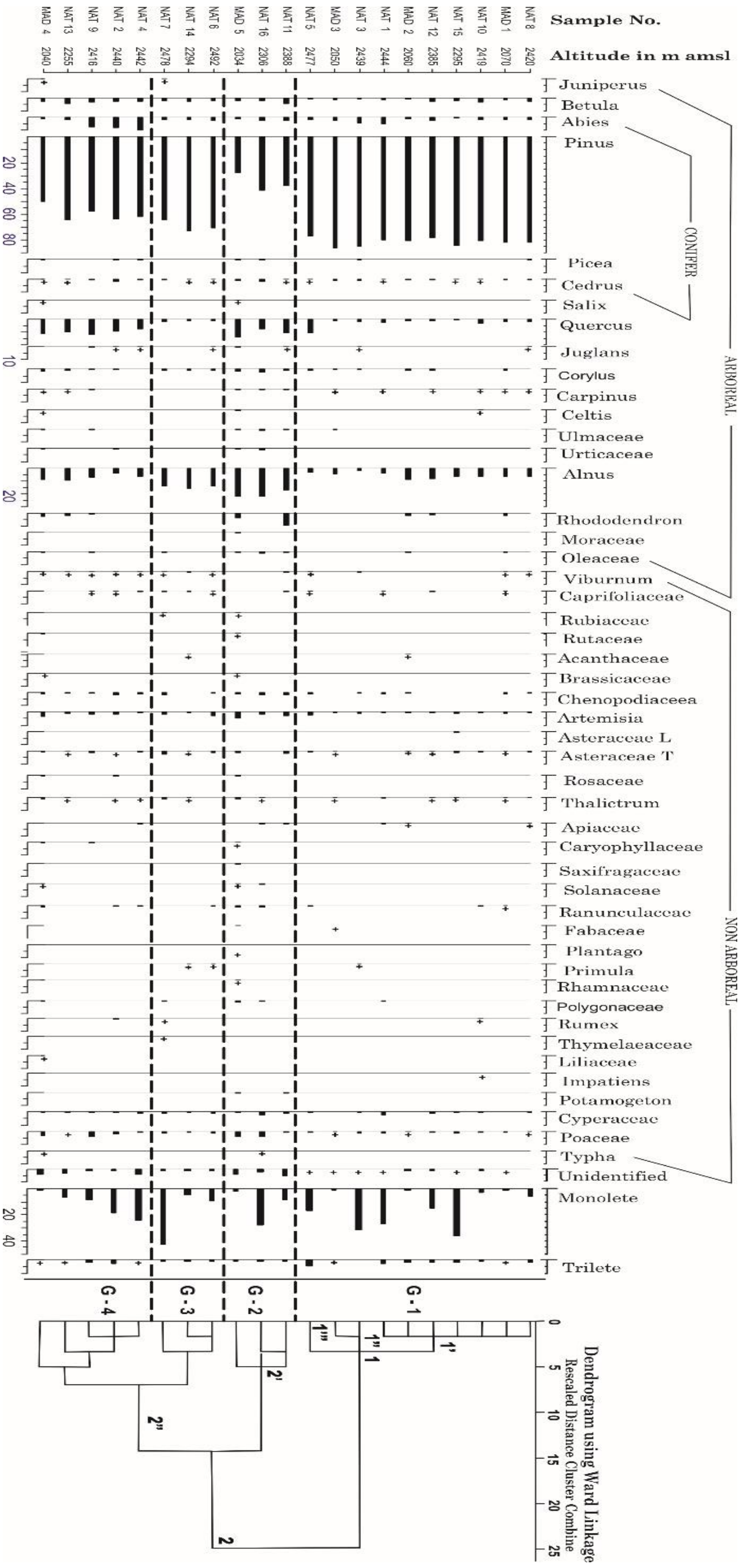

Fig. 5. Modern hierarchical pollen diagram with sample pollen spectra grouped according to the similarity in the pollen assemblage irrespective of the altitude.

sampling locations within the altitudinal range, the samples were analyzed for their similarity index through hierarchical relationship using the SPSS 21 software. This analysis also excludes the fern spore (monoletes and triletes) counts as explained above. The second pollen diagram (Fig. 5) thus shows the grouping of the samples in which the pollen spectra of each sample are arranged according to their similarity index irrespective of the altitude and site. In both pollen diagrams, the taxa were arranged as arboreal and non-arboreal from left to right corner and the frequency of taxon less than 1% was marked by '+' sign.

To find any change in the pollen spectra since last several years due to the increased anthropogenic impact on the forests, the pollen frequency of an exploratory earlier pollen vegetation study (Gupta & Sharma 1993) from this region was compared with this study. This comparison thus assessed the changes of 2.5 decades.

Results

The surface samples yielded a good number of pollen grains of arboreal and non-arboreal taxa in which former were distinctly dominant over the latter. In both sites, some reported pollen taxa are transported from the high altitude areas including treelines viz., *Abies, Cedrus* and *Betula*. They could be referred to as external or allochthonous pollen, in contrast to pollen of species of the two study sites, which could be called internal or autochthonous pollen. Both the pollen spectra (Figs. 4, 5) prepared, thus helped to measure the pollen influx of internal and external plants, for developing the pollen-vegetation relationship and for understanding the comprehensive ecological scenario.

Pollen assemblage zones

I. Altitudinal zones:

Variations in the frequency distribution of pollen and spores have been noticed throughout the altitudinal range, based on which the pollen spectra have been divided into three Altitudinal Zones (AZ-1 to AZ-3) using the constrained cluster analysis pollen diagram (Fig. 4).

AZ-1 – represents the surface samples near the Nachiketa Tal (NAT) within the altitudinal range of 2,492–2,416 m asl. Amongst dominant arboreal taxa, *Pinus* had the highest frequency (58–85%). The extra-local species pollen recorded were *Abies* (~2–10%), *Cedrus* (1–2%) and *Picea* (rare). The broadleaved taxa observed in pollen samples were *Alnus* (1.8–14.4%) and *Quercus* (1.5–12%). Pollen of *Betula*, though occurring in treeline areas were also present (0.7–3.1%). The other broadleaved taxa such as *Corylus, Carpinus, Juglans, Ulmus,* and *Celtis* recorded infrequently. *Rhododendron* pollen were present in only one sample at the bottom of this zone. The pollen of non-arboreal taxa were less common, but fern spores with monoletes (7–43%) and triletes (~5%) were common. Pollen of Chenopodiaceae (1.5%), *Artemisia* (0.3–2.7%) and Asteraceae-Tubuliflorae (T) type (2.7%) were also encountered in samples. From moist areas, pollen of Cyperaceae (0.2–2.3%) were present throughout, with sporadic presence of Ranunculaceae, *Thalictrum*, Polygonaceae, etc. Poaceae (0.3–4.1%) also had sporadic-to-fair representation in this zone.

AZ-2 – In the samples of this altitudinal zone (2,388–2,070 m) the frequency of pine pollen (40–84%) was as high as in AZ-1. Compared to AZ-1, *Abies* (0.4–3%) became sparser and *Picea* became negligible. Among broadleaved species *Alnus* (6–22.4%) showed a noticeable increase, *Quercus* (1–12%) and *Betula* (2.2–4.7%) did not show any noticeable change, *Juglans* became almost absent, and *Rhododendron* (Ericaceae) was more prominent (10.1%) in one sample. Chenopodiaceae, Asteraceae, and *Artemisia* also remained almost unchanged compared to AZ-1. Monolete spores (4.3–35.9%) were frequent while the frequency of trilete spores was low ~0.3–1.8%. Pollen of Cyperaceae (0.2–2.5%), Poaceae (0.4–4%) and other species of ground vegetation were infrequent.

AZ-3 – In samples from the altitudes 2,060–2,030 m which were from the chirpine forest of Mahidanda (MAD) site, *Pinus* (30–87%) was clearly dominant, while treeline species *Abies* and *Betula* declined further and became rare. *Quercus* (1.1–14%) was prominent only in the samples collected from valley depressions with comparatively lower altitudes. *Alnus* (4.8–23.1%) occurred almost in same frequencies as it did in AZ-2 and *Rhododendron* (2–4%) appeared in all samples but in lower frequencies. Fern spores (Monolete 1–2.2% and Trilete ~1.6%) and pollen of Poaceae (0.2–4%) and Cyperaceae were infrequent. Pollen of Chenopodiaceae (1.4%), *Artemisia* (0.6–4.7%), Brassicaceae (~0.2%) and Asteraceae-T (0.2–1.7%) too poorly represented.

II.Ecological Groups:

The ecological similarities between the samples of the two study sites have been analyzed through the hierarchical analysis. It groups the ecologically

Table 5. The pollen percentage variability of few important taxa in the hierarchical pollen diagram.

Groups	G-1	G-2	G-3	G-4
Pinus	81	36	70	60
Abies	3	3	3	6
Quercus	3	11	1	10
Alnus	2–8	20	14	10
Betula	2	2	2	3
Rhododendron	1–2	<1	nil	2–3
Artemisia	0.8	3	1.6	1.6
Chenopodiaceae	<0.5	1	0.6	0.7
Asteraceae	1.5	1	1	1
Cyperaceae	1–2	1–2	0.5	0.6
Poacaeae	2–3	3–4	1–2	3
Apiaceae	<0.5	0.2	Nil	<0.5
Polygonaceae	<0.5	0.5	<0.5	<0.5
Ranunculaceae	<0.5	0.9	<0.5	<0.5

similar samples irrespective of the altitudes. In the hierarchical analysis samples are divided into four Groups (G-1 to G-4). In the G-1, samples from the altitudinal gradient of ~2,477 to 2,034 m asl shows abundance of *Pinus* (~81%) which contrasts with the low presence of *Quercus* (3%) and *Alnus* (2–8%). The G-2 includes samples taken from altitudes of 2,388, 2,031 and 2,306 m asl. This group contrasts with minimum pollen frequency of *Pinus* (36%). Among broadleaved taxa, *Alnus* (20.17%) is dominant followed by *Quercus* (10.5%). G-3 samples from the altitudes of 2,294, 2,478 and 2,492 m asl exhibits high values of *Pinus* (70%) followed by the *Alnus* (14%). *Quercus* (1.1%) is sharply less in frequency. The G-4 from the altitudes 2,033–2,442 m asl shows *Pinus* ~60% and *Quercus* ~10%. *Abies* (6%) and *Betula* (3.06%) have maximum values in this group as compared to the above groups. Details of taxa represented in each group are shown in Fig. 5 and Table 5.

Discussion

Pollen deposition scenario

An overview of pollen spectra (Fig. 4) reveals that pollen assemblages could be classified as local (autochthonous) arboreal, local non-arboreal and external (allochthonous). Among local arboreal, *Pinus* pollen were generally dominant while *Alnus* and *Quercus* were prominent, but poor second/third. Allochthonous pollen grains were of *Abies, Betula* and *Cedrus,* growing in high elevation areas including treelines. The valley winds are likely to be a major transporting agent of pollen. Relatively high frequency of *Abies* pollen in the samples of zone AZ-1 is likely to be due to the close proximity to the *Abies* forests.

Grouping of the samples (Fig. 5) based on correspondence in their pollen assemblages provides a comprehensive scenario of the ecological similarities amongst the samples irrespective of altitude. The pollen variations can also be related with the vegetation distribution at these altitudes. Group 1, clustering 10 samples from the two sites (NAT and MAD) shows dominance of *Pinus* pollen. High pine pollen frequency in samples collected from MAD site dominated by pine trees is expected, whereas, its high representation in some NAT samples, despite its low presence in vegetation indicates their transportation by wind from external sources. Thus, chirpine's presence could be overestimated by pollen studies in certain situations, because of its high pollen production and an efficient wind dispersal (Vishnu-Mittre & Robert 1971; Vishnu-Mittre & Sharma 1966). The Group 2 samples with high frequencies of *Alnus* and *Quercus* fairly represented the broadleaved forest, as the samples of this group are collected from sites dominated by broadleaved taxa growing along the moist depressions. The Group 3 was again dominated by the pollen of *Pinus* followed by those of *Alnus,* indicating the close proximity of *Alnus* and also an efficient dispersal of *Pinus* pollen through wind. The Group 4, apart from the dominance of *Pinus* pollen, also had *Quercus* and *Alnus* pollen in good numbers.

The ground or non-arboreal taxa are less represented in pollen samples and cannot provide an accurate picture of their presence or abundance. However, good amount of fern spores in several samples could be linked well to the abundance of ferns in moist patches.

Previous studies from several sites above the growth limit of *Pinus* in the higher Himalayas (Bera *et al.* 2011; Kar *et al.* 2015, 2016; Ranhotra & Bhattacharyya 2013; Quamar & Srivastava 2013), also reported *Pinus* pollen in good frequencies. From the Bara Shigri glacial samples Bhattacharyya (1989b) reported high amount of *Pinus* pollen much away from the source of provenance. The valley wind dynamics (Egger *et al.* 2002; Maharjan & Regmi 2015; Schmidli & Rotunno 2012) and topography of the valley could play an important role in pollen transport (Chauhan & Sharma 1993; Sharma 1985; Quamar *et al.* 2017). In the present study, only a few samples collected from the oak forest showed a good pollen representation of *Quercus* and *Alnus* (Fig. 5). However, in some such samples *Alnus* pollen were relatively over represented, possibly because of their greater wind dispersal than *Quercus* pollen. *Rhododendron* had good pollen frequencies in few samples collected near its trees and sporadic to absent in the samples away from them. Poor pollen production and entomophilous dispersal nature of *Rhododendron* pollen (Hirao *et al.* 2006; Orwa *et al.* 2009) might explain its under representation.

We have compared our data to that of an earlier study conducted some 25 years ago from the Nachiketa site using moss cushions (Gupta & Sharma 1993). *Pinus* is seen to increase from 20–40% in 1993 to 30–80% in the present study that is its pollen frequency has almost doubled in about two and one-half decades. On the other hand, banj oak pollen has decreased to 12% in the present study from the earlier 15–45%. Increase in chirpine at the expense of banj oak is a common feature in middle ranges of Central Himalayas because of the frequent man-made fires and lopping of banj oak branches for fodder and firewood (Singh & Singh 1992). Chirpine being fire tolerant takes advantage of fire. The depletion of *Quercus* spp. has also been discussed by others (Khali & Bhatt 2014; Singh & Rawat 2012) as the wood of oak species is used as firewood, leaves as fodder for cattle and forest floor litter as fertilizer.

Conclusion

Surface pollen studies could be used to monitor changes in species composition of forests under the influence of human disturbance and climate change. However, corrective measures would be required because species like chirpine are likely to be over represented in pollen samples because of relatively greater pollen production and an effective pollen transport by wind. In mountains, species of different climatic conditions can occur within a small area because of rapid elevational difference. Therefore, a pollen assemblage may include species which do not occur together. However, comparison between different datasets of different time-span on a site can effectively document the changes in species composition.

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Static tree line of Himalayan silver fir since last several decades at Tungnath, western Himalaya

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Abstract: The impact of climate change on trees is conspicuous in the form of tree line response at the higher mountain region. Based on tree ring data, we investigated the age stand structure and tree line dynamics of the Himalayan fir (*Abies spectabilis*) at Tungnath, Uttarakhand, western Himalaya. This species forms the upper ecotone limit at ~3335 m asl in association with *Rhododendron campanulatum*, the latter extending further and forming the krummholz ecotone limit. The stand structure and age distribution of fir reveals the presence of high girth class trees at lower altitudes with the oldest tree of ~379 years age at ~3000 m asl. A good number of trees older in age than the age of uppermost tree (~109 years) at ~3353 m asl show the recruitment of fir at the ecotone limit by the early 20th century AD with the shift rate of ~13 m per decade. The highest advancement rate of ~39 m per decade is found during 18th Century AD. Over 300 years old ring width chronology of silver fir indicates that the temperature of winter months, especially February, have positive influence on the tree growth. The presence of trees younger than 100 years within the forest stand near ecotone limit indicates subsequent infilling of forest and also explains the growth behavior of fir trees in relation to increasing temperature of winter months during the last century. Evidences of no regeneration above the present fir limit and the presence of few seedlings within the upper ecotone limit could be related to mixed response to climate and other local factors at this site. In spite of rapid warming silver fir tree line in Tungnath area has not shown upslope advance. It seems that the positive effect of warming in tree growth is nullified by water stress resulting from increased evapotranspiration.

Key words: *Abies spectabilis*, climate-growth relationship, treeline shift, tree ring width, Uttarakhand, Western Himalaya.

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Introduction

In mountainous regions climate has a significant impact on the vegetation growth by defining distribution limits to the species. Global warming influences the natural upper tree line shift to higher elevations due to increase in air and soil temperatures (Holtmeier 2009; Körner 2012; Paulsen & Körner 2014). There are evidences of advancement of natural tree line at some places in the Himalayan region (Dube *et al.* 2003; Gaire *et al.* 2014; Shrestha *et al.* 2014; Tiwari *et al.* 2017; Yadava *et al.* 2017) and other parts of globe (Gehrig-Fasel *et al.* 2007; Kullman & Oberg 2009; Lloyd *et al.* 2003; Moen *et al.* 2004; Moiseev & Shiyatov 2003). The warming trend that followed the little ice age event witnessed unprecedented 20th century warming (Briffa *et al.* 1995; IPCC 2013; Jones &

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Moberg 2003; Mann *et al.* 1999; Pant & Rupakumar 1997) that might have played important role in the tree line shifts. Local site factors, such as physiography, species richness and interactions, herbivory, historical disturbances (natural or anthropogenic) or other biotic factors may also modulate or override the impact of climate on tree line position and responsiveness (Cairns *et al.* 2007; Holtmeier & Broll 2005, 2007; Odland 2015; Payette 2007). In a recent meta-analysis of treeline response to climate warming based on data set of 166 sites, but mostly of Europe and north America, Harsch *et al.* (2009) have reported that since 1900 AD tree line has advanced at 52% of the sites, shown no elevational shifts at 47% sites, and receded at 1% site. Himalayan region though highly vulnerable to climate change (Xu *et al.* 2009) and characterized with variety of treeline structure and growth form (Holtmeier 2009; Schickhoff 2005; Shi & Wu 2013) has remained poorly investigated in terms of tree line response to climate change (Holtmeier & Broll 2007; Schickhoff *et al.* 2015). The analysis of tree line shifting is much complex owing to number of interacting factors which affect the response to climate (Bolli *et al.* 2006; Rössler *et al.* 2008; Schickhoff *et al.* 2015; Vittoz *et al.* 2008). Dubey *et al.* (2003) and Yadava *et al.* (2017) examined the behavior of *Pinus* species from western Himalaya and discussed the control of local site factors along with climate warming for the variable advancement rate at different sites. Studies on Himalayan fir (*Abies*) from Nepal (Gaire *et al.* 2011, 2014; Shrestha *et al.* 2014; Tiwari *et al.* 2017) show mixed response of this species to climate as well other geographic, biotic and landuse factors. We need to generate more data on stand structure and dynamics of the tree line at local species level to improve our understanding of tree line dynamics and factors controlling them. For the present study we have selected *Abies spectabilis,* an important constituent of cool-moist upper temperate to subalpine forests and treeline in Himalaya extending from Afganistan to the eastern parts of India (Sahni 1990). This study from the Indian western Himalaya aims to i) analyze the stand structure of *Abies spectabilis* (silver fir) in treeline ecotone, ii) assess the temporal recruitment pattern and shift rate of this species along the altitudinal gradient, and iii) analyze the temporal growth dynamics in relation to climate. The findings of this study are expected to help in assessing the sensitivity and growth response of this species to the climate change and other causative factors.

Materials and methods

Study area

Tungnath area (30°′29–30°30′N and 79°12′–79°13′E), is a part of Kedarnath Wildlife Sanctuary in the Garhwal region of Uttarakhand, Western Himalaya (Fig. 1). The area forms the upper catchment (2700–3800 m asl) of river Alaknanda, a principal tributary of river Ganga and has religious importance due to the presence of Tungnath Temple at the altitude of ~3500 m asl. The study area is approachable by motorable road till the small settlement named Chopta at the altitude of ~2800 m asl, followed by mule track to the Temple.

The forest at study area falls under the upper temperate to subalpine zone, which gives way to alpine meadows above the timberline ecotone. The studied altitudinal transect (from ~2750 m asl to above tree line) has preponderance of mesic and shade loving species of conifers (*Abies spectabilis, Taxus wallichiana*) and broadleaved taxa (*Quercus semecarpifolia, Rhododendron arboreum, R. campanulatum, Betula utilis*). *Abies spectabilis,* (D.Don) Mirb, commonly called Himalayan silver fir is tall (upto 50 to 60 m), evergreen conifer with altitudinal range from lower temperate (~2400 m asl) to near alpine zone (4400 m asl) in the Himalayan region (Champion & Seth 1968; Gaire *et al.* 2011; Ghimire *et al.* 2008). In the present study site *A. spectabilis* grows in association with broadleaved taxa, especially *Q. semecarpifolia* (oak) and *R. arboreum* along with other species *viz., Acer caesium, Prunus cornuta, Taxus wallichiana* and *Sorbus foliolosa* untill ~3100 m asl. The dominance of *A. spectabilis* occurs above ~3100 m asl mainly in association with *B. utilis* and *R. campanulatum,* and forms the ecotone limit at ~3335 m asl (Fig. 2). Above fir limit *R. campanulatum* dominates and forms the krummholz vegetation layer on thin soil cover. *Danthonia cachemyriana* is the common grass species, while *Carex* spp. and *Kobresia royleana* represent the major sedges. The area has high influence of anthropogenic activities with frequent disturbance in the silver fir community for construction and fuel consumption (Rai *et al.* 2012). Grazing by sheep, goats, mules and cattle during entire growing season is common in the area.

The three years climate data of (2008 to 2010, Adhikari *et al.* 2011) show long winters (October to April), short summers (May to June) and rainy season (July to September). Near timberline ecotone, the mean annual temperature (MAT) averages around 6.65 ± 0.68°C, ranging between −8.91 and 25.6 °C for January and May, respectively, the

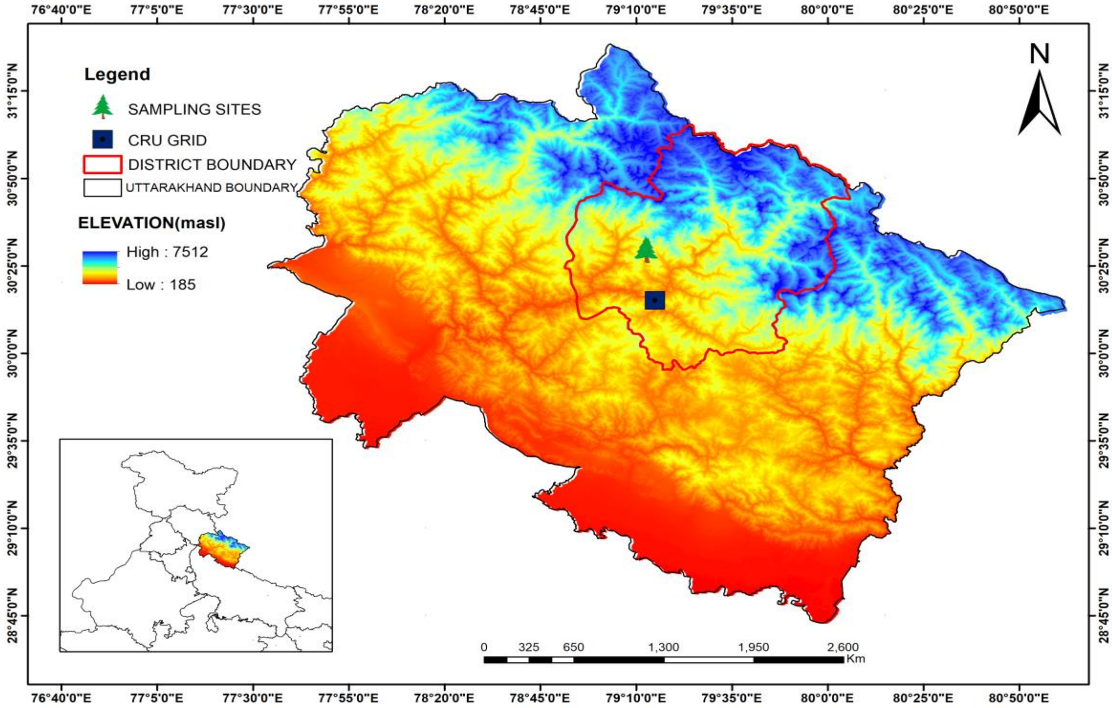

Fig. 1. Digital elevation map of Uttarakhand showing locations of study site and source of climate data. Tree symbol denotes the tree sampling site (Tungnath) of *Abies spectabilis*. Solid box denotes the closest grid data point (CRU-TS3.22) of climate.

warmest month being July with mean temperature of 12.56 ± 1.23 °C (Fig. S1). Annual precipitation is 2400 ± 430 mm, of which 89.5% comes through Indian summer monsoon (ISM) during June-September. Snow cover, largely due to westerlies, lasts for 85 ± 22.7 days yr^{-1} during winter months. However, for developing the tree growth climate relationship, the required long term measured climate data are not available for the area. The gridded data for the area from Climatic Research Unit (CRU) of the University of East Anglia [CRU-TS v.3.22; (05x05 degree) grid, available at http://www.cru.uea.ac.uk/cru/data/hrg/)] for the period 1901–2014 CE (Harris *et al.* 2014, Figs. 1 and 3) have therefore been used for developing the tree growth and climate relationship.

Field sampling and processing

About 300 tree core samples of fir were collected in May 2016 and 2018 from 153 silver fir trees growing on the south facing slope between ~2780 and ~3353 m asl along the Chopta-Tungnath transect. Two cores per tree were collected at the breast height (~1.3 m above the base) and for each tree the geographical locations and the girth at breast height (GBH) were recorded. Trees with relatively thick girth were selected to get longer chronological records. Apart from this, 125 fir trees were randomly surveyed and measured for GBH only to assess the girth class distribution. The extracted cores were air dried and then mounted in wooden frames. The upper surfaces of the core were cut by sharp edge razor blade and polished with coarse and fine grade sand papers to enhance the surface resolution of cells of annual rings, which is to make ring boundaries distinctly visible under microscope. Rings of each core were counted under the stereo zoom microscope (Lieca) and each ring was assigned a calendar year through cross dating. To establish the relationship between tree growth and climate, the ring widths were measured to the nearest 0.001 mm precision using the LINTAB-6 measuring system attached to computer with measuring software TSAP-Win scientific version (Rinn 2003). Cross dating and quality check were done using the COFECHA (Holmes 1983) computer program and ring-width chronology was developed. The corrected ring-width data were standardized using the computer program ARSTAN (Cook 1985). Detrending of measured ring widths with negative exponential or linear regression function was done to enhance the common climatic signal and to

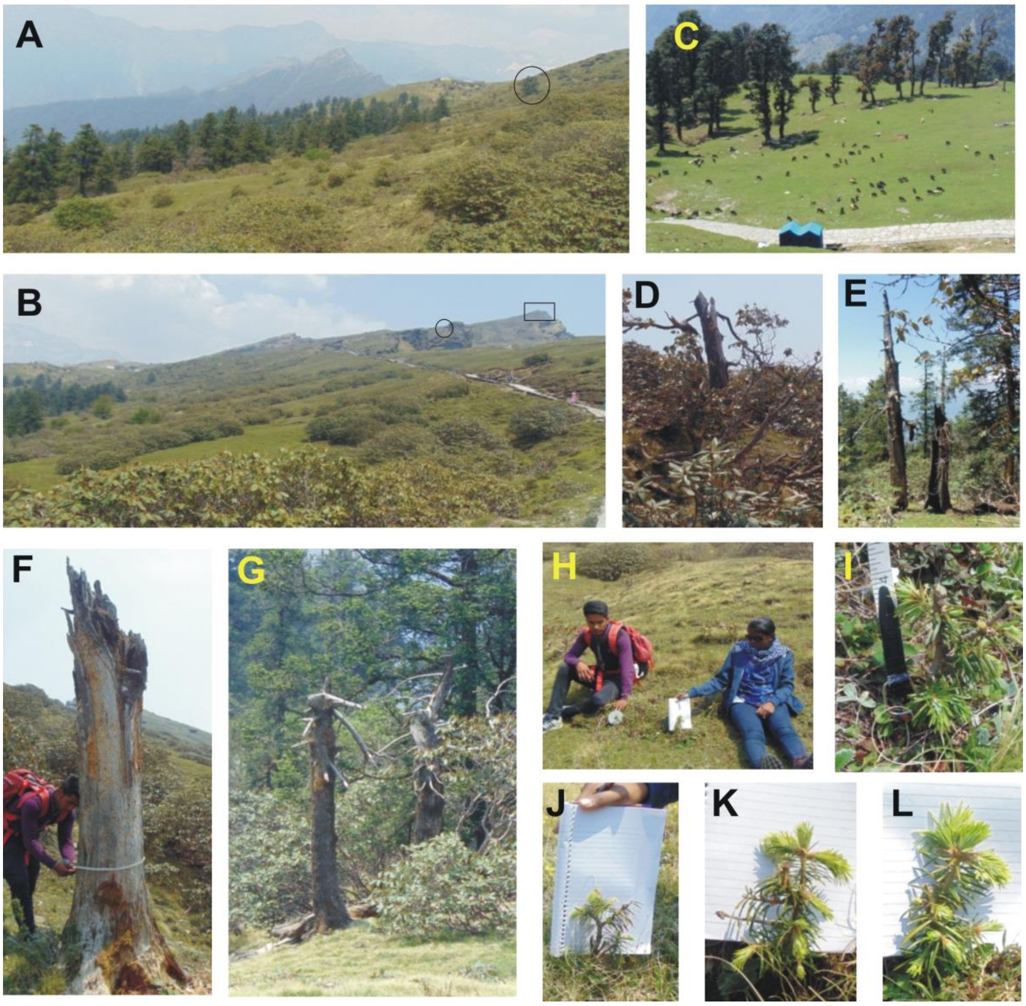

Fig. 2. A) Upper ecotone limit of *Abies spectabilis* (fir). Circle denotes the uppermost fir tree recorded at Tungnath transect. B) Topography of the Tungnath transect. Circle denotes the location of Tungnath temple above fir limit. Rectangle shows the highest summit point. C) Growth of *Quercus semecarpifolia* and grazing activity in the meadows along the transect. D to G) Dried and broken stumps of fir near upper ecotone limit of fir. H to C) Growth of seedlings on the slopes near upper fir limit.

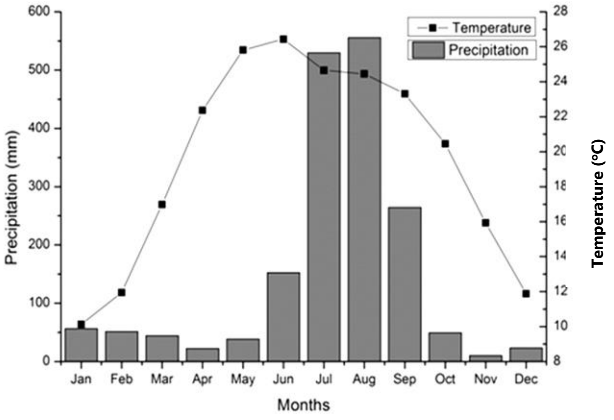

Fig. 3. Climate data from CRU-TS3.22 showing monthly mean temperature and precipitation.

remove the low frequency trends due to aging and stand dynamics of the individuals.

Growth dynamics and shift rate

To understand the growth dynamics and altitudinal shift rate of fir, various relationship models were developed amongst the tree diameter at breast height (DBH), tree age and their altitudes. DBH of each tree was calculated dividing the measured GBH (circumference) by the value of π (3.14). Each tree sampled for cores was assigned an age following the standard method of annual ring counts, cross dating and necessary corrections (Camarero & Gutierrez 2004; Gaire *et al.* 2014; Speer 2010). Complete cores of around 120 trees

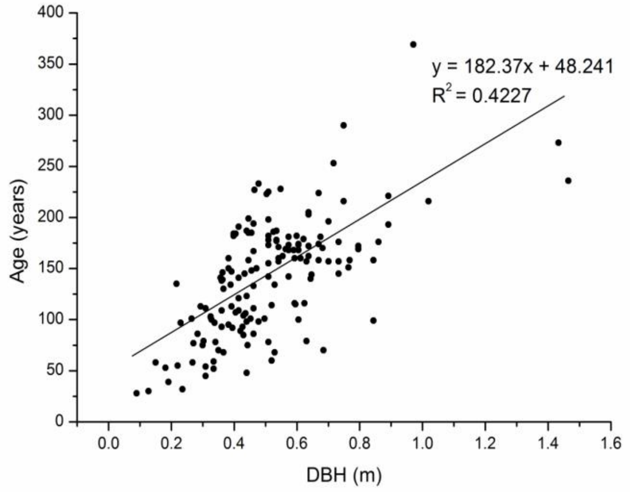

Fig. 4. Diameter at breast height (DBH) and Age relationship of *Abies spectabilis* from Tungnath, Uttarakhand.

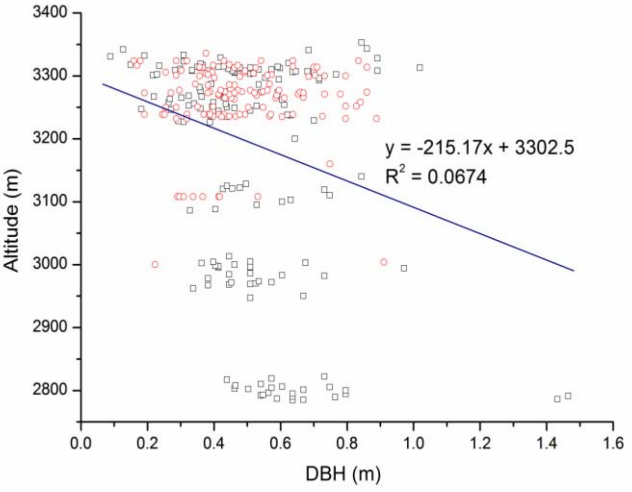

Fig. 5. DBH and Altitude relationship of *Abies spectabilis* growing at Tungnath, Uttarakhand. Black squares represent the DBH of fir trees sampled for tree ring cores. Red circles represent DBH of fir trees not sampled for tree ring cores.

having the length from bark to pith were taken to develop the DBH and age relationship model (Fig. 4). To correct the age for the core extraction height, a decade was added to the counted age of each tree (Gaire *et al.* 2011). Some trees with their GBH over 2 meters were found to be rotten and pith length cores were not available. Considering the variation in growth distribution of *A. spectabilis* above and below 3100 m asl altitude, the DBH-age relationship model has also been tested separately for the trees growing above and below the 3100 m asl respectively (Figs. S2–S3). This allowed assessing the stand structure and growth variability of *A. spectabilis* at different elevational levels. The DBH and age regression models were used to estimate the near approximate age of rotten and uncored trees with measured GBH. The girth class and age distribution, and the growth rate dynamics of this conifer has been analyzed by establishing the relationships between DBH and altitude, and age and altitude of the trees using linear regression model (Figs. 5 and 6). Temporal advancement or shift rate of fir to higher elevation has been approximated following the standard calculation (Gamache & Payette 2005; followed by Gaire *et al.* 2014; Tiwari *et al.* 2017 and others) by dividing the difference between the altitudes of uppermost individual and oldest individual with the difference between the age of oldest individual and uppermost individual. Also, to understand the establishment year of *A. spectabilis* at different altitudinal transects and to know the temporal variations in the shift rates, the same were calculated separately by dividing the altitudinal transects into 100 and 200 m bands (Fig. 6).

Results

Upper limit and stand structure of Abies spectabilis

Along the altitudinal transect of Chopta-Tungnath, *A. spectabilis* forms the upper limit at ~3335 m asl with ±5 meters of altitudinal variation which might be due to local factors. The uppermost tree was recorded at ~3353 m asl altitude. To analyze the stand structure, various correlation analyses were performed amongst age, DBH and altitude and they showed significant correlation values. Correlation between DBH and age was positively significant (r = 0.64, $P < 0.05$) with 42% variability explained by DBH (Fig. 4). Correlation between DBH and age was calculated separately for lower (below 3100 m asl) and high (above 3100 m asl) parts of altitudinal transects. For the lower part of transect, regression model based on cores of 54 trees showed positive correlation (r = 0.53, $P < 0.05$) explaining only 26% variability (Fig. S2). For 98 trees growing above 3100 m asl the significant positive correlation (r = 0.67, $P < 0.05$) explained 47% variability (Fig. S3). The age of around 125 uncored fir trees was calculated using the DBH-age regression model.

All along the altitudinal gradient, DBH ranged from 0.09 to 1.46 m, with lower DBH trees mainly

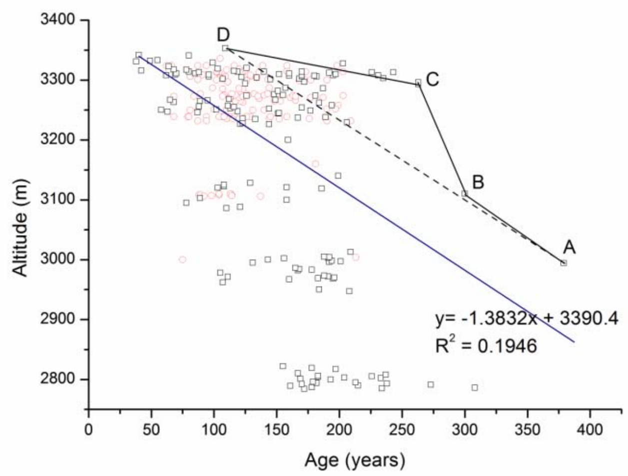

Fig. 6. Age and Altitude relationship and shift rate of *Abies spectabilis* growing at Tungnath, Uttarakhand. Black squares represent the measured ages from tree ring cores of sampled fir trees. Red circles represent the calculated ages of unsampled fir trees using the DBH-Age relationship model. A & D marks respectively the oldest and the uppermost growing fir trees. A-D broken line represents the average shift rate from 1637 to 1907 AD. A-B, B-C and C-D solid lines marks the temporal variations in the shift rate of fir along the transect.

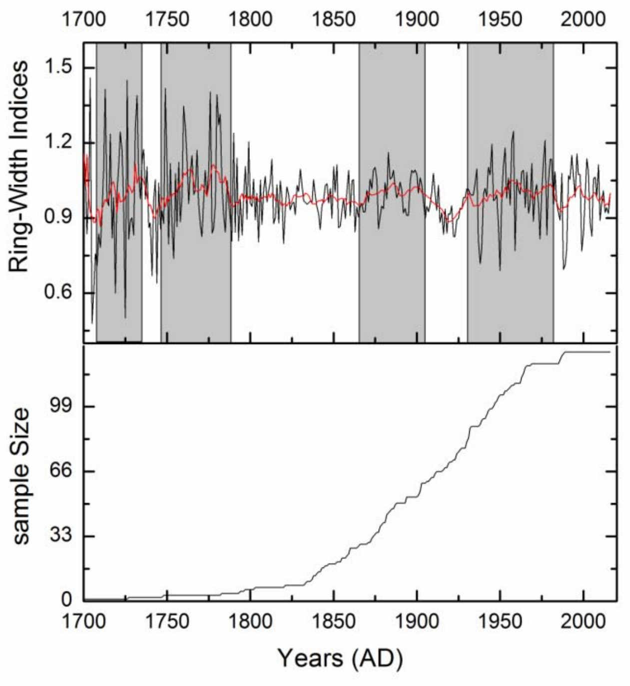

Fig. 7. Residual tree ring chronology plot (1700–2016 AD) and sample size plot of *Abies spectabilis* at Tungnath. Grey shaded portions in the ring width indices (RWI) highlights the high radial growth years.

in higher elevations. The correlation between DBH and altitude was found significantly negative (r = −0.34, $P < 0.05$), indicating decrease in girth size (DBH) of trees with the increase in altitude, but explaining only 7% variability in DBH by altitude (Fig. 5). Though the trees with the highest DBH (1.43 and 1.46 m) were found growing at the altitudes 2786 and 2791 m asl respectively, several high girth class trees were also found towards the upper ecotone limit. Between the altitudinal transect of ~3200 m asl and upper fir limit, the DBH of fir trees ranged from ~0.09 to ~1.02 m.

The correlation analysis between altitude and age (corrected) of ~278 trees, showed significant negative correlation (r = −0.46, $P < 0.05$) with 19% variability (Fig. 6), indicating the younger trees at higher elevation. The tree of maximum age (379 years, DBH - 0.97 m) was recorded at ~2994 m asl, which is above the altitude of maximum girth trees. Two trees of maximum DBH (1.43 and 1.46 m) were calculated for age ~308 and 314 years, respectively.

Shift rate along the altitudinal transects

The tree ring cores collected from the trees with large girths growing between ~2780 to ~3353 m altitude provided the records of older trees that helped to assess the temporal episodic shift rates within the transect. The age vs. altitude plot (Fig. 6) showed that the oldest tree was ~379 years old (A in Fig. 6) and at altitude of ~2994 m asl, indicating that the species was growing near 3000 m asl altitude at least since ~1637 AD. There were few more trees with age more than 300 years (~308 and 314 years) and they occurred near ~2800 m asl, lower than the altitude of oldest tree. The youngest tree recorded was ~38 years old (GBH/DBH - 0.28/0.09 m) and it occurred at ~3331 m. The age of other young trees was 40 years (GBH/DBH - 0.6/0.13 m), 49 years (GBH/DBH - 0.4/0.13 m) and 55 years (GBH/DBH - 0.97/0.31 m), all growing between ~3332 and 3342 m. The tree growing at the highest elevation of ~3353 m asl was 109 years old (D in Fig. 6). During recent survey in May 2018, we found the existence of few seedlings (5 to 20 cm tall) of fir near ecotone limit within altitudinal gradient of ~3305 – 3338 m asl (Fig. 2), whereas no saplings were observed from the area.

The average shift rate of fir along ~3000 to 3353 m transect (A to D in Fig. 6) was estimated as 13.1 m per decade. However, considering that the youngest individual was recorded at elevation ~3331 m elevation, the average shift rate was calculated as 9.8 m/decade. To understand the recruitment

Table 1. Statistics of residual chronology of *Abies spectabilis* from Tungnath, Uttarakhand for the time span 1700–2016 AD.

Cores/Trees	127/86
Mean sensitivity	0.144
Standard deviation	0.158
Autocorrelation	0.026
Mean correlation within trees	0.382
Mean correlation between trees	0.177
Mean correlation among all radii	0.179
Signal to noise ratio (SNR)	19.151
Expressed population signal (EPS)	0.950

dynamics of fir since mid 17th Century AD, the shift rate was calculated for different altitudinal bands considering the oldest and youngest trees within those transects (Fig. 6). The upslope shift rate of silver fir fluctuated temporally between ~3000 and 3353 m altitude transect. It was ~1.46 m yr^{-1} between 1636 and 1715 AD (A to B in Fig. 6), ~3.95 m yr^{-1} between 1715 and 1772 AD (B to C in Fig. 6) and 0.38 m yr^{-1} between 1773 and 1907 AD (C to D Fig. 6).

Tree growth - climate relationship

A 317 years tree ring width chronology (Fig. 7) was developed from 127 cores of fir trees growing near the ecotone limit. Ring width chronology was transformed into ring width index chronology by removing age trends. Of various detrending methods, negative exponential method provided the significant values for various chronology statistics (Table 1). The residual chronology was used to develop the relationship between tree growth and climate using the software DENDROCLIM2002 (Biondi & Waikul 2004). More than 100 years gridded data (CRU-TS3.22) for mean annual temperature and precipitation was used to develop the relationship. Significant positive relationship was found between the ring width indices and temperatures of previous year November and current year February months (Fig. 8). For precipitation, the relationships were not significant. The observed growth trend (Fig. 7) showed high growth during the early to late 18th century AD with intermittent low growth years from 1738 to 1749 AD. The growth declined after 1790 AD and continued with minor fluctuations till ~1925 AD. Thereafter good growth was recorded with minor decreasing trend in recent years.

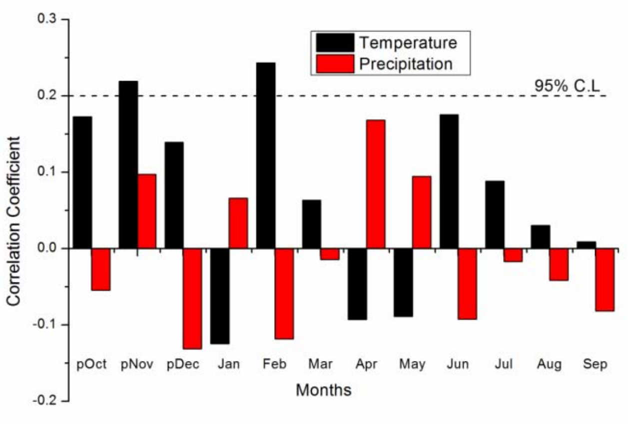

Fig. 8. Correlation of Tungnath fir chronology with mean monthly temperature and with monthly total precipitation (1901 to 2014 AD; CRU-TS3.22). Horizontal dashed line represents the 95% confidence level.

Discussion

Stand age structure and tree line dynamics

The upper limit of *A. spectabilis* ecotone at the Chopta-Tungnath Temple transect is recorded around 3335 m asl which is lower than the reported limits of silver fir in other areas of the central and western Himalaya (Bhattacharyya *et al.* 2011; Gaire *et al.* 2014; Shrestha *et al.* 2014; Tiwari *et al.* 2017). Several reasons could account for the lower silver fir tree line at Tungnath, including summertime grazing, cutting of young trees by local people and also low summit height. Effects of summit syndrome could have substantial role in lowering the timberline elevation, thus, refraining the timberlines to reach their climatically governed limits (Odland 2015). Our data indicate that silver fir occupied ~3300 m elevation during mid to late 18th century and thereafter reached the present elevation of ~3335 m asl by early 20th Century AD with the overall calculated advancement of ~350 meters in ~270 years (from 1637 to 1907 AD). However shift rate varied over time and was highest during the 18th century AD (1715 till 1775 AD). The presence of a ~109 year old tree at the elevation of ~3353 m asl indicates the recruitment of this species by the early 20th century (1907 AD) at that elevation. The elevational distribution of DBH and age (Figs. 5–6) showed that in the treeline ecotone the trees of middle to high girth classes were more in number. This also reported by Rai *et al.* (2012). However, the presence of younger trees aged < 100 years in the forest stand suggests subsequent establishment of silver fir, towards the ecotone limit during the 20th century. The absence of trees or saplings of age less than the age of youngest recorded tree i.e. 38 yrs, indicates no obvious recruitment during the past four decades of rapid warming. Rai *et al.* (2012) also reported the absence of natural regeneration of silver fir community above the fir limit. It shows that the silver fir tree-line remained stable for last four decade. This is contrary to recent tree-line advancement reported from several sites of the greater Himalayan regions of India (Dubey *et al.* 2003; Yadava *et al.* 2017) and Nepal (Gaire *et al.* 2011, 2014; Liang *et al.* 2011; Tiwari *et al.* 2017, etc.). However, analogous to our study the stationary or insignificant shifts have also been reported earlier from some areas of Himalayan and Tibetan regions. From Sygera Mountains (SE Tibet), Liang *et al.* (2011) reported insignificant upslope movement of Smith fir stands at the tree line since mid 20th century but with considerable increase in the stand density. Schickhoff *et al.* (2015) reported similar insignificant alteration in the tree line position and increasing stand density from Rolwaling Valley (Nepal). Despite climatic warming, a near stationary stand structure of silver fir for over several past decades has also been reported by Shrestha *et al.* (2014) and Gaire *et al.* (2011) from central Nepal. A remote sensing based study (Bharti *et al.* 2012) has shown an increase in biomass in a subalpine forest's canopy during 1980–2010 at Nanda Devi Biosphere Reserve, Uttarakhand, but no shift of the upper treeline. From Hengduan Mountains (NW Yunnan), Baker & Moseley (2007) have documented a significant infilling of tree-limit ecocline and upward shift of the timberline since 1923 AD, and argued climate warming as factor for the advancement. However, it was later on detected as an effect of cessation of land use and other human disturbances rather than a result of climate change (Schickhoff *et al.* 2015). Schickhoff *et al.* (2015) estimated 85–90% of treelines to be anthropogenic along the entire mountain arc, and only 10–15% to be orographic/ edaphic and climatically governed. According to Harsch & Bader (2011) at the climatically driven area the trees become progressively smaller and less in age with the increase in elevation. Whereas in the Tungnath area the presence of good number of old trees (> 100 years) might suggest the role of other non-climatic factors in controlling the tree line. Rai *et al.* (2012) discussed the role of anthropogenic activities in the fir community at the Tungnath, as the site is at an approachable altitude. Grazing could also be an important reason for non-survival of seedlings. Shrestha *et al.* (2014) have noticed grazing as main factor for poor regeneration of seedlings. Grazing by herbivores have been taken as an important determinants of tree line position and tree growth and population structure elsewhere also (Cairns *et al.* 2007; Speed *et al.* 2011) and could be a potentially important factor in the mesic area, as young *Abies* individuals have high forage value and may be susceptible to grazing by wild and domestic herbivores (Shrestha *et al.* 2014). In a study in Swiss Alps, land abandonment was reported to be the principal driver of treeline rise, and only a small fraction of upward shift was reported to be due to climate change (Gehrig-Fasel *et al.* 2007). In our study, topography and ground conditions above the present fir ecotone limit at the Tungnath area might not be conducive to the regeneration of fir (Fig. 2). Further, the trees of younger age at the lower elevation (below 3000 m asl) might be the result of clearing of older trees for timber. The low correlation value of DBH–age (Fig. S2) for the fir trees growing at altitude lower than 3100 m asl in comparison to high correlation value for trees growing above 3100 m elevation (Fig. S3) explains non-uniformity in the growth of lower altitude fir trees, which might be due to the competition for space and nutrients from other dominantly growing broadleaved species.

Climate growth relationship

The tree ring width chronology extending from 1700 to 2016 AD built here showed much variation in growth pattern. In the high altitude areas temperature seems to be an important factor in controlling tree growth and tree lines changes (Cook *et al.* 2003; Grace *et al.* 2002; Gunnarson & Linderholm 2002; Payette 2007). The positive response of tree growth to winter temperature observed in this study is similar to some other sites of Himalaya viz. western Himalaya (Borgaonkar *et al.* 2009; Yadava *et al.* 2017), Nepal (Bräuning 2004, Chhetri & Cairns 2016), Sikkim (Bhattacharyya & Chaudhary 2003) and Tibet (Liu *et al.* 2012; Wang *et al.* 2008; Yang *et al.* 2014). The increased temperatures in winter and early spring might favor photosynthesis and other physiological activities that lead to early initiation of cambium formation and division (Fritts 1976; Tranquillini 1964). The low winter temperatures at the higher elevations retard growth by causing bud damage, reduced root activity, and frost desiccation (Wang *et al.* 2008). The comparison of ring width

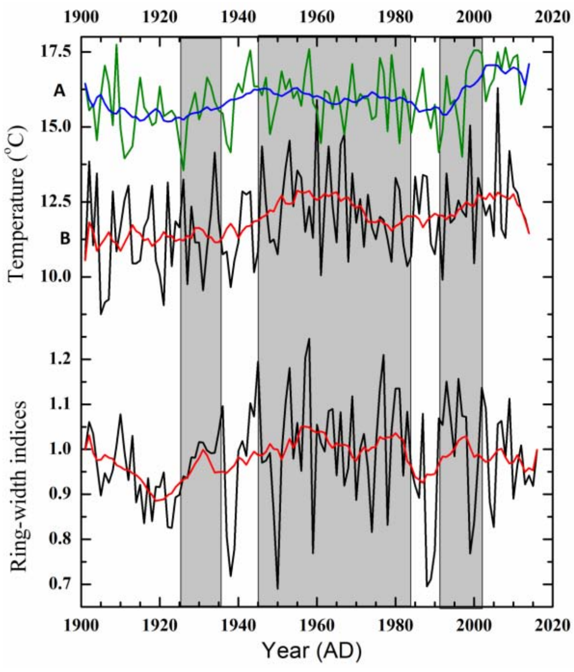

Fig. 9. Plots showing comparison of mean temperature (1901 to 2014 AD, CRU-TS3.22) of November (A) and February (B) months with residual ring width chronology (1901 to 2014 AD) of Tungnath fir. Grey shaded portion highlights the years with high radial growth and years with high mean monthly temperatures blue and red lines represents 11 year moving average.

chronology developed here with that of *A. spectabilis* from the other Himalayan regions (Chhetri & Cairns 2016; Gaire *et al.* 2014; Sano *et al.* 2005; Shekhar *et al.* 2017) shows similarity in growth patterns. The high and low radial growth years throughout the chronology might correspond respectively to warm and cool winter months of the years. High radial growths in most of the years during 18th century (1710–1735 and 1747–1785 AD) in this study (Fig. 7) might be due to winter warming reported from several sites of the south Asian regions. Sano *et al.* (2005) based on *Abies* chronology from western Nepal reported a warming trend from 1750 to 1790 AD during pre-monsoon months that reverted to cool conditions subsequently ~1810. Shekhar *et al.* (2017) reported significant reduction in mass balance of Himalayan glaciers during past 400 years, using fir chronology from Dokriani valley, Uttarakhand, indicating increased winter warming. Cook *et al.* (2003) in his October–February temperature reconstruction from Nepal also showed general warming trend over past 400 years. The 18th century warm conditions might have enhanced the growth of fir, this also corresponded with the calculated high shift rate of fir at the Tungnath area. Subsequent below average radial growth from 1795 to 1870 AD, also corresponding to reduced shift rate, might indicate winter cooling episode. Gaire *et al.* (2014) from central Himalaya reported low radial growth between mid and late 19th century AD and from 1940 to 2003, the latter time span of tree growth contrasts to high growth from 1945 to 1986 AD in our study, which might be due to local factors playing role in growth responsiveness. The high radial growth from 1870 to 1910 in our chronology also correlates with the warmest periods of reconstructed temperature of Nepal in tree-ring studies (Chhetri & Cairns 2016; Cook *et al.* 2003; Sano *et al.* 2005).

The growth trend of silver fir during last century (1901 till 2014 AD) has also been compared with the CRU-TS3.22 mean temperature data of November and February months. These two months are reported to have significant role in the growth of fir in this region. A continuous increasing trend in the mean temperature of November and February from 1901 to 2014 AD shows a near synchronity with the growth pattern of this tree (Fig. 9). Increased tree growth during 1925–1936, 1945–1986, 1992–2003 with the intermittent below average radial growth periods during 1911–1924, 1937–1944, 1987–1991, correlates with high and low temperature years respectively. Similar growth trends since last century has also been observed in the Himalayan fir from other studies (Borgaonkar *et al.* 2011; Chhetri & Cairns 2016; Singh & Yadav 2000) and Tibet (Liang *et al.* 2011). Temperature analysis over the Indian subcontinent (Hingane *et al.* 1985) also supports warming winter which could be the reason for high radial growth. Interestingly, no increased growth trend has been observed since 2003 onwards despite observed high mean temperatures of November and February months. This might be attributed to site-dependent controlling factors or to high temperatures crossing the threshold limit of the optimum tree growth at the site as also evident by the presence of few dried-broken stumps of fir trees (Fig. 2) as well as few inside rotten trees. At the lower altitudes warming might have induced increase in the evapotranspiration and reduced the photosynthesis due to intensified pre-monsoon drought. Regeneration of fir after a gap of few decades, discussed earlier by the existence of few seedlings on slopes near the fir ecotone limit might indicate recent changes in local conditions such as restriction of grazing or conducive growth environment due to forest canopy structure and other protective ground features.

Conclusions

Our study indicates that climate as well as other local factors have significant role in the growth and tree line dynamics of *Abies spectabilis* at the Tungnath area for past 300 years. This study thus justifies the importance of area specific control on tree growth response that can have vital relevance in assessing tree growth dynamics and predictions in regional aspects. At this site fir reached its present upper ecotone limit by the early 20th century with the average shift rate of ~13 m per decade. High shift rate of fir during 18th Century AD, and subsequent decline, corresponds well with the high and low growth trends during this time period. Amongst several factors, winter warming could have played an important role for the high growth and advancement of fir to upper elevations. The occurrence of fir trees younger than 100 years within the forest ecotone limit might be the result of observed increasing trend in the winter temperature during the 20th century. However, gap in the regeneration of fir for last four decades contrasts with the continued winter warming trend. The increased land use pressure for last few decades might also have played a significant role in the stability of fir ecotone limit and could be reasoned for poor regeneration. Recent year regeneration of fir by the presence of few seedlings near the ecotone limit could indicate regeneration and advancement of fir in the Tungnath area. But the continued land use might also play role in tree line dynamics and thus needs future monitoring on the overall survival and growth of fir in relation to climate and other factors.

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Supporting Information

Additional Supporting information may be found in the online version of this article.

Fig. S1. Climate data of Tungnath, Uttarakhand. (After Adhikari *et al.* 2011).

Fig. S2. DBH and age relationship of *Abies spectabilis* growing at the elevation lower than 3100 m asl at Tungnath, Uttarakhand.

Fig. S3. DBH and age relationship of *Abies spectabilis* growing at the elevation above 3100 m asl at Tungnath, Uttarakhand.

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Early snowmelt impact on herb species composition, diversity and phenology in a western Himalayan treeline ecotone

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Abstract: The rapid warming in Himalaya has begun to impact ice and snow and high elevation ecosystems, of which alpine treelines and meadows are particularly affected. The main objective of this study is to find out the impact of early snowmelt on herb communities of treeline ecotone (3200–3300 m elevations) located in Tungnath, Uttarakhand Himalaya. The focus is on species composition, species diversity and phenology. For this, we have followed two research approaches: first, comparing the herb communities of sites and microsites differing in the timing of snowmelt and the amount of snow cover, and second, comparing the phenology of common herb species with the past studies undertaken at the same and similar sites. We sampled several microsites which differed in the timing of snowmelt and were accordingly divisible into early snowmelt and late snowmelt microsites, the difference between them being of 3–5 days. Of the 86 species recorded across the sites, 84% were hemicryptophytic perennial forbs, and about 70% of them were native. Both herb species richness and species diversity were significantly higher in early snowmelt microsites than in late snowmelt microsites, both in high snow cover and low snow cover habitats. The total plant density ranged between 82–626 individuals m^{-2} in early snowmelt microsites and 69–288 individuals m^{-2} in late snowmelt microsites. It seems that the early snowmelt in a warming climate would promote species diversity and plant density. Comparison to the past studies indicates that because of climatic warming species have advanced and lengthened their vegetative and flowering phenophases. We could not assess whether migration of species from lower elevations contributed to high species richness of early snowmelt microsites. However, it cannot be ruled out, given that continent-wide species enrichments near mountain summits have been recorded elsewhere.

Key words: Climate change, early snowmelt, life form, phenophase, species diversity, treeline ecotone.

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Introduction

The high mountain ecosystems are under tremendous pressure at present because of biodiversity loss, habitat destruction, landscape modification (Bruun *et al.* 2006; Körner 2003) and climate change (Beniston 2003; Pauli *et al.* 2012). A major consequence of climate warming is an early snowmelt, increase in soluble N deposition in high mountain habitats and diversity loss (Hattenschwiler & Korner 1997; Torseth & Semb 1997). The increase in soil moisture at an early stage of the plant growth due to early snowmelt may change the community composition, species richness and the occurrence patterns of individual species (Körner 2003; Le Roux *et al.* 2013). The

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decrease in winter snow cover is one of the fastest changing climate features under current scenario (IPCC 2007), and is especially evident in mountains as an upward shift of the snow line, and a thinner snow cover of shorter durations (Laternser & Schneebeli 2003; Lopez-Moreno 2005; Mote *et al.* 2005). Duration and extent of snow cover, and snowmelt water determine the beginning and length of growing period, and the release of water and nutrients which are crucial for plant growth (Inouye & Wielgolaski 2003; Jones *et al.* 2001; Körner 2003; Pomeroy & Brun 2001).

Snow is also an important environmental factor controlling micro-climate and plant growth in an alpine ecosystem (Wipf & Rixen 2010) and its cover acts as an insulator during the cold season, protecting the plants and soil underneath (Sturm *et al.* 1997). In alpine and arctic systems, the occurrence of plant communities is closely associated with the spatial distribution pattern of snow (Evans *et al.* 1989; Odland & Munkejord 2008; Walker *et al.* 1993). In a short-term, plant growth (Galen & Stanton 1995; Siffi 2007; Walker *et al.* 1993; Wipf *et al.* 2006), and in long-term, vegetation composition (Galen & Stanton 1995; Seastedt & Vaccaro 2001; Welch *et al.* 2005) are affected by change in snowmelt timing. Snowmelt also controls biochemical, microbial and plant processes in winter (e.g. Campbell *et al.* 2005; Sturm *et al.* 2005), which persist well into growing season (Jones *et al.* 1998; Weih & Karlsson 2002). An early snowmelt results in a longer growing season and higher growing degree days potentially, but it also increases frost damage (subzero temperature) because of earlier dehardning (Cumming & Burton 1996; Gorsuch & Oberbauer 2002; Inouye 2000; Kimmins & Lavender 1992).

Consistent and repeated differences in snowmelt patterns largely determine the nature and intensity of stress and/or disturbance that plants have to cope with and, as such are expected to be a strong ecological driver of species sorting for alpine plant communities (Choler 2005). The alpine region is often regulated by extreme climates, such as low temperature, precipitation in form of scanty rainfall, blizzard and snowstorms, high wind velocity and high intensity of ultraviolet (UV) radiation (Nautiyal *et al.* 2004). The plants have adapted themselves to these climatic conditions and developed a mosaic of different life forms, such as dwarfed, stunted, woolly and spiny ones (Walker *et al.* 1994). There is a significant impact of intense anthropogenic disturbance on the structural and functional attributes of alpine vegetation communities, which are rich in high-value medicinal, aromatic and threatened plants. The degradation of alpine plant communities and treeline ecotone is further accelerated due to other drivers of change, such as extreme weather events, drought and forest fires (Singh *et al.* 2011; Xu *et al.* 2009).

In Himalayan region studies on the relationship between snowmelt and plant growth and species composition are negligible. However, decrease in snow fall and early snowmelt is a part of surveys, and general perceptions of local communities. Here, we analyze the impact of decreased snow cover and early snowmelt on phenology and some other attributes of plant communities above treeline. For this, we followed two approaches: in one we compared two slopes differing in the amount of snow cover and snowmelt timing, in the other, we compared the dates of phenophases with those of past studies. Temperature increases due to global warming during the last two to three decades in Himalaya have been particularly high and widespread (Singh *et al.* 2011; Yao *et al.* 2012). Therefore, we hypothesize that plants would respond to the warming by prolonging growth period and advancing phenophases. This is a preliminary study, which could be used to build up long-term studies to understand the impact of early snowmelt on plant communities of alpine treeline ecotones and the alpine meadows which occur above them.

Materials and methods

Study area

Tungnath, the study area lies in the upper catchment of the Alaknanda (one of the two tributaries of river Ganga) and the Mandakini rivers of Uttarakhand, a western Himalayan state of India (Fig. 1). Alpine meadow communities occurring in Tungnath included *Rhododendron campanulatum* krummholz, and several herb communities, consisting of forbs, grasses and sedges. The year is divisible into four seasons *viz.*, short summer (May to June), monsoon (July to mid-September), autumn (mid-September to October) and long winter (November–April). The period with snow cover is of about 4–5 months (December–April) and snowmelts during April–May between 3200–3300 m. In Tungnath timberline ecotone (3300 m), Adhikari *et al.* (2012) reported that temperature ranged between −8.9 in January and +25.6 °C in

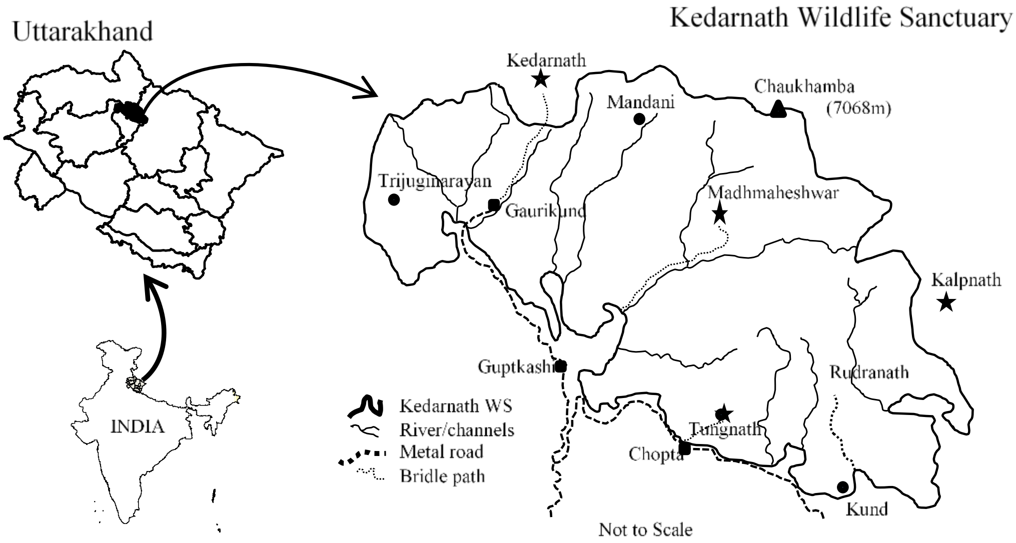

Fig. 1. Location map of the study site.

May, with an average of 6.7 ± 0.7 °C during 2008–2010, mean temperature of the warmest month July was 12.6 ± 1.2 °C. Annual precipitation was 2410.5 ± 432.2 mm, of which 89.5% was recorded during June–September (4 months). From the past climatic data for the period, from 1981 to 2017 obtained from NASA (http://cosweb.larc.nasa.gov./#dataaccess) for Tungnath region over time was discernible, following changes over the 36 years: relative humidity ($r^2 = 0.289$, $P < 0.05$), dew/frost point ($r^2 = 0.403$, $P < 0.01$), minimum ($r^2 = 0.298$, $P < 0.05$) and maximum temperatures ($r^2 = 0.007$, $P < 0.001$) have increased. However, during pre-monsoon (March to May), which is dry and windy, relative humidity ($r^2 = 0.226$, $P < 0.05$) and dew/frost point ($r^2 = 0.129$, $P < 0.05$) have decreased, while wind speed ($r^2 = 0.060$, $P < 0.001$), maximum ($r^2 = 0.145$, $P < 0.05$) and minimum temperatures ($r^2 = 0.061$, $P < 0.001$) have increased. The decline in pre-monsoon humidity could be due to the rise in temperature and an increase in wind speed. The annual rainfall has increased over time during the 36 yr period ($r^2 = 0.324$, $P < 0.01$).

Study design

To determine the effect of snow on vegetation, we selected two slopes different in snow cover, as recorded on April 28, 2017, when we could reach the site for the first time after the winter snow fall. We observed that the site with high snow cover had 70–80% area under snow cover with thickness up to 1.2 m. On that day, the branches of krummholz were partly covered with snow and much of the area was not accessible to us. The low snow cover site had 30–40% area under snow and maximum depth *ca.* 70 cm. These values are rough based on only a few samples, and are good enough only to indicate that the two sites clearly differed in snow cover. Subsequently, we observed that the snow cover lasted at least 20–25 days longer on High Snow Cover (hereafter referred as HSC) site than Low Snow Cover (hereafter referred as LSC) site (Fig. 2). HSC site was close to treeline forest which included *Abies spectabilis, R. campanulatum, Sorbus foliolosa* as well as *Quercus semecarpifolia*, the slopes were steep 35–55°, more rocky (40–55%), moderately sheltered from wind and relatively less exposed to the sun. On the other hand, in LSC site slopes were gentle (30–40°), less rocky (25–30%), wide and open to sun and wind. Timberline had largely *Abies spectabilis* and *Quercus semecarpifolia* was absent. However, HSC and LSC sites were not homogenous, so for sampling purpose, each one was divided in two sub-sites, referred to as HSC-A and HSC-B and LSC-A and LSC-B (Fig. 2). A and B sites of HSC and LSC differed in the composition of tree species of nearby forest, krummholz patches, snow duration and others (Table 1). On each of these sites/sub-sites, we selected three study plots each within Early Snowmelt (hereafter referred as ESM) and Late Snowmelt (hereafter referred to as LSM) microsites, based on frequent observations. The ESM microsites were exposed with convex surface, consequently snowmelt began earlier than no LSM microsites with

Table 1. Characteristic features of selected microsites between 3200 and 3300 m at Tungnath treeline.

Site	Low snow cover (LSC)		High snow cover (HSC)	
Sub-site	LSC-A	LSC-B	HSC-A	HSC-B
Slope (°)	35–40	30–35	40–55	35–45
Aspect	North	North-West	North-West	North-West
Tree and shrub species in adjoining timberline areas	*Abies spectabilis, Rhododendron campanulatum*	*A. spectabilis, R. campanulatum*	*Quercus semecarpifolia, A. spectabilis, R. campanulatum, Sorbus foliolosa*	*Rhododendron arboreum, Q. semecarpifolia, A. spectabilis, Betula utilis, R. campanulatum, Berberis kumaonensis*
Tree canopy cover (%)				
Tree	7	15	20	15
Krummholz	20	35	60	20
Grazing	Less	Moderate	Heavy	Heavy
Snow depth (m)	0.5–0.6	0.6–0.7	1.0–1.2	0.8–1.0
Snowmelt (Visual observation)	Early	Early	Late	Late
Snow duration (days) in microsites	ESM 45–50 LSM 55–60	ESM: 55–65 LSM: 65–70	ESM: 70–80 LSM: 75–85	ESM: 55–60 LSM: 70–80
Last date of snow presence	29 March, 2017	3 April, 2017	28 April, 2017	17 April, 2017

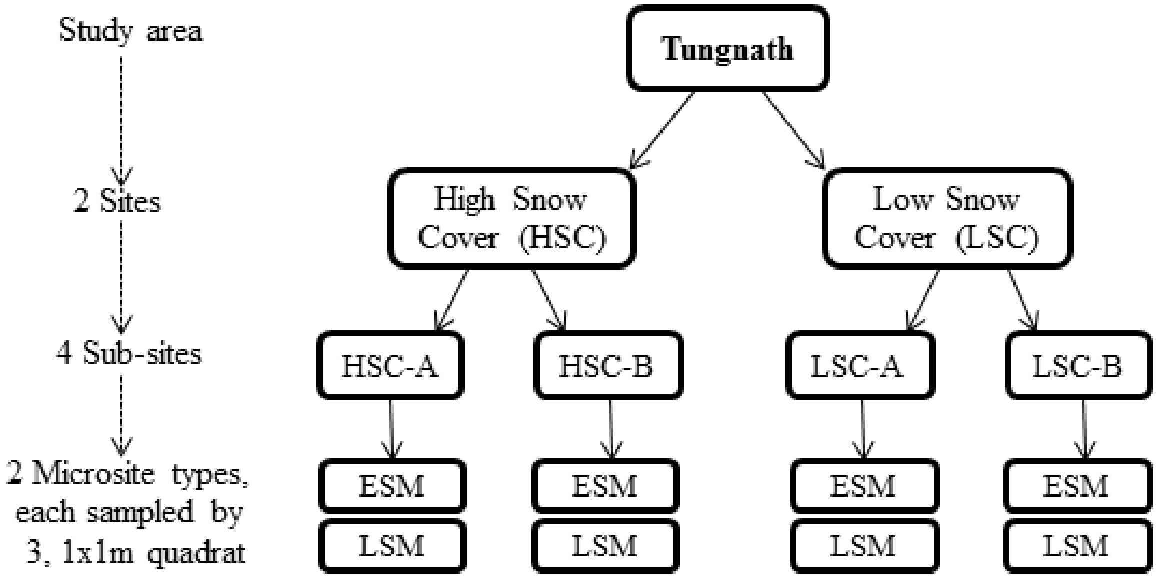

Fig. 2. Schematic representation of sampling design. LSC: Low snow cover, HSC: High snow cover, ESM: Early snowmelt, LSM: Late snowmelt.

sheltered and concave surfaces. The difference in snowmelt time between ESM and LSM microsites was generally of 3–5 days in LSC site, while in HSC site it was 10–15 days. A plot (50 × 50 m) was identified in each HSC and LSC sub-site (with two microsite types ESM and LSM, respectively). In each microsite, 3 permanent quadrats (1 × 1 m; Fig. 3) at an average distance of 10 m were laid for vegetation composition and phenology monitoring during the growth period (May–October, 2017).

Fig. 3. View of study area as on 19-02-2017 (top), early snow melt (left, with more plant cover) and late snowmelt (right, still with bare soil surfaces) microsites as on 27-05-2017.

Types and forms of plants

The species were divided into following categories with regard to their life span: annuals, plants which live for one growing season; perennials, plants which grow and bloom over spring/summer season and die every autumn/ winter and grow again from their root stock, and biennials, plants which complete life cycle in two years; in this plants germinate, grow and survive through winters, and next year grow more, bloom and die.

Growth form

The direction and extent of growth and branching of the main-shoot axis or axes determine the growth form of a plant. It may be largely associated with eco-physiological adaptation, such as maximizing photosynthetic production, sheltering from severe climatic conditions, and resistance to grazing by optimizing the height and positioning of the leaves and rosettes and prostrate growth forms are associated with heavy grazing. Here, plants were classified based on Pérez-Harguindeguy *et al.* (2013) as semi basal herbs, short basal herbs, erect leafy herbs and tussock-forming grasses, dwarf shrubs and climbers.

Life form and nativity

Species occurring in treeline area were divided into Raunkier's life form (Raunkier 1934) to develop life form spectrum.

The place of origin/first record of the species,

Table 2. Various stages, their names and description as per BBCH scale (Hess *et al.* 1997).

Stage	Code	Code details	Code description
Germination/sprouting	0	Germination/sprouting/bud development	From dry seed till leaf breaks the soil
Vegetative/growth phase	1	Leaf development (main shoot)	First leaf to nine or more leaves/whorls development
	2	Formation of side shoots/ tillering	First side shoot/tiller to nine or more shoot/tiller visible
	3	Stem elongation/shoot development (Main shoot)	Beginning of stem elongation to nine or more nodes
Flowering/vegetative propagation	4	Vegetative propagation/ booting (Main shoot)	Development of propagation organ to first awl visible
	5	Inflorescence emergence (Main shoot)/heading	Inflorescence/flower bud visible to full emergence
	6	Flowering (Main shoot)	First flower till the end of flowering when fruiting begins
Fruiting and Maturation	7	Development of fruit	Fruit begins to develop till maturity for species and location
	8	Ripening or maturity of fruit and seed	The beginning of ripening or fruit colouration till fully ripe
Senescence	9	Senescence or beginning of dormancy	Plant dead or plant resting or dormant

where it occurs naturally ‘indicates the nativity of the species (Anonymous 1883–1970), and the species introduced in an area where it did not occur previously through anthropogenic activities are called ‘Non-Native’. We used *Index Kewensis Plantarum Phanerogamarum* (Anonymous 1883–1970) to know the nativity of a species.

Species richness and diversity

Species richness was taken as a count of a total number of species in a particular area. The index of diversity was calculated after Shannon & Wiener (1949). If pi is the proportion of individuals (from the sample total) of species i.e. then diversity (H′) is,

$$H' = -\sum_{i=1}^{s}(Pi)(lnPi)$$

Where, P is a proportion (n/N) of individual of one particular species found (n) to a total number of individuals found (N), ln is a natural log, ∑ is sum of the calculations, and s isa number of species.

Sorenson Similarity Index (Is) between different sites was calculated following Sorenson (1948).

$$Is = \frac{2C}{A+B} \times 100$$

Where, *Is* the Sorenson Index of Similarity; *C* the common species to both comparable sites; *A* the total number of species in site *A* and *B*, the total number of species in site *B*.

The contribution of each species to the dissimilarity (%) between the two groups was calculated from the Bray-Curtis dissimilarity matrix through SIMPER analysis in PAST between ESM and LSM microsites.

Beta-diversity, a measure of species compositional change along environmental gradients within an area was calculated as the ratio of total species to the mean number of species per sample (Whittaker 1975) among months and sites. We performed the non-parametric test because data did not follow central tendency. To check the variance in density between months, sites and microsites Kruskal-Wallis test was performed.

Phenological observations

The phenological changes were observed visually to monitor how the species respond to climate variations at a monthly interval. Therefore, records of various phenophases such as growth initiation, vegetative phase, flowering, fruiting, seed formation and senescence, of each species were taken from May to October in 2017 following Biologische Bundesanstalt Bundessortenamt und CHemische Industrie (BBCH) scale (Table 2; Hess *et al.* 1997). The existence of a particular phenophase was considered if 5% of the individuals showed that phenophase. Based on growth initiation time, the plants were divided into two categories, early growth species (up to mid-May) and late growth species (mid-May to June).

To find out the changes in phenology of study plants caused due to change in climatic conditions over a time period, we have compared present phenological observations of thirteen common species with the studies conducted in past at Tungnath by Sundriyal *et al.* (1987) for *Anaphalis royleana, Anemone obtusiloba, Bupleurum longicaule, Danthonia cachemyriana, Geranium wallichianum, Oxygraphis polypetala, Pedicularis pectinata, Taraxacum officinale* and *Trachydium roylei*, Nautiyal *et al.* (2001) for *Selinum vaginatum* and a similar alpine site of west Himalaya i.e. Dyara (Bijalwan *et al.* 2013) for *Geum elatum, Parnassia nubicola* and *Potentilla atrosanguinea.* Since the frequency of phenological observation was long (1 month), the comparison gives only a rough estimate of change.

Results

Plant growth period (period from the beginning of growth to the time when about 80% of plant shoots had senesced) was about 5–6 months from about mid-April to mid-October. Soil moisture values (47–50%) during the peak growing period (July) were similar for ESM and LSM microsites, soil moisture was never a limiting factor for plant growth. The number of snow fall days during 2016–2017 winter (December to April) was 38 days.

Plant forms and growth cycle

In total, 86 plant species were encountered in quadrat sampling during the study period, of which the percentage of forbs was 90% and that of perennial species 90.6%, there were only few annuals (8.2%) and biennials (1.2%). Growth forms of the species in the present study were in the order: semi basal = short basal (32.9% each) > erect leafy (28.2%) > dwarf shrub (2.4%) > climber, shrub and tussock (1.2% each). A majority of species had a long growth cycle (64%), followed by intermediate growth cycle (31%) and short growth cycle (5%). Tall forbs were 34%, medium size forbs 23% and short forbs 34%, while the rest were climbers, shrub, undershrub, grasses and sedges (10%). The life form was dominated by hemicryptophytes (84%).

Species richness and diversity

Even within a short growing period, the growth initiation in species was staggered. The ESM and LSM microsites were similar in total species number (74 and 72 species, respectively) and numbers by growth forms (semi-basal 26 and 24 species and short basal 25 and 24 species, respectively). The total species number in the study area increased as the growth period progressed from 44 in May to 80 in September. Generally, species number in a month was markedly higher in ESM than LSM microsites, the difference being particularly large at HSC-B sub-site (38 in ESM and 27 in LSM microsite) in July (Fig. 4). Two-way ANOSIM was applied to test for significant variations in species richness between sub-sites and across months. It showed significant differences (R = 0.93 and R = 0.91, respectively).

At the peak of species richness, 60% species were common to both ESM and LSM microsites. The species richness (species number m^{-2}) generally peaked in July and ranged between 15.0–20.7 in LSM and 19.7–24.0 in ESM microsites across four sub-sites. In LSC site plant density was significantly high for ESM microsite than LSM microsite, while such difference was not obvious for HSC site, possibly because of the shorter growing period due to longer stay of snow. The Shannon-Weiner diversity index was relatively higher in ESM microsites (2.832 ± 0.055) than LSM microsites (2.775 ± 0.048; Fig. 5). It seems that early snowmelt allowed basal leaf forms (*Ranunculus, Fragaria, Oxygraphis, Trachydium*) to express themselves prominently.

The ß-diversity (calculated across quadrats use to sample species richness) between sites was higher in HSC (2.59) than LSC (2.28), among sub-sites it was higher in HSC-A (2.09), followed by LSC-A (1.88), HSC-B (1.86) and then LSC-B (1.83); between microsites it was higher in LSM (2.78) than ESM (2.42). The ß-diversity across months was higher in LSM (1.9–2.3) than ESM (1.7–1.9).

Species similarity among sub-sites and microsites

The overall similarity in species context between ESM and LSM microsites was 82%, however, the similarity between ESM and LSM microsites within each sub-site was much lower (LSC-A 32%, LSC-B 31%, HSC-A 31%, and HSC-B 38%). The similarity between ESM microsites of HSC and LSC was 70%, while between LSM microsites of HSC and LSC was 53%. However, the similarity between HSC and LSC sites was 88%. SIMPER (Similarity Percent) analysis showed 72% and 67% dissimilarity, respectively, among LSM

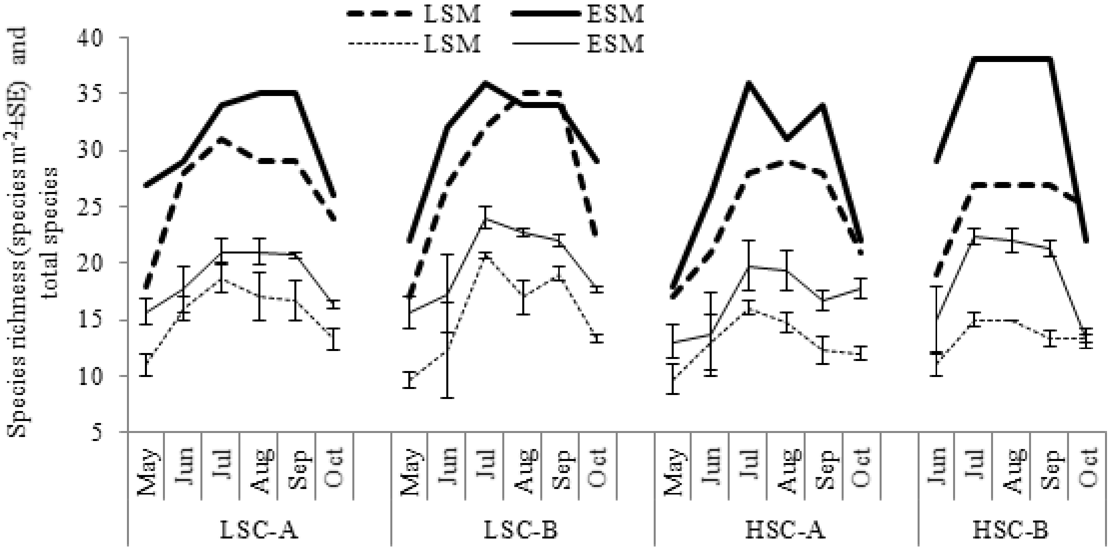

Fig. 4. Herb species richness across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath treeline in Garhwal Himalaya. Total species depicted in thick line and average species richness (number m^{-2}) in thin line. LSC: Low snow cover, HSC: High snow cover.

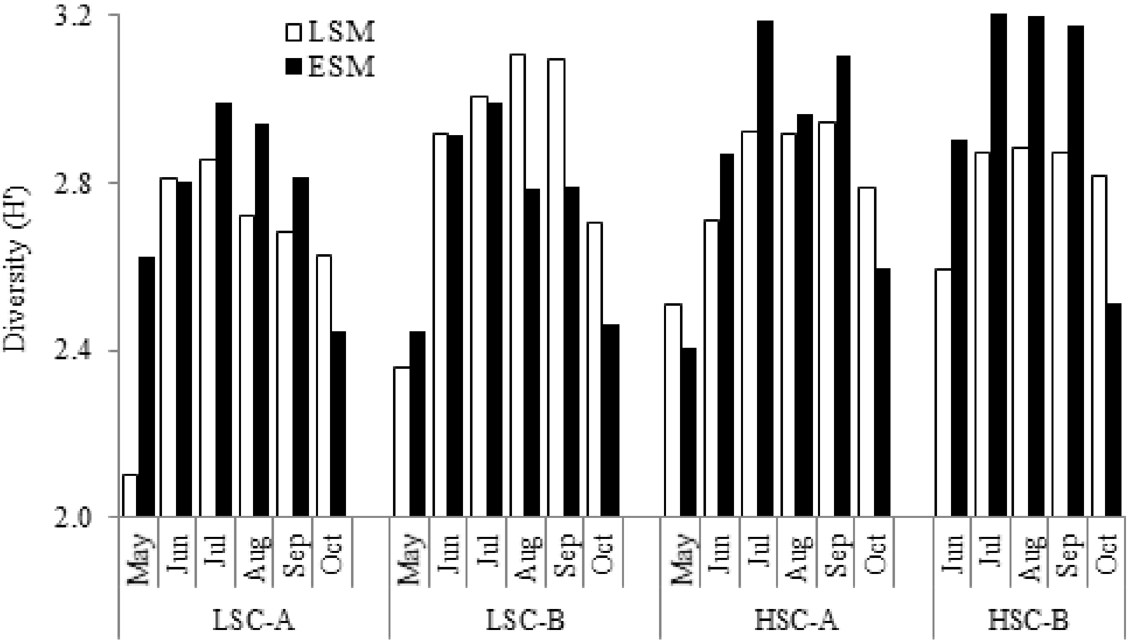

Fig. 5. Patterns of species diversity (H') across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath treeline in Garhwal Himalaya. LSC: Low snow cover, HSC: High snow cover.

and ESM microsites. The major species which contributed to dissimilarity in descending order were *Fragaria, Ranunculus, Polygonum, Carex, Bistorta, Trachydium, Anemone, Poa, Circaea* and *Potentilla* for LSM microsites and *Ranunculus, Trachydium, Carex, Oxygraphis, Fragaria, Anaphalis, Prunella, Polygonum* and *Anemone* for ESM microsites.

Habitat preference of plant species

Bistorta amplexicaulis, Fragaria nubicola, Geranium wallichianum, Potentilla atrosanguinea and *Viola biflora* were present in all quadrats. The species which were present in all LSM microsites were *Myriactis wallichii* and *Veronica cana* (both erect leafy), while *Anaphalis nepalensis, Kobresia, Selinum vaginatum* (all semi-basal), *Oxygraphis polypetala, Polygonum filicaule, Potentilla lineata* and *Potentilla polyphylla* (all short basal) occurred in all ESM microsites. *Aster albescens, Corydalis cornuta, Cynoglossum glochidiatum, Gaultheria trichophylla, Gentiana argentea, Gentiana tubiflora, Gerbera gossypina, Goodyera repens, Ligularia sibirica, Morina polyphylla, Persicaria nepalensis, Primula reidii, Rumex nepalensis* and *Swertia auriculata* were present in ESM microsites only, while *Arisaema propinquim, Aster methodrus, Clematis barbellata, Galium asperifolium, Halenia elliptica, Hemiphragma heterophyllum, Ligularia amplexicaulis, Parochetus communis, Smilacina purpurea, Thalictrum foliolosum, Trillium govanianum* and *Viburnum glanduliflorum* were present only in LSM microsites.

On the basis of monthly average density the dominant species by sites and sub-sites were as following:

LSC-A:

ESM: *Ranunculus hirtellus* (70.2 ± 9.1 individuals m^{-2}) followed by *Trachydium roylei, Oxygraphis polypetala* and *Fragaria nubicola* (56.8 ± 3.7, 48.1 ± 2.2 and 38.7 ± 6.2 individuals m^{-2}, respectively)

LSM: *Fragaria nubicola* (53.2 ± 13.0 individuals m^{-2}) followed by *Carex setosa* (22.5 ± 2.0 individuals m^{-2}).

LSC-B:

ESM: *Ranunculus hirtellus* (97.9 ± 6.1 individuals m^{-2}) followed by *Carex setosa, Trachydium roylei* and *Oxygraphis polypetala* (61.7 ± 12.1, 42.1 ± 6.9 and 35.5 ± 4.0 individuals m^{-2})

LSM: *Fragaria nubicola* (20.9 ± 3.9 individuals m^{-2}) followed by *Trachydium roylei* and *Bistorta amplexicaulis* (20.1 ± 1.4 and 16.7 ± 4.2 individuals m^{-2}, respectively).

HSC-A:

ESM: *Anaphalis nepalensis* (24.6 ± 2.2 individuals m^{-2}) followed by *Carex setosa* and *Polygonum delicatula* (16.4 ± 3.3 and 15.7 ± 4.0 individuals m^{-2}, respectively)

LSM: rapid changes in species dominance was seen where no two months had same dominance in terms of plant density, as the majority of species (*Bistorta amplexicaulis, Fragaria nubicola, Polygonum delicatula, Polygonum filicaule* and *Potentilla polyphylla*) contributed similarly (10.2–14.0 individuals m^{-2}).

HSC-B:

ESM: *Ranunculus hirtellus* (39.1 ± 0.2 individuals m^{-2}) followed by *Fragaria nubicola* and *Lysimachia prolifera* (18.3 ± 1.9 and 16.5 ± 4.2 individuals m^{-2}, respectively).

LSM: *Ranunculus hirtellus* (41.1 ± 1.9 individuals m^{-2}) followed by *Poa annua, Polygonum filicaule* and *Bistorta affinis* (22.3 ± 2.4, 19.1 ± 2.3 and 17.1 ± 2.7 individuals m^{-2}, respectively)

The average plant densities were markedly higher in LSC (313.7 ± 30.3 individuals m^{-2}) than HSC (187.6 ± 13.6 individuals m^{-2}) sites. Similarly, the plant densities were higher in ESM microsite (325.2 ± 30.4 individuals m^{-2}) than LSM (182.1 ± 12.0 individuals m^{-2}) microsite (Fig. 6). The plant density was signify-cantly higher in ESM (441.8 ± 30.2 individuals m^{-2}) microsite than LSM (196.3 ± 15.2 individuals m^{-2}) microsite of LSC, but ESM (208.5 ± 18.7 individuals m^{-2}) and LSM (166.7 ± 18.6 individuals m^{-2}) microsite of HSC site did not differ significantly (Fig. 6). The difference in densities was tested through Kruskal-Wallis test (non-parametric one way ANOVA), which were highly significant across months ($F = 17.69$, $df = 146.6$, $P < 0.001$), sub-sites ($F = 13.06$, $df = 322.5$, $P < 0.001$) and microsites ($F = 9.896$, $df = 205.3$, $P < 0.001$).

Phenology at microsite level

In general, phenophases were observed in more advanced stages in ESM than in LSM microsites.

At community level as indicated by species number, the vegetative phase peaked in June, flowering and fruiting in August and senescence phase in October in both ESM and LSM microsites (Fig. 7). Because observations were taken at a monthly interval, differences between ESM and LSM could not be detected with regard to phenology at the community level. In the initial months of growth period i.e. May and June the species number was high in vegetative phase (26–32 in ESM and 31–34 in LSM microsites).

The ESM microsites supported the vegetative as well as the reproductive growth of plants even after the rainy season and no difference was observed in fruiting and seeding phase between ESM and LSM microsites. The flowering phase peaked in August with 40 species in ESM and 38 in LSM microsites. Senescence started during June and July in ESM and LSM microsites, respectively and more species were senescing during September in LSM (36) microsites than ESM (31) microsites. The senescence was more rapid in ESM microsites than LSM microsites (Fig. 7).

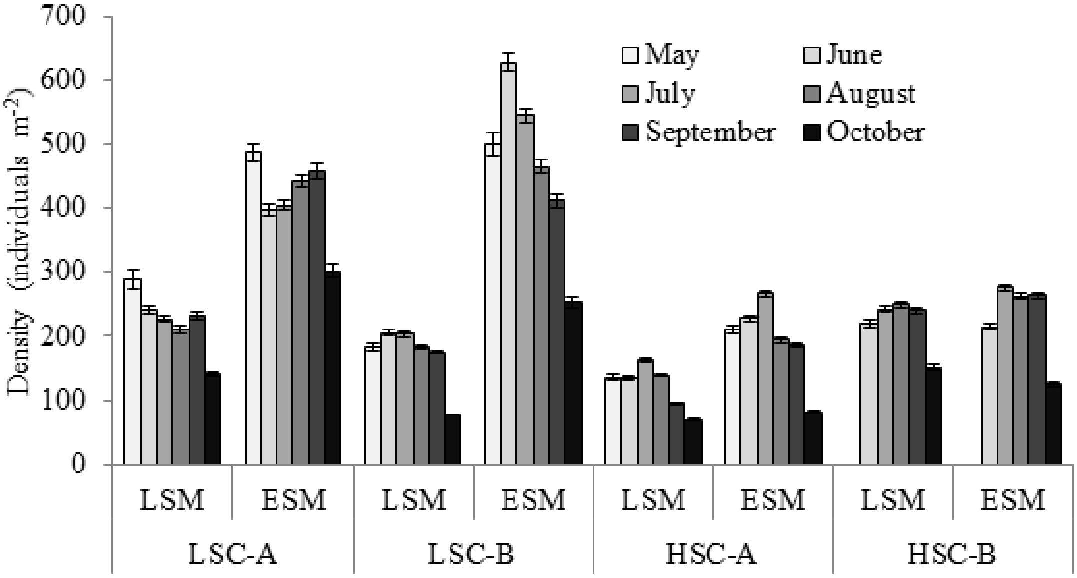

Fig. 6. Plant density (individuals m⁻²) at different sites across months at treeline in Tungnath region, Garhwal Himalaya. LSC: Low snow cover, HSC: High snow cover, ESM: Early snowmelt, LSM: Late snowmelt.

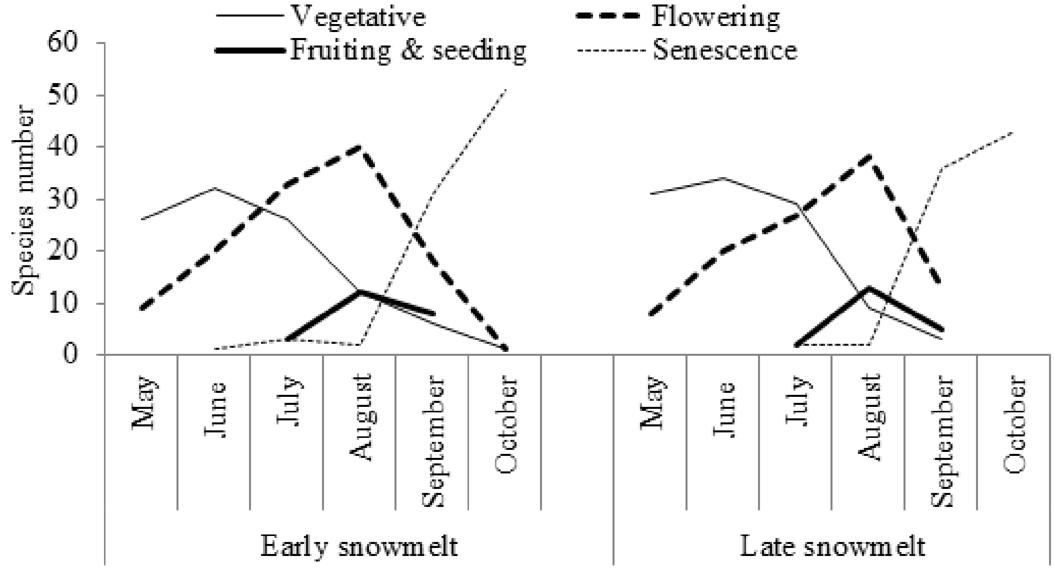

Fig. 7. Number of species across months in different phenophases in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath.

Change in phenology based on comparison with past studies

As compared to past studies, in our study the flowering advanced for Anaphalis (3 weeks), Pedicularis and Anemone (2.5 weeks), Potentilla and Taraxacum (2 weeks), Bupleurum and Geum (1 month). The flowering phase in the present study was shorter by a week in *Trachydium* and delayed in *Selinum* by 2 weeks as compared to Sundriyal *et al.* (1987; Table 3). The flowering phase was extended in *Selinum, Parnassia* and *Geum* by one month period and in *Danthonia* and *Potentilla* by 2 weeks as compared to that of Sundriyal *et al.* (1987). *Oxygraphis* flowered twice, the first flowering phase was delayed by 1 week and the second by 3 weeks; the length of flowering duration increased by

Table 3. A comparison of timing and length of plant phenophase of the present study with those past studies conducted at the same and similar areas, Tungnath and Dyara. VP: Vegetative phase, FP: Flowering phase, FrP: Fruiting phase and SP: Senescence phase.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
Comparison with the study conducted by Sundriyal *et al.* (1987) in 1984 in Tungnath region				
Anaphalis royleana	VP	May to mid-June	May to early August	Extended more than 2 months
	FP	mid-June to mid-July	July to late September	Advanced by 3 weeks
	FrP	July last to August	September	Delayed by a month
	SP	September and October	October	Delayed by a month
Danthonia cachemyriana	VP	May to mid-June	May to July	Extended by a month
	FP	late-June to early August	August	Delayed by 1.5 months and extended 2 weeks
	FrP	early August to Mid-September	last week of August	Confined to a week
	SP	mid-September to October	September-October	Advanced by 2 weeks
Oxygraphis polypetala	VP	early May (2 weeks)	May to August	Extended by 3.5 months
	FP	late May (2 weeks)	late May to mid-June and early to last August	Showed 2 growing cycles, delayed by 1 week and extended by 2 weeks in the first stage and 3 weeks in later stage and length of the period was more in a later stage
	FrP	June to mid-August	late May to June and late August to September	Showed 2 growing cycles; advanced by a week and length of phase was slightly more in later part
	SP	mid-August to October	October	Delayed by 1.5 months
Pedicularis pectinata	VP	up to mid-June	May to August	Extended by 3.5 months
	FP	mid-June to July	Late May to July	Advanced by 2.5 weeks
	FrP	August to early September	July	Advanced by a month
	SP	early September to October	September to October	Advanced by a week
Trachydium roylei	VP	May to mid-June	May to mid-June	No change
	FP	mid-June to early August	Mid-June to July	Reduced by a week
	FrP	early August to late September	August to mid-September	Advance by a week and reduced by 2 weeks
	SP	late September to October	mid-September to October	Advanced by 2 weeks
Comparison with the study conducted by Bijalwan *et al.* (2013) in 2008 in Dyara				
Anemone obtusiloba	VP	May	May to September	Extended 4.5 months
	FP	June-July	mid-May to July	Advanced by 2.5 weeks
	FrP	August	Absent	Not seen, may be for a short period
	SP	September - October	October	Delayed by a month
Bupleurum longicaule	VP	mid-June to mid-August	mid-June to mid-July	Reduced by a month
	FP	mid-August to mid-September	mid-July to late August	Advanced by a month
	FrP	September later half	late August to September	Advanced by 3 weeks
	SP	October	October	Reduced by a week

Contd...

Table 3. Continued.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
Geranium wallichianum	VP	May to mid-July	May to late August	Extended by a month
	FP	mid-July to late August	early June to September	Advanced by a month and extended by a month
	FrP	late August to September	September to mid-October	Reduced by a week and extended by 2 weeks
	SP	October	September - October	Advanced by a month
Taraxacum officinale	VP	May to mid-July	May-June	Reduced by 2 weeks
	FP	Mid-July to early September	July to early September	Advanced by 2 weeks
	FrP	September	Mid-July to September	Advanced by almost 2 months
	SP	October	October	No change
Comparison with the study conducted by Nautiyal *et al.* (2001) during 1988-1998 in Tungnath				
Selinum vaginatum	VP	May to mid-July	May to early September	Extended by 1.5 month
	FP	Mid-July to August	August - September	Delayed by 2 weeks and extended by a month
	FrP	September	Absent	Not seen, may be for a short period
	SP	October	October	No change
Comparison with the study conducted by Sundriyal *et al.* (1987) and Bijalwan et al. (2013)				
Geum elatum	VP	May to early June/May to mid-June	May-June	Extended by 4 and 3 weeks from 1984 and 2008, respectively
	FP	Early June to early July/mid-June to Late July	June to early August	Advanced by 1 and 2 weeks and extended by a month and 2.5 weeks, respectively from 1984 and 2008
	FrP	Early July to August/late July to September	July to early September	Advanced by 1 and 3 weeks and extended by 1 week and reduced by 3 weeks from 1984 and 2008, respectively
	SP	September-October/October	September-October	Similar to 1984 and advanced by a month from 2008
Parnassia nubicola	VP	mid-May to early July/mid-May to late August	Early June to mid-August	Extended by 3.5 weeks from 1984 and 2008, extended by 3 weeks and advanced by a month from 1984 and reduced by 3 weeks from 2008
	FP	early July to mid-August/Late August	July to mid-September	Advanced by 1 week and 1month and extended 1 month and 3 weeks from 1984 and 2008, respectively
	FrP	mid-August to mid-September/September	September	Delayed by 2.5 weeks and extended 2 weeks from 1984 and similar with 2008
	SP	mid-September to October/October	October	Delayed by 1 and 2 weeks from 1984 and 2008, respectively

Contd…

Table 3. Continued.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
Potentilla atrosanguinea	VP	May to early July in 1984 & 2008	May to late August	Extended by 1.5 months
	FP	early July to mid-August/early July to early September	July-August	Advanced by 2 weeks from both and extended by 2 weeks from 1984 and reduced by a week from 2008
	FrP	mid-August to mid-September/early September to early October	Late July to Late September	Advanced by 3.5 weeks and 1 month and 2 weeks from 1984 and 2008, respectively reduced 2 weeks from 2008 and extended by 1 week from 1984
	SP	mid-September-October/October	Early September to October	Advanced by 2 weeks and 1 month from 1984 and 2008, respectively

about two weeks. In the present study, the duration of flowering was extended by 2.5 weeks for *Geum* and 3 weeks for *Parnassia* and it was shortened by a week for *Potentilla* as compared with those reported by Bijalwan *et al.* (2013; Table 3).

The fruiting was delayed in *Anaphalis* by a month and in *Parnassia* by 2.5 weeks and advanced in *Pedicularis* by one month. The length of fruiting duration was shortened in *Trachydium* and *Geum* (1 week) and *Potentilla* (3.5 weeks), and extended in *Parnassia* (2 weeks) and *Potentilla* (1 week) as compared to Sundriyal *et al.* (1987; Table 3). The fruiting in *Danthonia* was confined to a week and it was not observed in *Selinum* and *Anemone*. The flowering phase was advanced in *Bupleurum* (3 weeks) and *Taraxacum* (2 months) and the length of duration increased in *Geranium* (2 weeks) as compared to that of Bijalwan *et al.* (2013). The senescence was delayed by 1 month in *Anaphalis*, 2 weeks in *Oxygraphis* and 1 week in *Parnassia* (as compared to Sundriyal *et al.* 1987) and by 2 weeks in *Parnassia* (as compared to Bijalwan *et al.* 2013). The senescence advanced by 2 weeks in Danthonia and Trachydium and by 1 week in Pedicularis as compared to Sundriyal *et al.* (1987) and by 1 week in Guem and Potentilla as compared to Bijalwan *et al.* (2013) However, no change was observed in *Selinum* (as compared to Nautiyal *et al.* 2001) and *Geum* (as compared to Sundriyal *et al.* 1987) from the past studies.

Discussion

Our study shows that the advancement of snowmelt affects species diversity, growth and phenology of herbaceous species in the Himalayan treeline ecotone.

Comparison between early and late snowmelt microsites

The t-test indicated that the means of species richness between sites (HSC and LSC) and between microsites (ESM and LSM) were significantly different (P = 0.007 and 0.0001, respectively) at the 95% confidence interval. The monthly peak of species richness in ESM microsites (average 21.8 ± 0.4 species m^{-2}) was significantly higher than in LSM microsites (average 17.6 ± 0.6 species m^{-2}), indicating the positive effect of longer and favourable growth period on species diversity. The plant growth in treeline and alpine areas is influenced by the timing of snowmelt, post snowmelt temperature and soil moisture (Winkler *et al.* 2018). In Tungnath temperature is getting warmer due to global change over a long growth period (5–6 months) and soil moisture is constantly high during this period (Joshi *et al.* 2018; this issue). Sites, where snowmelt occurs earlier, are more productive and species-rich than where snowmelt is delayed (Kudo 1991; Stanton *et al.* 1994; Litaor *et al.* 2008).

Species richness is not entirely dependent on macro-climate, it is also influenced by variations in soil water content and other variables related to topography (Nabe-Nielsen *et al.* 2017). This study (Nabe-Nielsen *et al.* 2017) also indicates that impacts of snow loss due to climate change could result in an increase in species richness. Early snowmelt results in a longer period of growth provided there are species to take this advantage. The higher diversity of ESM microsites contributed to the lengthening of phenophases and overall growth period. Warming-induced acceleration in species enrichment on mountain summits has been recorded at a continental scale in Europe largely because of the migration of the species from lower elevations (Pauli *et al.* 2012). In our study, we have not analyzed to what extent the higher species richness in ESM was because of the migration of species from lower elevations or free-ranging species. It would be interesting to investigate to what extent an early snowmelt facilitates the establishment of such species.

In the present treeline ecotone sites three types of species with regard to distribution occurred: wide-ranging species, such as *Fragaria nubicola*; largely alpine, such as *Oxygraphis polypetala, Carex setosa, Ranunculus hirtellus* and *Trachydium roylei*; and largely treeline and subalpine species such as *Poa annua* and *Viola biflora*. Early snowmelt may also promote the occupation of the sites by wide ranging species (Kudo & Hirao 2006; Sherwood *et al.* 2017).

The species richness across various alpine sites in western Himalaya is reported to range from 27 to 56 species (average 30.5 ± 8.3 species; Rawat 2007), thus the species richness in present study site (49.8 ± 5.5 species) is towards the higher side of this range. Our species density values (species number m^{-2}) are similar to that (15–21 species m^{-2}) reported for Zemu valley in Sikkim by Tambe (2007). It shows that in alpine herbaceous communities species richness does not differ between a Uttarakhand Himalayan site (Tungnath) and a Sikkim site, though in lower elevations Sikkim is far more species-rich than Uttarakhand.

The diversity values of present study are less than those reported for herb layer of timberline zone (3.06–3.25) by Rai *et al.* (2012), south and south-east facing slopes of the Greater Himalaya (3.01–3.30) by Rawat (2007) and treeline gaps (3.23) by Kala *et al.* (1998). However, our diversity values are higher than those reported by Rawat (2007, 2.1–2.4) for greater Himalaya as a whole, Kala *et al.* (1998, 2.47) for Valley of Flowers National Park, Singh (1999, 2.39) for Upper Tirthan Valley between 3200–3300 m and Tambe (2007, 1.44–2.48) for alpine landscape of Khangchendzonga National Park.

The turnover rate of species as indicated by ß-diversity was higher in LSM than in ESM and between HSC and LSC sites it was higher in the former. The association of high turnover of species in communities where snow cover was more and snowmelt was delayed needs to be investigated. It could be related to shorter lifecycle duration of species and grazing activities.

As per Raunkaiers' life form spectra, hemicryptophyte (83.5%) dominated the study site (Tungnath), which is a common feature of the alpine meadows in Himalaya (Dad & Khan 2010; Kumar *et al.* 2016; Nautiyal 1996; Nautiyal *et al.* 2001; Rawat 2007; Sundriyal *et al.* 1987; Vashistha *et al.* 2011). A comparison with those of past studies indicates that the proportion of hemicryptophytes has increased in the study area. They are better adapted to grazing, trampling and other environmental factors viz. wind, heavy rainfall/ erosion, and heavy frost than that of other life forms (Hanninen 2016; Sternberg *et al.* 2000). The studies conducted by Ram & Arya (1991) in Rudranath region, Pangtey *et al.* (1990) for Central Himalaya and Dhar & Kachroo (1983) in Yusmarg indicate the higher proportion of Chamaephytes (31, 47 and 46%, respectively), which could be due to their drier conditions. We recorded that about 70% species are native to the Himalayan region, 11% are of the Indian subcontinent and 8% Indian origin. A high number of native species indicates the high conservation value of Tungnath region, as also

Table 4. Change in phenophase duration and timing (initiation) based on comparison with past studies (Bijalwan *et al.* 2013; Nautiyal *et al.* 2001; Sundriyal *et al.* 1987). Number in parenthesis denotes species of the total common species (# 13). Duration and time period of phenophase: +, increase and–, decrease.

Phenophase	Vegetative	Flowering	Fruiting	Senescence
Change in the length of phenophase duration (d = days)	+55 d (11), −21 d (2)	+21 d (7)	+16 d (4), −25 d (2), 0 d (7)	-
Change in timing of initiation (d = days)	−2 d (1)	+22 d (9), −18 d (4)	+17 d (6), −15 d (5), 0 d (2)	+16 d (8), −26 d (5)

reported by Rana & Samant (2009) for Manali Wildlife Sanctuary.

Changes in timing and length of phenophase over time

Our analysis based on a comparison between present and past studies carried out at the same and similar sites indicate that the length of the vegetative phase has increased on an average by 40 days. This extension has occurred both because of early initiation and delayed termination of the vegetative phase. Evidently, conditions have become favourable because of warmer temperature and high soil moisture availability. Flowering has advanced and extended in the majority of species but not to the extent of vegetative phase. The timing of bud break both, vegetative and flowering is also dependent on whether the bud is preformed or not. In alpine vegetation, nearly 50% species have preformed buds (Winkler *et al.* 2018). The growth of such plants partly depends on the growth condition of the previous year (Körner 2003). In a number of species, fruiting has delayed and shortened. This indicates that in the past when temperature was low, species resorted to fruiting when under stress, while the present favourable conditions (warm and moist) have promoted vegetative growth at the expense of reproductive growth (Table 4). During the last 36 years, precipitation and minimum temperature have increased, indicating an increasingly warm and humid condition, which causes a change in phenological patterns for alpine species, in general.

Conclusion

Early snowmelt is already a major driver of community change in Himalayan treeline ecotones. ESM and LSM microsites indicate that early snowmelt leads to an increase in species richness and higher plant density. However, the impact of early snowmelt on plant density is modified by snow cover. A thick snow cover seems to suppress the positive effect of early snowmelt on plant density. The higher number of species in ESM microsites could suggest the migration of some free-ranging species to treeline ecotones, as being observed in alpine communities of other parts of the world. This needs to be investigated in view of the fact that the Himalayan treeline growth period is already quite long; in other words, it is not much shorter than in lower mountain areas.

Comparison of our data with those of past studies conducted at the same or similar site (based on 13 common herb species) indicates that the duration of vegetative growth period has increased in 77% species and flowering in 69% species. As for fruiting, the effect of warming is mixed. Flowering has advanced in 69% species, but species behaviour varies with regards to fruiting and senescence. The vegetative phase has extended for particularly long period in alpine-restricted species namely *Oxygraphis* and *Pedicularis* (3.5 months), *Anaphalis* (2 months), *Selinum* and *Potentilla* (1.5 months), *Geum* (3–4 weeks) and *Parnassia* (3 weeks).

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