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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

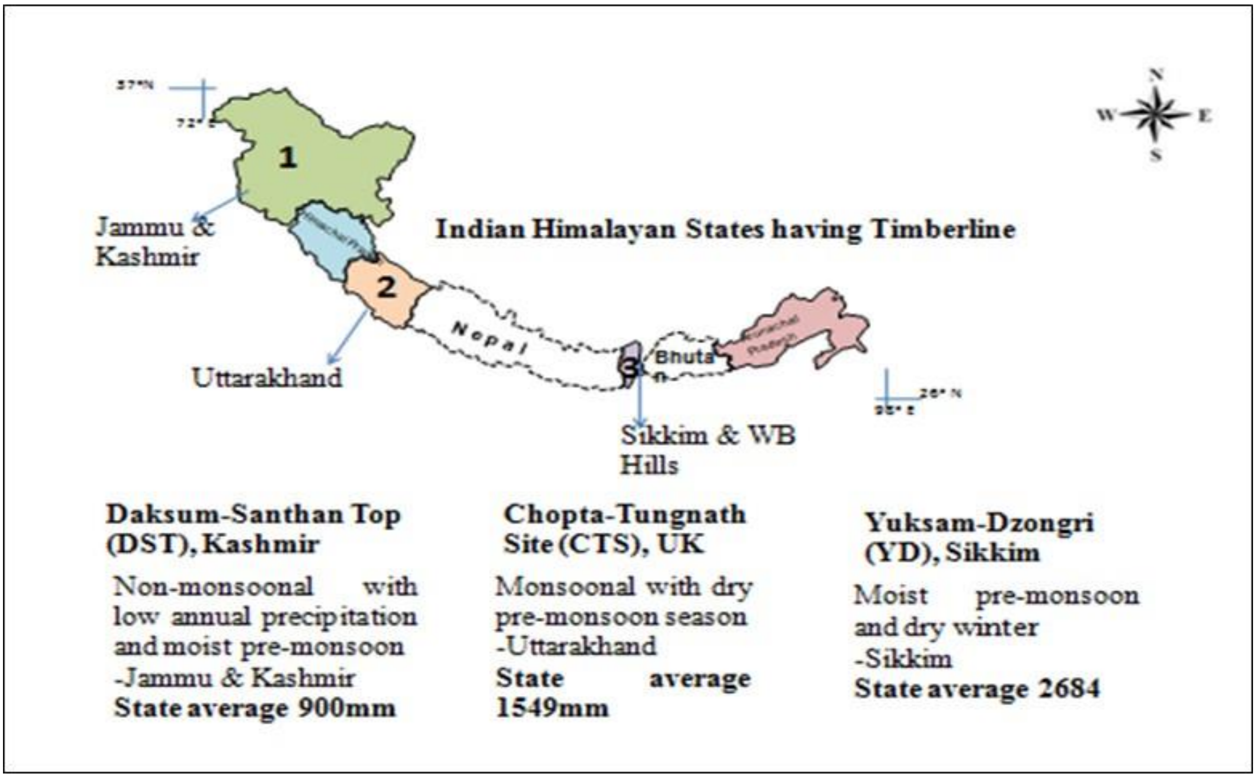

Fig. 1. Three study sites for detailed treeline/timberline study. The study sites cover much of the range of variation across the Himalayan Arc, and represent three precipitation regimes (Courtesy: Subrat Sharma, GBPNIHESD, Almora).

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

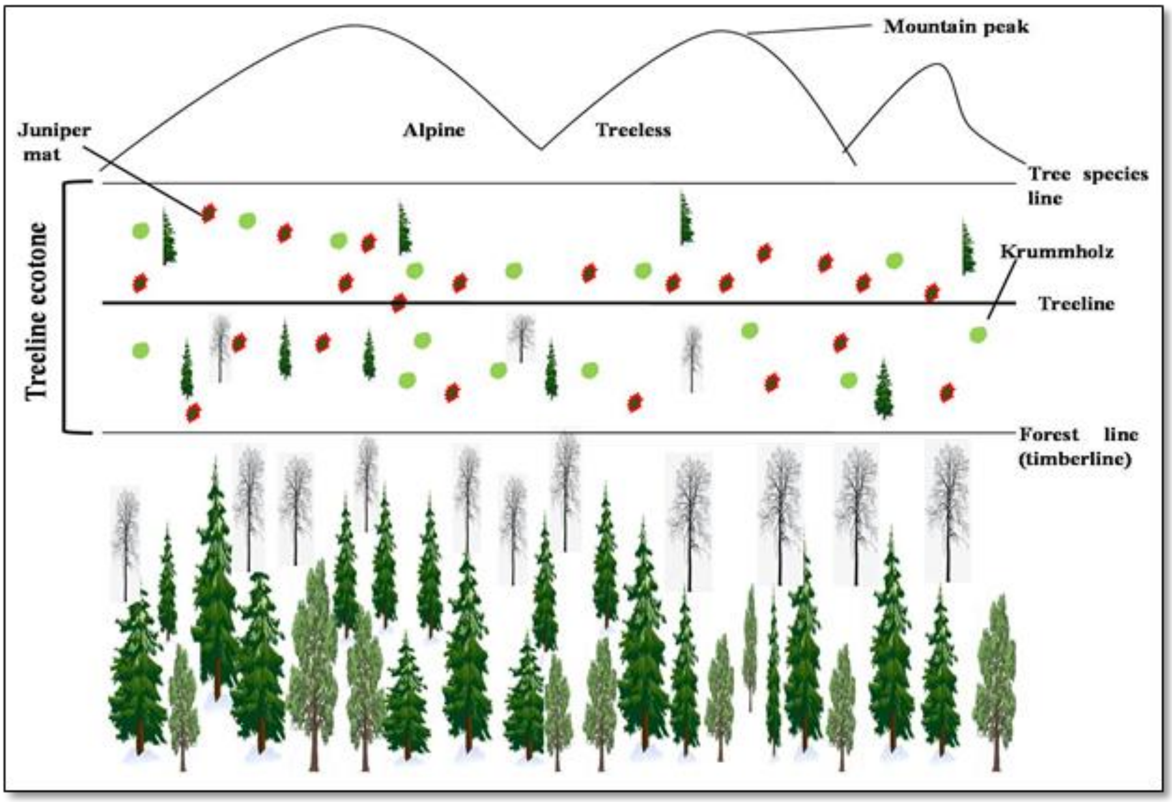

Fig. 2. A representation of treeline ecotone in Himalayas, indicating timberline, treeline and tree species line. Amongst scattered tree individuals, patches of krummholz and mats are shown. Juniper mats are common in Kashmir (developed with the help of Surabhi Gumber and Ripu Daman Singh).

(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

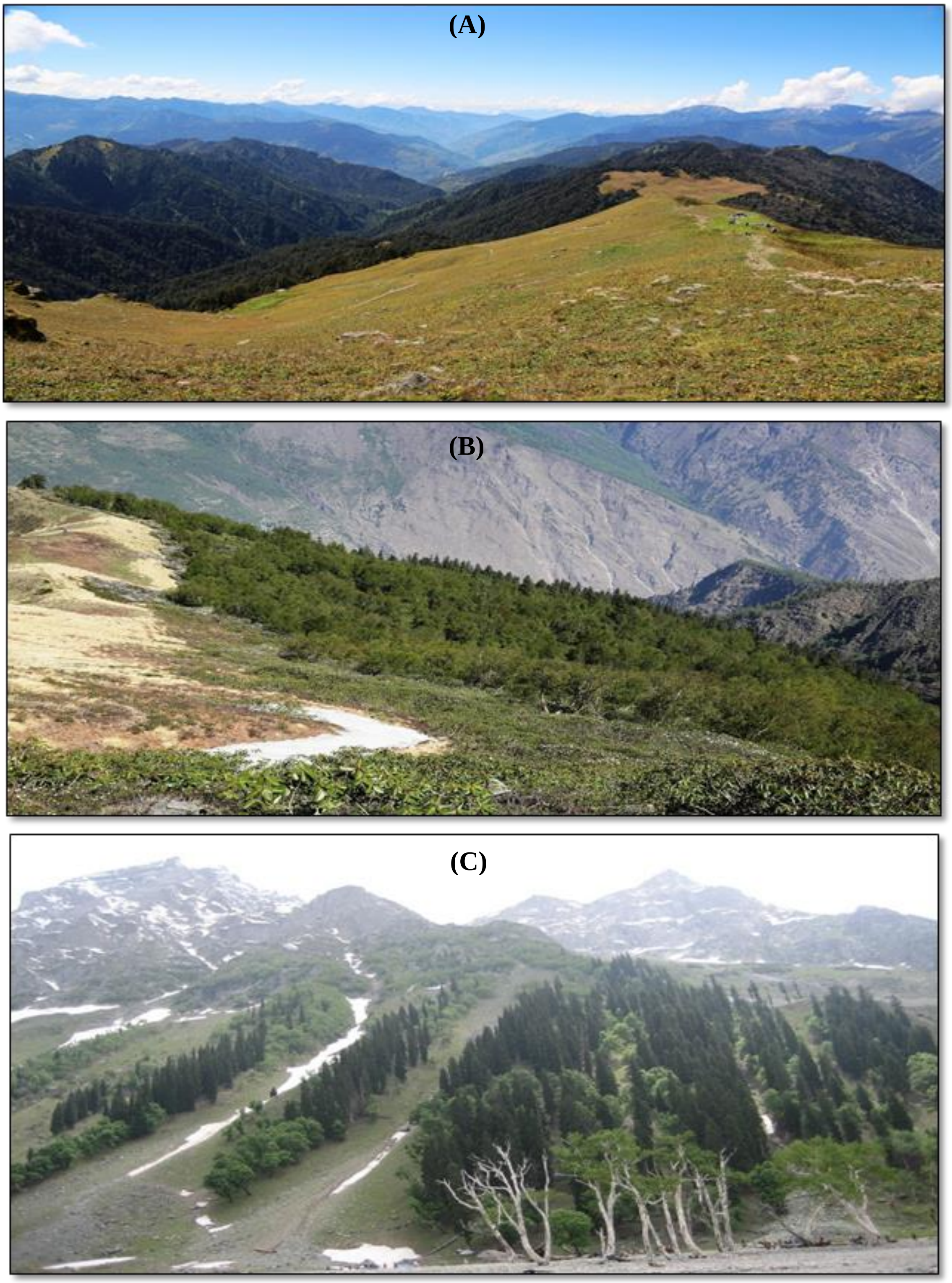

Fig. 3. Various forms of treeline: (A) Abrupt treeline- *Quercus semecarpifolia* forming abrupt timberline in Chaudas valley 3800 m (Courtesy: Dr. Vikram Negi, GBPNIHESD); (B) Diffuse treeline- *Betula utilis* and *Rhododendron campanulatum* forming treeline at Lata-Khark Nanda Devi Biosphere Reserve 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).

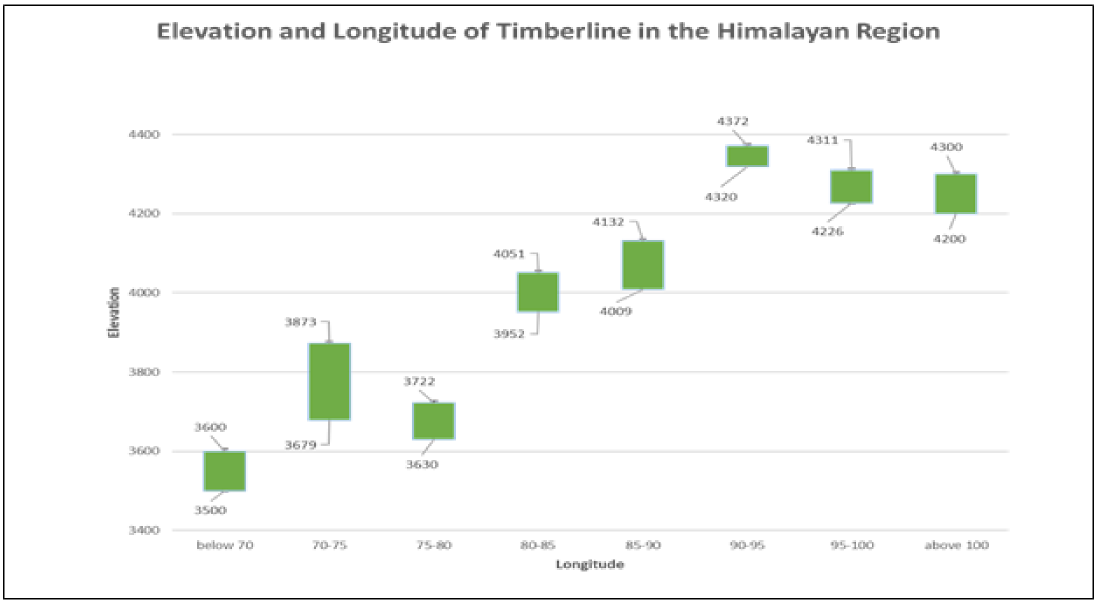

Fig. 4. Lowest and highest limit of treeline (average of pooled samples) in different longitudinal bands along the arc (west to east). Number in parenthesis indicates *n*. (Source-Drawn by Dr. Subrat Sharma, GBPNIHESD). Pattern of change in treeline elevation from west to east of the Himalayan Arc (data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

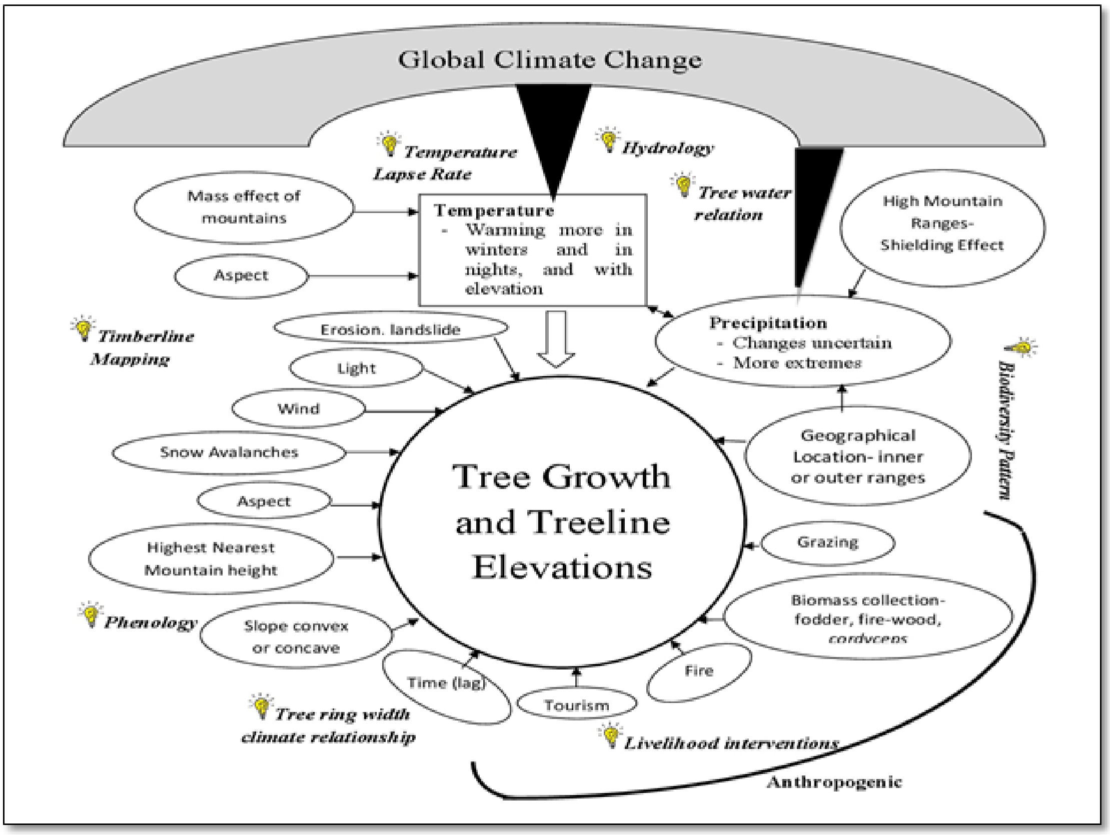

Fig. 5. A schematic representation of factors affecting tree growth and treeline elevations in Himalayas, both climatic and anthropogenic ones. Temperature is the major climatic factor to affect treeline, but role of precipitation can also be substantial. Both are being affected by global climate change. 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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