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Treeline Dynamics in the Himalaya

Timberline, an upper elevation limit of forests or tree growth in mountainous regions or in high latitudes, occurs below the lower limit of the snowfields. Its location depends largely on temperature but also on soil, drainage, and other factors. The mountain timberline always would be higher near the Equator than near the poles because of the effect of abundant rainfall in equatorial mountainous regions. The timberline in the central Rockies and Sierra Nevadas 3500 metres, whereas in the Peruvian and Ecuadorian Andes it ranges between 3000-3300 metres. In Himalaya, timberlines are located at much higher elevation approximately between the range 3400-4900 metres than most of the other mountain in the world. Tree-lines and timberlines are biological boundaries beyond which trees cannot grow for various reasons. Temperature and precipitation thresholds are the most important factors in determining whether a site is treeless or not, but vegetation type, soil type, snow cover, topography, and wind can locally codetermine the limit of tree growth. For instance, low temperatures at Alpine or polar treeline significantly reduce production of plant tissues (Korner 1999). Thus in comparison to other vegetational life-forms, trees are particularly affected by temperature deficits because of their strategy to accumulate large amounts of biomass to overgrow other plants. Moisture deficits determine the transition between forest and grassland communities.

Tree-line and timberline are often differentiated in most ecological studies. Tree-line (or tree limit) designates the limit of tree growth, and timberline (or forest line, forest limit) the limit of closed forests. In mountainous areas, the transitional zone between these two vegetational boundaries is usually rather narrow (100-200 m) under natural conditions. Anthropogenic impact (e.g., pastoral activities or timber extraction) tends to lower timberline more than treeline, causing an extension of the transitional zone (e.g., up to 300–400 m). Polar and drought-caused timberline and tree-lines can be separated by very broad transition zones such as parklands with widely spaced trees (Arno and Hammerly 1993). Above tree-line, tree species may grow as low, prostrate, or stunted individuals (<2 m). This zone is often referred to as the krummholz zone, and its upper limit as krummholz limit or tree-species limit. In the zone between timberline and the krummholz limit, total biomass drops dramatically since tall trees are gradually substituted by shorter shrubs and herbs. Net primary productivity also declines to some extent (Ellenberg 1996). Vegetational changes at treeline strongly influence many ecosystem elements and processes (e.g., animal life, soil formation, water balance, local climate, energy, and nutrient fluxes) and are, therefore have become an exceptionally fascinating domain of study in ecological and paleocological research.

The latitudinal and elevational limits of trees are controlled by temperature. The limitation is either directly by frost, a lack of energy that does not allow individual plants to accumulate enough carbon via photosynthesis to form a tree, or, as more precisely demonstrated, at lower temperatures plants are not able to reallocate the energy they can gain in photosynthesis sufficient to form a tree (Körner 1999). At finer spatial scales other factors, particularly geomorphology and available water for photosynthesis, could also be limiting factors (Malanson *et al.*, 2011).

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The "ENVIS Centre on Himalayan Ecology" collects, collates, compiles and builds quantitative and qualitative database of information in the fields related to the Himalayan Ecology. The information is disseminated regulary via online as well as hardcopies to several valuable stakeholders and various users such as DICs, Universities, Institutions along with other ENVIS Centres across India to support overall Environmental Information System in India.

Editorial note

Alpine treeline ecotone, occurring between a subalpine forest and alpine meadow, is an extremely temperature-sensitive transition zone. 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. The alpine regions in Himalaya are considered climate hotspots and indicator zones of species geographic range shift induced by climate change and global warming. Over past few decades accelerated rates of warming are noticeable in most of the Himalayan regions. 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. 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. The studies from Swiss Alps suggest that, because of global warming, the growth ring width of trees growing in the region 0–250 m below the current treeline prior to 1940 decreased with proximity to the treeline and the density of tree rings from the boreal region has decreased since 1960 – an indicator of faster growth. Agriculture is not practiced mostly above 2800 m; hence the main traditional purposes for visiting alpine areas are for grazing, seasonal migration in search of sustaining the livelihood, hunting, and to traverse the range crests to reach settlements across the ranges. The sensitive timberline zones in some mountainous areas are disturbed by fire, and other human activities including development and tourism. Therefore, due to the perturbations in natural factors together with pronounced anthropogenic activities, the timberlines in mountainous areas are likely to be severely affected.

The Himalayas are warming at a rate 2-5 times higher than global average rate, leading to shrinking of glaciers and beginning of upward shift of altitudinal ranges of many species, particularly of timberlines. Timberlines and treelines are among the most intensively studied systems in some parts of the world (e.g. US and Europe). In contrary, despite of being the most sensitive to climate warming, they are least investigated possibly due to their remoteness and inaccessibility. In spite of its proven indicator and other values, the timberline in the Himalaya could not get desired attention of researchers. The initial studies, fragmented studied on timberline in Himalaya mostly highlighted the conservation significance aspect of this ecotone. Realizing the diversity of bio-physical systems across low to high altitude (temperature) gradient and east to west precipitation gradient, it becomes imperative to focus research on: (i) the altitude gradient which plays significant role in determining the climatic conditions, especially the temperature, and subsequently the biodiversity patterns, and (ii) the precipitation gradient that varies significantly from east to west Himalaya. This calls for developing more insights and understanding on the patterns of the timberline, and also from comparable altitude sites in different climate regimes precipitation zones of the Himalaya. Realizing the gap in research, a maiden attempt was made to study different facets of the timeberline in Himalaya through a multi-location, multi-Institution, and a multi-disciplinary approached Indian Himalayan Timberline Research Project (IHTP) supported by Ministry of Envionment, Forest, and Climate Change (MoEF&CC) Govt. of India under the National Mission on Himalayan Studies (NMHS). The objectives of the study were to, (i) map timberline at a regional level in the Himalaya, (ii) estimate surface temperature lapse rate (TLR) in different precipitation regimes across the IHR, (iii) analyse altitudinal pattern of vegetation, (iv) document and analyse tree phenological responses, and tree-water relations in response to warming climate, (v) study relationship between tree ring growth and climate change, (vi) understand the impact of depletion of snow-melt water on growth of tree seedlings, grasslands species composition and selected functional processes, and (vii) promote participatory action research (Citizen Science) on innovative interventions to improve livelihoods in conservation and management of timberline resources.

This volume of newsletter on Himalayan Ecology presents articles on diverse topics of timeberline for general readership so as to generate a wider popularization of timberline

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Phenology of timberline zone-potential indicators of climate change in the Himalaya

Phenology is the study of the timing of recurring biological events, the causes of their timing with regard to biotic and abiotic forces, and interrelation between phases of the same or different species. Phenological parameters are the most sensitive to climatic conditions and regarded as climate change indicators. Researchers world over have found strong influences on air temperature, photoperiod, rainfall, solar radiation, soil temperature, water content, soil type and nutrient supply on phenological responses. In the Himalayan region a few studies have shown that plant growth and phenophases here are triggered with the occurrence of favourable temperature, snow melt and consequent soil water availability (Sundriyal *et al.*, 1987). Thus, phenology is probably the simplest and cost-effective means of observing the effects of climate change (CC) on plant growth and an important tool in global CC research. Phenological changes have major implications for various ecological and evolutionary phenomena, including ecosystem productivity, species interactions, community structure, and conservation of biodiversity. Therefore, the understanding of environmental changes associated with the high-altitude limit of forests, generally called timberline or tree line (Korner 1999), is of critical importance because of its high sensitivity to temperature changes. Hence, timberline is often used as an indicator of CC. In the mid-elevation forests of this region and other parts of the Himalaya CC induced changes in leafing and flowering phenology of trees (viz., *Rhododendron* spp.) and alpine herbs (Telwala *et al.*, 2013) have been reported. However, little is known about the responses of climatic conditions on the phenology in the treeline zones of the Himalayan mountains.

Under the Indian Himalayan Timberline Project, funded by National Mission on Himalayan Studies, Ministry of Environment, Forest & Climate Change, Government of India, Tungnath site (Lat. 30.49' Long. 79.21' Alt. 3358 - 3562m asl; Uttarakhand) was selected for phenological investigations of five major timberline forest species viz., *Abies spectabilis, Betula utilis, Quercus semecarpifolia, Rhododendron arboreum,* and *R. campanulatum* (Fig. 1). Phenophases such as bud-break and leafing, flowering, fruiting, leaf senescence and leaf fall, and changes in leaf traits such as leaf area, leaf mass and leaf nitrogen concentration were monitored periodically from May 2016 onwards for 100 marked trees of each of these species (Fig. 2). In addition, climatic data (air temperature, relative humidity, soil temperature and soil moisture) for the study site was measured periodically. The mean maximum temperature (15.5°C) and mean minimum temperature (6.7°C) recorded during peak growing season (July-September 2016) was found higher than that reported by Sundriyal *et al.*, (1987) for the growing season at this site (July-September 1984). It indicates that substantial rise in atmospheric temperature has taken place in the past over 30 yrs which may have implications on the phenology and structure and functioning of these tree species and timberline forest ecosystem.

Fig. 1. *R. campanulatum* shrub community in Tungnath. In the background timberline formed by *A. spectabilis* and *Q. semecarpifolia* is seen

This study spanning over a period of five years has concluded that the major treeline species of Tungnath respond to increase in atmospheric temperature with respect to earlier onset of bud-break and leafing. In the warmer year 2017 (MAT as well as growing season temperature) probability of earlier bud-break and leafing increased significantly ($P< 0.001$) for all the species. Thus, it can be stated that onset of growth signal is temperature dependent even if mild increase in MAT occurs between one year and the other. However, the implications of large differences during the growing season (April -August = 4.3°C) between air (14.1°C) and soil temperature (9.74°C) need to be further investigated on the occurrence of phenophases of the treeline species. Also, cooler soil associated low soil nutrient mineralization must have impeded the growth and development of plants, which is still not known from Himalayan treeline. Therefore, long-term studies are important for understanding the future directions of phenological and compositional changes in vegetation in the climate-sensitive timberline zone of the IHR to have a clear mechanistic understanding to predict the potential impacts and changes by human activities and related CC in this fragile and sensitive region.

Fig. 2. Trees of Abies pindrow marked for phenological observations in Chopta-Tungnath

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Structural attributes of herbaceous vegetation: A case study from high altitude ecotone region

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In mountainous areas the transition from forest to alpine is usually rather narrow (100-200m vertical extent) formed by treeline and timberline, which are biological boundaries beyond which trees cannot grow often designated by limits of tree growth (Treeline) and limits of forest growth (Timberline). This transition is driven by temperature decline due to increasing elevation and precipitation thresholds along with vegetation type, soil, snow cover, topography and wind can determine limit of tree growth especially moisture deficit. It determines the transition between forest and grasslands representing an ecotone of vast biodiversity importance as vascular plants decrease with altitudinal gradient leading to an increase in endemic and native species. The warming in mountains affect the structural and functional attributes of the ecosystems, especially plants sensitive to associated changes with temperature and precipitation. These systems are experiencing ecological changes, especially warming induced biodiversity changes and species redistribution affecting richness, growth and phenology of species. Multiple studies have reported upward shifts of the treeline and expansion of shrubs into alpine and sub-alpine regions, while range-restricted species, particularly polar and mountain top (alpine) species are first groups in which the entire species have gone extinct due to recent climate change. The Indian Himalayan Region (IHR) is youngest mountainous ecosystem and among most threatened non-polar region of the world, as they arepredicted to experience temperature rise of 5-6°C, and precipitation increases of 20–30% by the end of the twenty-first century (Kohler *et al*., 2009). Being part of the great Himalayan mountainous system, Uttarakhand Himalaya is much sensitive and vulnerable to the local, regional and global changing climate, due to altitudinal gradient, varied climatic conditions and diverse set of floral and faunal composition.Keeping in view,the aim of the study is to understand temporal changes in structural attributes of herbaceous vegetation in Timberline and Treeline (here after referred as TML and TRL, respectivey) ecotone region at and around Tungnath, West Himalaya. The study was conducted in Timberline/treeline ecotone, which lies on southern fringe of Kedarnath Wildlife Sanctuary. The study area is dominated by Silver fir, Kharsu oak and mixed-conifer forests in sub-alpine region and forms the timberline (3200-3300m), whereas *Trachydium*, Mixed herbaceous, *Danthonia*, Mixed *Danthonia* and Polygonum communities dominates the alpine region with dwarf *Rhododendron krummholz* forming the treeline (3300-3400m). The melting of snow is faster in treeline zone as compared to timberline zone. Eight permanent plots were markedin both TML and TRL zone each and three permanent quadrats were laid in each plot and monitored fortnightly to collect data on abundance, species richness and phenology. A total of 100 species were recorded from TML (86 species) and TRL (72 species) ecotone, of which 56 were common. The species native to Himalaya in TMLand TRL are 70% and 80%, respectively. The percentage of hemicryptophytes decreased as one moves upwards from timberline to alpine. Average species richness (species m^{-2}) was higher in TRL than TML (Table 1). Total species richness for TML (49.8)was higher than TRL (45.5)and is on higher side of the range (27-56 species) reported for Central Himalaya (Rawat 2007). A significant difference was observed for species richness between TRL and TML ecotone ($p < 0.001$; Fig. 1). The peak species richness was observed during July-Augustin the study area, while peak average species richness (numbers m-2) was observed in July (20.5 in TRL, 20.31 in TML). During peak i.e. August, 38 species in TML and 41 species in TRL were encountered. The plant density was low in TML as compared to TRL (Table 1). A significant difference in plant density was observed between TRL and TML ($p < 0.004$; Fig. 1 & 2). Average peak density for TML and TRL was observed in May, while peak density for TML was observed in June (626.3 individuals m^{-2}) andTRL (878.3 individuals m^{-2}) in May, shows importance of snowmelt water during early growing season for species (Table 1). The diversity (H') in general was higher in TML than TRL throughout the growing season, however diversity was higher in TRL. The diversity peaked in July (3.21) for TML and August (3.29) for TRL. The average diversity was highin TML might be because of overall higher number of species present in TML than TRL. Four major phenophases of plants (vegetative, flowering, fruiting and senescence) were observed. In TRL fruiting and senescence initiated 1 and 2 months before TML. The flowering duration extended by a month in TML as compared to TRL. Thirteen species showed two distinctive flowering phases across growing season in either TML or TRL or both (*Oxygraphis, Rannunculus, Fragaria, Swertia ciliata, Gentiana argentia, G. tubiflora, Gaultheria, Epilobium roylei, Clemetis, Prunella vulgaris, Anemone rivularis, Selinum vaginatum* and *Trachydium*), however, *Plantago major* and *Lysimachia prolifera*, showed two distinctive vegetative phenophase. Plant growth in treeline and timberline is influenced by snowmelt timing and soil moisture availability. Many studies demonstrate positive influence of advance in snowmelt timing on site productivity. Besides macro-climate, species richness is also majorly influenced by soil water content variations and other variables related to topography on micro-climatic scale (Nabe-Nielsen *et al*., 2017). Furthermore, snow loss due to early melt might lead to an increase in species richness. But in the present study we found that although early snow melt indeed increases abundance and growth of individuals within community in TRLand does not have significant effect on species richness within the community as t-test indicated no such difference between TML and TRL for species richness. The diversity values (H') of present study are lower than that reported for herb layer of south and south-east facing slopes in Greater Himalaya (3.01-3.30) and treeline gap (3.23), however, higher than that of Greater Himalaya as a whole (2.1-2.4), Valley of Flowers National Park (2.47), Upper Tirthan Valley (2.39) and alpine landscape of Khangchendzonga National Park(1.44-2.48). The overall dominance of hemicryptophyte (85%) in study area is a common feature of treeline and alpine meadows in Himalaya with some exceptions(Rudranathand Yusmarg, Kashmir)having high proportion of Chamaephytes (31 and 46%, respectively), which could be due to drier conditions during growth period. As compared with past studies the proportion of hemicryptophytes has increased in the study area. Seventy percent species are native to Himalayan regionindicates the high conservation value of Tungnath region. The growth initiation started immediately after snowmelt during Mayin the study area.The vegetative phase peaked during May and June (68%), while majority species flowered between June and September peaking in August (75%). But some species like *Geranium, Lysemichia, Nepeta, Oxygraphis, Plantago major, Poa, Polygonum filicaule, Potentilla polyphylla* and *Primula denticulata* showed early flowering in TML than TRL. This may be due to warmer temperature in TRL, which may be encouraging few species to postpone anthesisfor better opportunities. Across globe, many studies have revealed early snowmelt as a major driver for community changes, which are mostly toward positive side showing increase in species richness and density. The response of community might be different on micro-habitat basis than altitudinal basis. This needs to be investigated, as growth period in Himalayan alpine region is quite long and climatic condition and orography across alpine Himalaya are much diverse.

Fig. 1. Timberline, treeline and alpine zones at and around Tungnath

Table 1. Ecological attributes of Timberline (3200-3300 m asl) and Treeline (3300-3400 m asl) ecotone at and around Tungnath

Parameters	Timberline	Treeline
Total species	86	72
Dominant species	*Trachydium roylei, Oxygraphis polypetala, Rannunculus hirtellus*	*Trachydium roylei, Oxygraphis polypetala, Rannunculus hirtellus*
Species unique to area	29 (*Ainsliaea aptera, Arenaria neelgherrensis, Arisaema propinquim, Aster albescens, A. methodorus, Clematis barbellata, Corydalis cornuta, Halenia elliptica, Impatiens scabrida, Ligularia sibirica, Parochetus communis, Primula redii, P. edgeworthii, Persicaria nepalensis, Pimpinella diversifolia, Rubus nepalensis, Senecio graciliflorus, Swertia auriculata, Synotisalata, Thalictrim foliolosum, Viburnum grandiflorum*)	15 (*Bupleurum candollei, Corydalis cashmeriana, Galearis spathulate, Jurinia dolomiaeae, Myriactis nepalensis, Picrorhiza kurroa, Plantago ovata, P. brachyphylla, Ranunculus diffuses, Saussurea auriculata, S. nepalensis, S. taraxacifolia, Tanacetum dolichophyllum, Vicatia coniifolia*)
Nativity (Himalaya)	70%	80%
Life cycle (dominant Perennial	91%	85%
Growth Form Erect leafy Semi basal Short basal Others (dwarf shrub, grasses, sedge)	32% 31% 31% 6%	29% 28% 28% 15%
Life form (dominant) Hemicryptophyte Others (Chamaephyte, Therophyte, Geophyte	84% 16%	85% 15%
Growth cycle < 2 months 3-4 months > 4 months	4.6% 32.5% 63.9%	6.9% 27.7% 65.2%
Species Richness (number m^{-2}) Range (Average)	12.5-21.0 (17.3±1.3)	8.7-22.3 (17.7±1.6)
Density (individuals m-^{2}) Range (Average)	69.3-626.3 (267.5±22.9)	82.9-878.3 (355.8±34.9)
Diversity (H') Range (Average)	2.1-3.2 (2.6± 0.1)	2.1-3.3 (2.8±0.1)

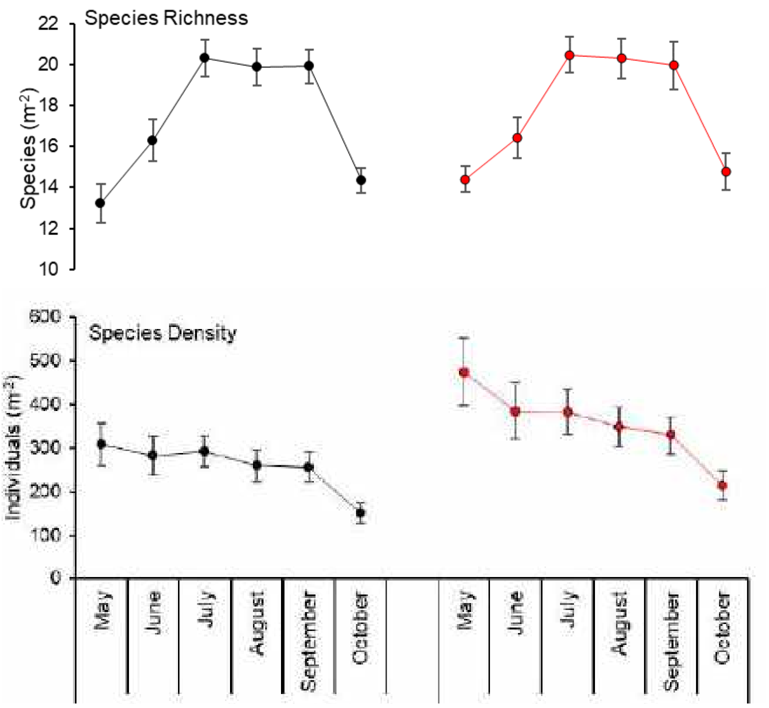

Fig. 2. Species richness and density across months in TML and TRL ecotone

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Assessing growth response of treeline vegetation to climate change using dendrochronology

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The tree-line in Himalaya, a climatic sensitive ecosystem, is considered as an indicator of climate change. Tree-line broadly refers to an ecotone representing the transition between timberline and unforested alpine vegetation (Körner 2003). Conventionally, it is defined as a theoretical line connecting the upmost or north-most trees surpassing an explicit minimum height (≥2m). Studies have shown that the timberline vegetation responds to varying environment conditions through changes in their growth, growth forms, phenology, species composition of communities, regeneration, and shift in their habitat. Considering the projected climate change, elevation range shift of alpine vegetation and tree growth–climate relationships have received attention amongst the researchers across the globe. However, because of remoteness and unreachability, most tree-lines in Himalaya are less investigated for vegetation vis-a-vis climate change.

Tree-line sensitivity to climate change

Tree-line is considered as an evident indicator ecosystem for assessing of landscape response to climate. The life and growth form of trees varies sharply because of the harsh climate at the upper fringe of mountain forests. Natural processes also lead to various kinds of treeline structures, viz. diffused, abrupt, island and krummholz. As the rates of increase in temperature in Himalaya are reportedly high, its impacts are expected to be much evident at tree-line owing to which vegetation and species response to climate change has been receiving interest to researchers globally. The present climate modification could alters the patterns and processes in tree-line ecotones eventually effecting the elevational position of tree-lines in mountains (Korner 1998; Wieser *et al*., 2014).

Aapplication in assessing the response of vegetation to climate change

The long-term climate data on Himalayan tree-line are scanty; hence, tree-ring proxies are used to reconstruct past climate for impact studies. The 'dendrochronology' and its sub-disciple 'dendroclimatology' is one among the foremost wide accepted scientific ways for reconstruction of past climate (Fig. 2).

Fig. 1. Treeline marked by *Abies spectabilis* at Tungnath

This approach dates annual tree-rings to their actual year of formation to study recent, historical, prehistoric events and environmental conditions. Trees are intimately bound to the environment, with their growth influenced by natural and anthropogenic factors systematically recorded within the ring-widths. With dendroclimatology methods climate data is extracted mathematically from the tree-ring reconstructed back to the age of the trees. Recent interest in global climate change has prompted enhanced application of tree-ring analysis to verify the growth expansion and climatic variations in the past.

$$Rate\ of\ shift(per\ year) = \frac{Upmost\ elevation\ of\ young\ tree - Upmost\ elevation\ of\ oldest\ tree}{Age\ of\ oldest\ tree - Age\ of\ youngest\ tree}$$

Assessment of tree-line shift using Dendrochronology

The common method practiced to estimate tree-line shift involve monitoring, recruitment patterns of trees in identified plots, reconstruction of stand age structure, the use of historical aerial photographs (Baker *et al*., 2007), and associated analysis of remotely sensed information. The tree-line expansion is studied with the age of individuals within the tree-line ecotone (Camarero *et al*., 2004). To calculate the shift rate of tree-line, maximum elevation of live individual trees ≥2 m in height are taken. The tree-line shift rate (m/yr) is calculated by dividing the change in tree elevation by the time elapsed in their growth (Gamache *et al*., 2005), as described in the following equation. Prominent rates of treeline shift for the different region across the world.

The field based observations on tree-line shift in Himalaya show that the species response to climatic changes vary with (i) substantial upward shift (Gaire *et al*., 2014, 2016; Tiwari *et al*., 2017a); (ii) moderate upward shift (Chhetri *et al*., 2016); and (iii) almost stationary tree-line position (Gaire *et al*., 2011; Liang *et al*., 2011; Schickhoff *et al*., 2015; Shrestha *et al*., 2014). Many studies have discovered that there has been fast compaction of tree-line ecotone within the recent decades indicating the possibility of tree-line shifting to higher elevation in close to future (Gaire *et al*., 2014; Shrestha *et al*., 2007; Tiwari *et al*., 2017a). Tree-line dynamics seems to be additionally associated with changes in snow precipitation than to global warming (Negi 2012). Remote sensing investigations indicate an upward shift of treeline up to 80m in Uttarakhand between 1962 and 2009 (Singh *et al*., 2012). The increase in vegetation cover, reduction of snowcover and upward shifting of alpine plants has been reported in central Himalayan range (Panigrahy *et al*., 2010). However, the tree-ring based studies from Himalaya indicate varied range of tree-line shifts in Himalaya (Fig. 1).

Recent dendro-ecological study from Tungnath in western Himalaya reported upward shift of *Abies spectabilis*, a key plant taxa of tree-line ecotone, at the rate 1.37m/yr, (Singh *et al*., 2018) (Fig. 1). The brief synthesis of calculated shift rates of tree-line ecotone conifers from some Himalayan region is presented in Table 1.

Table 1. Treeline shift rate in Himalaya based on Dendro-ecological studies

Studies	Sites	Species	Shift Rate
Singh *et al*., (2018)	Chopta-Tungnath Region, Uttarakhand	*Abies spectabilis*	1.37 m/yr
Yadava *et al*., (2017)	Uttarakhand & Himanchal Pradesh	*Pinus wallichiana*	1.1-5.4 m/ yr
Gaire et al., (2017)	Western Nepal	*Abies spectabilis, Betula utilis*	0.93 m/yr 0.42 m/yr
Tiwari *et al*., (2016)	Chimang Lake, Mustang district, Central Nepal	*Abies spectabilis*	Transect CI: 0.52 m/yr Transect CII: 1.74 m/yr
Gaire *et al*., (2014)	Manaslu Conservation Area, Central Nepal Himalaya	*Abies spectabilis*	2.61 m/yr

Findings on advancing tree-lines in Nepal Himalaya showed considerable recruitment of seedlings and saplings in the recent decades particularly after 1950s. However, tree-lines in some parts of the region have remained stationary (Gaire *et al*., 2016; Shrestha *et al*., 2014). Due to rapid warming, drought stress is the most visible impact along with the prolonged growing season (Dawadi *et al*., 2013; Liang *et al*., 2014; Panthi *et al*., 2017; Tiwari *et al*., 2017a, b) which directly influence regeneration at tree-line ecotone. The upward movement of tree-lines in Himalaya has remained variable during the past century and depends on site conditions (Yadava *et al*., 2017). Long-term observation of forest stands at tree-line is important while interpreting tree-line dynamics. Further, the dearth of long-term environmental records of temperature, rainfall, cloud cover, snow, etc., within the region has confounded past distribution range of high mountain forests.

Fig.2. Coring of *Abies spectabilis* tree using an Increment Borer

The summary of the tree-line studies using dendrochonological techniques shows that the tree-line is advancing at an average rate of 0.4 to 2.61 m/year in the Himalayan region. The sitespecific, species-specific regeneration and treeline dynamics demand that future conservation and adaptation measures ought to be designed considering differential responses of the tree-line forming species. The reconstructed climate records tree-line show long-term fluctuations in the climate with rise in temperature but weakening trend of precipitation in last few decades. Change in tree-line position is not only influenced by climate but additionally by abiotic, edaphic and human disturbances also. Therefore, the future studies ought to contemplate integrated approach by taking multiple species and sites along with the multiple factors like abiotic, edaphic and other factors like anthropogenic, grazing, forest fires, etc., for better understanding of response of tree-line vegetation to climate change.

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Leaf population dynamics and shoot growth of treeline species in Tungnath timberline ecotone

Alpine treeline ecotones across most of the world's mountains are being studied because of their potential for monitoring the effects of climate warming on forest ecosystems. Past studies have shown that treeline ecotones are good indicators of climate change (CC), where trees often respond to climatic warming with population structures, increase in seedling recruitment or tree-density, as well as upward shift of the treeline (e.g., Camarero and Gutierrez 2004). It has been shown that plant growth and phenophases here are triggered with the occurrence of favourable temperature, snow melt and consequent soil water availability (Singh, 2017).

In this study we selected five treeline forming tree species for shoot extension and radial growth in Tungnath (Uttarakhand) those 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) and Rhododendron arboreum (evergreen broadleaf) and R. campanulatum (evergreen krummholz species) distributed between 2955 and 3334 m asl (the upper limit distribution of these species). The shoot extension and radial growth was based on monthly measurements on 25 marked shoots in each of these five species from leaf anthesis to leaf drop (Fig. 1). In all of these species leaves are born gradually on the shoots during the onset of growth season (April-May), and the leaf recruitment rate rises rapidly during May-June, and culminates in July-end. The leaf recruitment period in the current year shoots was computed 8-12 weeks for these species. In case of A. spectabilis the shoot bears leaves (needles) of over three years of age and leaves are produced only in the current year terminal shoots. In this species leaf flushing is a brief activity (~3 months), and the peak leaf population in current year shoots remains stable for approximately 12 months. In B. utilis peak leaf number per shoot (mean= 5.5) remains stable only for two months between July and August, and by October the trees become leaf less. In Q. semecarpifolia peak leaf number per shoot (mean= 6.5) was attained in July-August, and leaf population remain stable until November (> 4 months), and by the end of next year March-end and early-April, trees become leaf less. In R. arboreum, peak leaf population (mean= 10.6/shoot) were attained in July-end to early-August and the leaf population remain more or less stable for 9 months until next year July, and leaf drop takes place gradually from September, and by next year March all the old leaves are dropped. In R. campanulatum leaf recruitment in current year shoots continues from June to August and the peak leaf number per shoot was recorded 4.7. Peak leaf population remains stable from August–March (8 months), and leaf drop starts from next year August and by November all the old leaf population

Table 1. Leaf population and shoot growth characteristics in the treeline ecotone tree species at Tungnath

Species	Leaf and shoot growth parameters			
	Mature shoot length (cm)	Mature shoot diameter (mm)	Leaf number / shoot in mature shoot	Duration of stable leaf population in shoots (months)
A. spectabilis	10.2±1.7	6.9±0.2	148.3±10.2	Aug-Sept (12)
B. utilis	13.3±2.7	2.9±0.12	5.5±1.8	July-Aug (2)
Q. semecarpifolia	5.7±1.6	3.47±0.1	6.5±1.7	Aug-Nov (4)
R. arboreum	5.6±0.9	6.5±0.14	10.6±2.2	July- April (10)
R. campanulatum	4.5±0.7	5.87±0.2	4.7±1.2	Aug- March (8)

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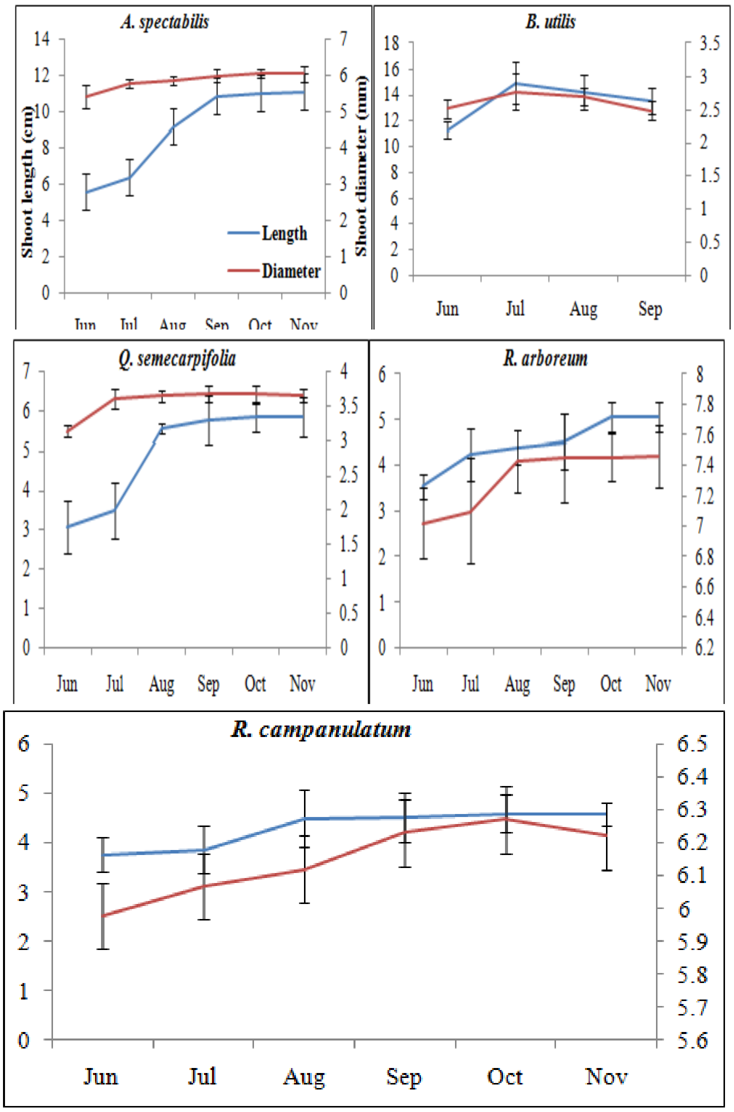

Fig. 1. Shoot Length (cm) & Shoot diameter (mm) of different studied treeline species

is dropped (Table 1). In all these species the shoot extension growth continued for 4-5 months till September. The peak shoot length attained by these species was lowest in R. campanulatum (mean= 4.5 cm) and highest for B. utilis (mean= 13.3 cm). The shortest shoot growth period was recorded for B. utilis (4 months) and the longest for A. spectabilis (5-6 months). Diameter growth of mature shoot was recorded lowest for B. utilis (2.9 mm) and highest for A. spectabilis (6.9 mm) (Table 1). Shoot grows in thickness in all the species for 4-5 months until October, except for B. utilis (August).

This study on phenological behaviour (leaf population and shoot growth) for major tree species over a sufficiently long period has generated some insights into intra-annual and intra-species growth patterns as influenced by the climatic condition, particularly atmospheric temperature. Mean annual temperature (MAT= 5.5 oC) and growing season mean (April-September= 9.6oC) recorded for the study site (Joshi et al. 2018) was much higher than the seasonal mean ground temperature of 6.7 oC recorded for high altitude climatic treelines (Korner and Paulsen 2004). Thus, dependence of leaf and shoot growth parameters on low magnitude of warming seems less related that need to be studied in the year of extreme events of warming, drought or snowfall for better understanding of phenological behaviour of treeline ecotone tree species.

Fig.2. Shoot growth measurement on *A. spectabilis* in Tungnath treeline study site

Fig. 3. Flora diversity *Betula utilis* D. Don, *Rhododendron campanulatum* D. Don

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Temperature lapse rate variability and its significance in mountain ecosystem

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Temperature Lapse Rate (TLR) is defined as the rate of change in temperature observed while moving upward through the Earth's atmosphere. The lapse rate of non-rising air, commonly referred as the normal or environmental lapse rate, is highly variable mainly because it is governed by radiation, convection, and condensation. Averaging about -0.65°C/100m in the lower atmosphere, it differs from the adiabatic lapse rate which is defined as the rate of change in temperature of an air parcel in response to the expansion or compression process associated with a change in altitude when no heat is added or lost during the process. Adiabatic lapse rates are usually categorized as dry or moist- the dry adiabatic lapse rate, also known as the DALR or unsaturated lapse rate, refers to the lapse rate of unsaturated air (i.e., air with relative humidity <100%). Whereas in case of wet adiabatic lapse rate, also known as saturated lapse rate or moist adiabatic lapse rate, the air parcel is saturated at dew point temperature. Low temperature prevails with increasing height for two reasons: (i) existence of less favourable radiation balance in the free air, and (ii) reduction in temperature of rising air associated with its expansion and decline in pressure (Barry and Chorley 2003). The difference between the rates of change of temperature of rising air and the state of the surrounding air determines acceleration or retardation of upward currents.

For these reasons, the air temperatures observed on mountains are generally lower than on low ground. The rate at which air cools with elevation varies from -1.0 dec C/100m for dry air (i.e. DALR) to about -6.5 dec C/100m for moist air (i.e. MALR). This value is often used globally by the researchers for the free-air TLR. However, various studies carried out in different parts of the Himalayan region indicate existence of high variability in TLR both spatially and temporally. The studies have also found varied range of seasonal TLRs for different sites across the Himalaya. In Himalayan region, there is a paucity of observed meteorological data particularly for higher elevation regions to relate it with changes in vegetation, especially upward movement of timberline due to global warming. Considering this data gap, temperature loggers were installed along Chopta-Tungnath transect in Uttarakhand (Central Himalaya) under the Ministry of Environment, Forest & Climate Change, Govt. of India under the Indian Himalayan Timberline Research project, funded by National Mission on Himalayan Studies (NMHS). To understand variations in TLR along tree line environment, the study was further extended to two other transects, namely, Yuksam-Dzongri Transact in Sikkim (Eastern Himalaya) and Daksum-Sinthan transect in Jammu & Kashmir (Western Himalaya) . The TLRs were estimated using standard methodology followed by (Joshi *et al.*, (2018). The tree-line along in these transects found ranging between 3400-4000m asl and tend to increase from the west to east, largely because of decreasing latitude. The results from the study showed that annual mean TLR increases from moist to dry sites. The value of TLR for these sites were observed as -0.50°C/100m, -0.52°C/100m and -0.66°C/100m for EH transect, CH transect and WH transect, respectively (Fig. 1). It increases with decreasing moisture, being markedly higher at WH transect of Kashmir part of Himalaya and lowest for EH transect in Sikkim, which is largely moist in comparison to other two sites (Joshi *et al.*, 2020).

The annual mean TLRs for EH transect and CH transectare distinctly lower than the commonly used value of -0.65 dec C/100m (Barry and Chorley 1987). Whereas, for the WH transect, slightly higher TLR was found. The observed average TLR in different parts of Himalaya are below commonly used value (Table 1). Considering the low values of TLR in Himalaya it can be inferred that the Himalayan region is experiencing pronounced elevation dependent warming as compared to other parts of the world which may further affect treeline ecotone in Himalaya in several way, such as decline in snow regime, increased evapotranspiration and water stress, modified vegetation distribution patterns of alpine region. The study also reflected variable Lapse rate among mountainous region; microclimate and seasons were considered as the insidious factors for such variation in Lapse rate. As per the other study conducted in Himalayan region, that highest mean TLR values exists for pre-monsoon months which is directly connected with strong dry convection i.e., corresponding to the clear weather season and considerable sensible heat flux. The second highest LR was recorded for post-monsoon season during which a relatively small thermal forcing effect occur after the rainy summer. Whereas, the shallowest lapse rate was observed for winter season associated with strong radiative cooling and flow of cold air over low-elevation areas, followed by monsoon season (Joshi *et al.*, 2018). TLR is often higher on drier slopes than that on the wet slopes, mainly because of the effect of moisture, solar radiation, topography and local climatic conditions. Seasonally, TLR were more pronounced in summer than in winter months. Further, TLRs were found lower during wet, monsoon season than in drier pre-monsoon, and it decreased with increasing wetness. These findings shows that, TLR is affected by aspects, seasons and location of the study site. Hence, single and constant value of TLR does not explain the complex atmospheric relationships between elevation and temperature throughout the year and for the larger landscape. Hence, spatially uniform and temporally constant lapse rates (-0.65 dec C/100m) the true are not representative of actual surface conditions over the Himalaya because the topography can modify the relationship between altitude and temperature.

The aspect differences can be even more important in controlling the temperature. As a result, mountain valleys, mid-slopes, and ridges are characterized by different temperature regimes. Many research fields (ecology, glaciology, water resources, hydropower, agriculture, etc.) require data on distribution of climatic variables along elevation gradient over a landscape. For such studies, TLR is used as important input parameter in various hydro-climatological-ecological models to investigate the potential impacts of climate change analyzed and simulated by means of process-based models. However, these models require high-quality climate input data. Often gridded climate data are not suitable for such investigations due to their low spatial resolution, hence estimates of the attitudinally varying temperature and precipitation is required to facilitate the climate impact research. Therefore, adequate estimates of near-surface temperature lapse rate based on ground based observations are needed to represent air temperature in remote mountain regions with sparse instrumental records.

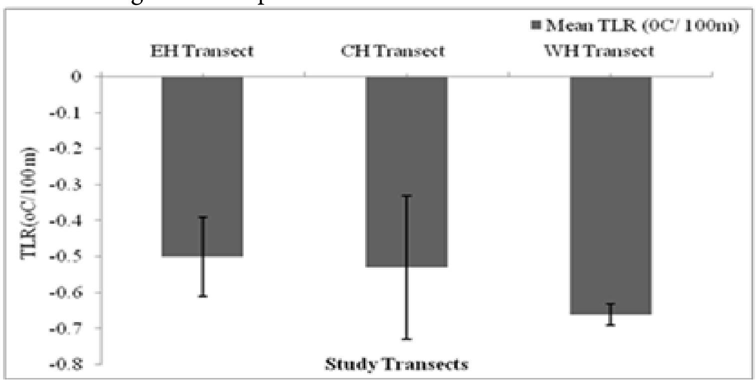

Fig 1. Variation in annual mean TLRs across three study transect in Indian Himalayan

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Timberline dynamics in response to climate warming: Remote sensing approach

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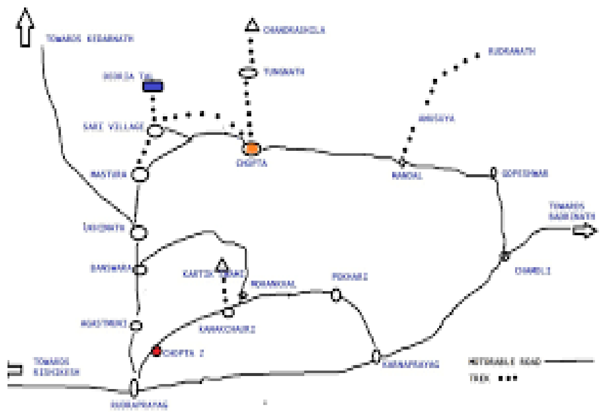
The high-altitude timberline is the most conspicuous and important vegetation limit in high mountains of the world, and the highest timberline in the Northern Hemisphere occurs in the Himalaya. Timberline of high mountains is indicator of climatic conditions (Danzeglocke 2005), and formation of current timberline (Holtmeier 2009) has been considered as output of present climate (air and soil temperature, rainfall). Himalaya and its high-altitude vegetation are climatically sensitive. Field based observations on high altitude vegetation are limited due to terrain, remoteness and accessibility, and are low in precision to understand regional patterns and to be used as inputs to models for generalization, e.g., extent and geo-spatial attributes of climatically sensitive timberline vegetation of Himalaya. Use of satellite images is promising technology to identify spatial attributes of timberline at a regional scale. Analyzing various auto-extraction techniques of remote sensing in the Himalaya reveals that all methods do not perform adequately. Results may incorporate methodological errors. An approach was standardized by defining rules for interpretation to address the issues of auto-extraction methods, with the aim to deploy for harmonious regional scale mapping of entire timberline of the Himalayan region, and also incorporateobservations from field-based studies. Satellite images of Landsat 8 (multi-spectral, spatial resolution of 30m)were used to generate a regional scale timberline (highest edge of the forest having canopy more than 30%) to map present positions. Image enhancement techniques were applied to improve the interpretability of image. Improved satellite images were then subjected to knowledge-based interpretation technique and timberline was delineated (Sah and Sharma 2018). It was realized that this approachwas more appropriate in mountainous conditions, particularly in rugged terrain of the Himalaya, where complex topography challenges auto extraction (Singh *et al.*, 2018). 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 (resolution of 30m, as of satellite data) was used to develop relationship between spatial characteristics of timberline with topographical features viz., altitude, slope, and aspect.

Use of remote sensing techniques can give several useful cartographic information about treeline ecotone in local scale (watershed level) using high spatial resolution, which are not possible by manual sampling (Latwal *et al.*, 2018). However, high spatial resolution images (<6m) can improve timberline data by 10% over the medium spatial resolution. Availability of useful high spatial resolution images is restricted by limited coverage, clouds, etc., hence become a low priority for useregional mapping (viz., entire Himalayan timberline) and historical data to analyze impacts of climate change studies. However, spatial resolution refines certain attributes of object under investigation (e.g., timberline), consistent availability of medium spatial resolution images is useful to develop present and past regional scenarios. For a regional scale mapping (e.g., Indian Central Himalaya; Fig. 1), medium resolution images may yield results with acceptable deviations in agreementwith field-based observations, if analyzed properly. A comparison of the information generated with remote sensing method in the 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.

Fig. 1. Continuous and Island type (isolated pieces/dots) Timberline in Uttarakhand (Source: Sah & Sharma 2018)

Through this method, first time two spatially distinct occurrence of timberlines were characterized; one being referred as 'Continuous Timberline' (CTL), which isparallel to permanent snowline in the Greater Himalaya and alpines occur between these two lines. Another spatially distinct type is away from permanent snow and occurs around isolated summits enclosingalpines on lower side, which is termed 'Island Timberline' (ITL). Isolated ITL type may occur in middle Himalayan ranges (Fig. 1). These are the first record of such characterization and presence of spatially different timberlines in the Himalaya or elsewhere. Development of harmonized geospatial database is useful input for regional modelling of change detection, future prediction, and geographical explanations of diverse mountain timberline along the 2000 km long Himalayan arc.



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Ecological facilitation by nurse plants in alpine tundra of Kashmir Himalaya

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Introduction

Facilitation by nurse plants in harsh environments is known to promote vegetation recovery in ecosystems that are affected by human activities such as grazing. Nurse plants are those plants that promote growth and development of other plant species beneath their canopy. In terms of the growth form, these nurse plants could be herbs and forbs, shrubs or other tree species. Nurse plant facilitation is a commonly reported plant–plant interaction and is known to influence the community structure in stressful environments, such as alpine and other high elevation habitats. Nurse plants facilitate the presence and persistence of other species through different mechanisms including the amelioration of various stresses, whether physical (e.g. direct effects of winds), physiological (e.g. freezing by low temperatures or desiccation by drought) or biotic (e.g. competition or predation). This is a primary mechanism involved in plant to plant facilitation and it is critical in structuring the plant communities under stressful conditions. Through these effects, facilitative interactions may modify community structure by influencing population dynamics as well as inter- and intraspecific relationships among individuals of the facilitated species. As a consequence, facilitation may enable the expansion of distribution ranges of species by enlarging their tolerance limits, thus increasing the local species richness, maintaining plant diversity, and allowing the persistence of communities in highly stressful environments. Cushion plants are an example of most effective alpine nurse plants that modify microclimatic conditions within their canopies to create favourable environments for other plants. Their low and compact growth form acts as an efficient heat and water trap and represents a clear model of evolutionary convergence across phylogenetically unrelated taxa in different regions of the world.

Ecological facilitation by nurse plants in Kashmir Himalayan alpine zone

In Kashmir Himalaya, these nurse plants are found in high abundance in the treeline ecotone zone which is a transition zone between closed forest and treeless alpine meadow. The two principally occurring nurse plant species which are shrubs by their growth habit include *Juniperus wallichiana* and *Rhododendron campanulatum* dominating the different aspects i.e., south facing and north facing slopes of these transects and seem to facilitate the growth and recruitment of tree and herb species (Fig. 1). These nurse plants act as a shield and hinder the degree of grazing by cattle at the treeline ecotone along north facing and south facing slope with the result there is high abundance of seedlings, saplings and adults of trees inside than outside these nurse plants (Fig. 2, 3).

Fig. 1. (a) *Juniperus squamata* acting as a nurse plant in facilitating Pinua Wallichiana and Abies pindrow tree species along south facing slope

Fig. 1. (b) *Rhododendron campanulatum* acting as a nurse plant in facilitating *Betula utilis* and *Abies pindrow* tree species along the north facing slope

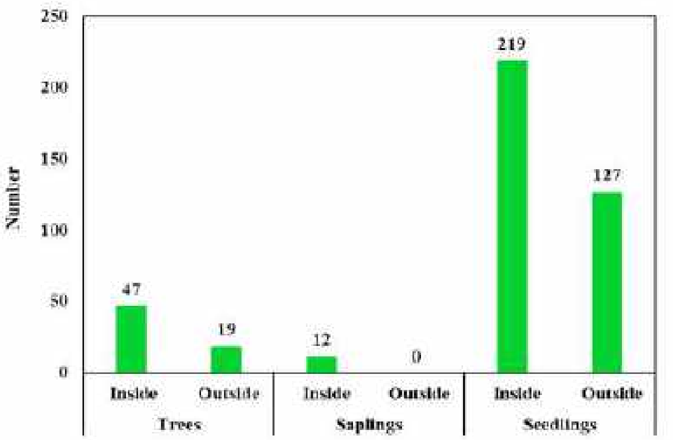

Fig. 2. Number of trees, saplings and seedlings inside and outside nurse plants along the north facing slope at the Daksum-Sinthan top site, Kashmir Himalaya

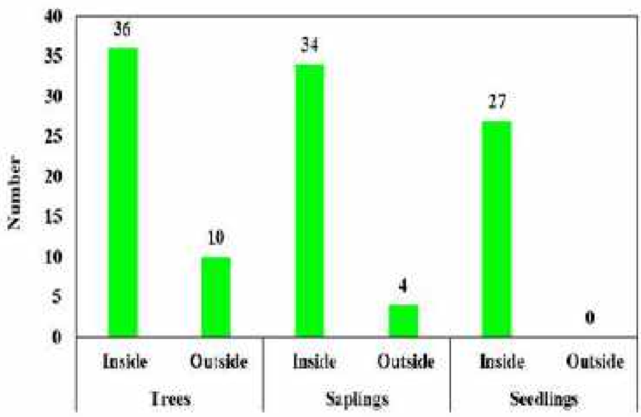

Fig. 3. Number of trees, saplings and seedlings inside and outside nurse plants on the south facing slope at the Daksum-Sinthan top site, Kashmir Himalaya

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Patterns of treeline in western Himalaya

Ecology of treeline has gained greater attention among scientists during past few decades owing to their high sensitivity to changing climate. As compared to other mountain ranges in the world, the understanding about the Himalayan treeline in very sparse and a handful of studies are available on the ecological aspects of the Himalayan treelines, though large numbers of studies were done on the ecology of high altitude forests specific to forest types or along the elevation gradients touching the treeline zone. Considering topography and disturbances in the region, there are three categories of treeline in the Western Himalaya, viz., (i) Anthropogenic treeline, (ii) Natural treeline, and (iii) Orographic treeline (Rai *et al.*, 2019). The anthropogenic treelines are generally located below 3300m closer to age old temporary settlements reflecting long history of human use especially by migratory pastoral communities, those who camp around treeline for the collection of fuelwood and use alpine meadows to feed their livestock. The natural treelines are found mostly in least disturbed mountain slopes, especially in the inner valleys of Gangotri National Park, Nanda Devi National Parks and inner regions in Byans valley. The orographic treelines are characterized by abrupt termination of subalpine forests below the potential elevations due to steeper rocky slopes. The dominant tree species at the treeline of Western Himalaya are Kharsu or brown oak (*Quercus semecarpifolia*), Fir (*Abies spectabilis*) and Bhojpatra (*Betula utilis*) found in various associations with other species whereas, Kail or blue pine (*Pinus wallichiana*) and Juniper (*Juniperus polycarpos*) also form pure forest stands in the inner dry valleys. *Rhododendron campanulatum* forms krummholz vegetation and dominates shrub layer with one or more species of *Salix, Rubus, Sorbus, Rosa, Viburnum, Lonicera* and *Spiraea*. All natural treelines ranged between 3500 to 4000m as discontinuous patches while in some areas it is extended up to 4200m. Timberlines of the western Himalaya are usually influenced by anthropogenic factors and often do not represent the potential elevation for tree growth. The major reason behind such conditions is long history of human use especially by migratory pastoral communities for the sustenance of their livelihood. Pastoralism plays an important role in the ecology of treeline habitats and the economy of rural people in the remote areas of the western Himalaya. The pastoralists move from lower altitudes of the Himalaya to higher alpine regions in summer and return back to lower altitude villages with the onset of autumn. The forested areas along the routes of transhumant pastoralists are affected by anthropogenic pressures, *viz.*, grazing by livestock and tree lopping by the herders for fuelwood. To demarcate such areas and evaluate the effect of anthropogenic disturbances, a preliminary documentation of the routes is needed. Undisturbed natural treeline is rare and found only in the interior valleys where grazing is prohibited by steepness of slopes and inaccessible topography. Sometimes on steeper rocky slopes treeline abruptly terminate far below the potential elevations and forms orographic treeline. Timberline of south-west facing slopes are formed mainly by *Quercus semecarpifolia* where *Rhododendron arboreum* also associate with it sometimes forms pure patches in steep rocky slopes near treeline where oak unable to grow. *Betula utilis* is typical species form treeline in the moist slopes in association with various species of *Salix* and *Rhododendron*. *Abies spectabilis* forms pure community or sometime mixed with birch in the north-west to north facing slopes. The anthropogenic treelines are generally devoid of regenerating individuals (seedlings, saplings) and represented by large trees only. In many places due to the cumulative impacts of livestock grazing, fuel wood and fodder extraction and lack of regeneration, the treeline is depressed to lower elevation and large forest gaps are being formed (Thakur *et al.*, 2011). The depressed treelines are mostly on the gentle warm slopes favorable for grazing of livestock and camping. These treelines are highly prone to disturbances as lack of regeneration may cause large forest gaps and depress treeline in lower elevations with the mortality of trees due to natural or anthropogenic causes. In most of the areas, the treeline is terminated sharply due to anthropogenic pressure or topographical barrier. In areas of varying disturbance level, recruitment of seedling is found under the canopy of krummholz vegetation, whereas seedling density is quite low in the areas devoid of understory of krummholz. Due to high grazing pressure,

Fig. (a) Anthropogenic treeline (b) Natural treeline (c) Orographic treeline

which led to trampling, seedling density is quite low. Along the alpine meadows *Q. semecarpifolia* treeline are always under anthropogenic pressure due to fuelwood consumption and grazing by cattle, mule and horses, south to south-west facing slopes are becoming drier with increasing elevation with oak predominance are being preferred by the grazers. In the highly disturbed area (Aali, Rudranath, Madhyamaheshwar) plenty of seedlings are found mainly due to canopy opening but poor conversion from seedling to sapling are recorded (sapling/seedlings = 0.7). In high disturbance areas high seedling density is found, as the canopy opening may favour the establishment of seedlings, while inaccessible terrains for grazing enhance the ratio of seedling to sapling. It is evident from the studies that the average elevation of treeline in the western Himalaya is around 3615m asl, but trees are recorded upto 4200m. The sites exhibiting the natural treeline in the western Himalaya are confined to a few strictly protected and inaccessible areas. The single mountain slopes providing adequate representation of treeline ecotone, alpine scrub and meadows covering wide altitudinal range free from chronic anthropogenic pressures are rather very sparse in the western Himalaya. Considering the immense ecological role of treeline in Himalaya in terms of environmental stability, habitat for several endangered species of flora and fauna, treeline deserves participatory monitoring using citizen science approach and restoration of degraded sites.

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