

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

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

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

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Introduction

The high mountain ecosystems are under tremendous pressure at present because of biodiversity loss, habitat destruction, landscape modification (Bruun *et al.* 2006; Körner 2003) and climate change (Beniston 2003; Pauli *et al.* 2012). A major consequence of climate warming is an early

snowmelt, increase in soluble N deposition in high mountain habitats and diversity loss (Hattenschwiler & Körner 1997; Torseth & Semb 1997). The increase in soil moisture at an early stage of the plant growth due to early snowmelt may change the community composition, species richness and the occurrence patterns of individual species (Körner 2003; Le Roux *et al.* 2013). The

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

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

Consistent and repeated differences in snowmelt patterns largely determine the nature and intensity of stress and/or disturbance that plants have to cope with and, as such are expected to be a strong ecological driver of species sorting for alpine plant communities (Choler 2005). The alpine region is often regulated by extreme climates, such as low temperature, precipitation in form of scanty rainfall, blizzard and snowstorms, high wind velocity and high intensity of ultraviolet (UV) radiation (Nautiyal *et al.* 2004). The plants have adapted themselves to these climatic conditions and developed a mosaic of different life forms, such as dwarfed, stunted, woolly and spiny ones (Walker *et al.* 1994). There is a significant impact of intense anthropogenic disturbance on the structural and

functional attributes of alpine vegetation communities, which are rich in high-value medicinal, aromatic and threatened plants. The degradation of alpine plant communities and treeline ecotone is further accelerated due to other drivers of change, such as extreme weather events, drought and forest fires (Singh *et al.* 2011; Xu *et al.* 2009).

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

Materials and methods

Study area

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

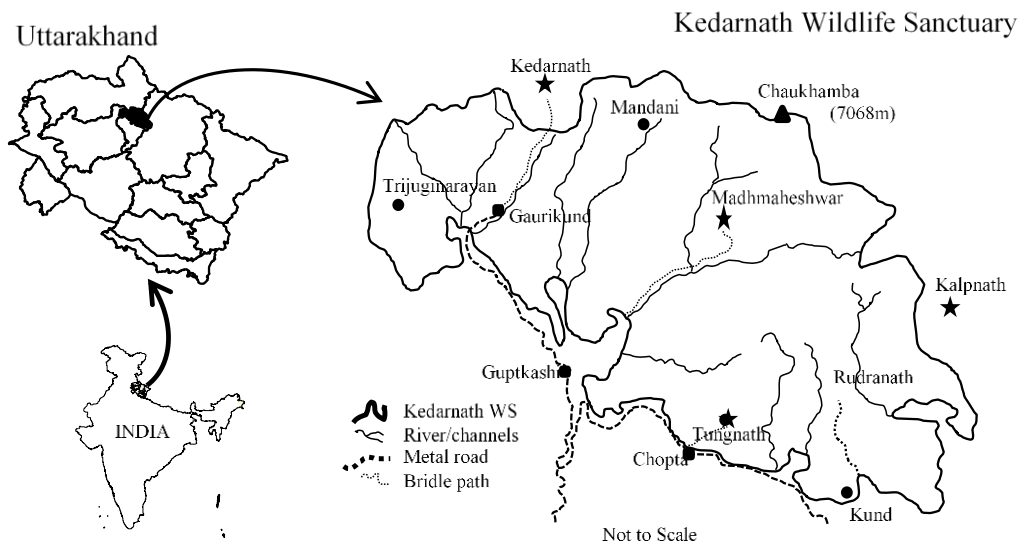


Fig. 1. Location map of the study site.

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

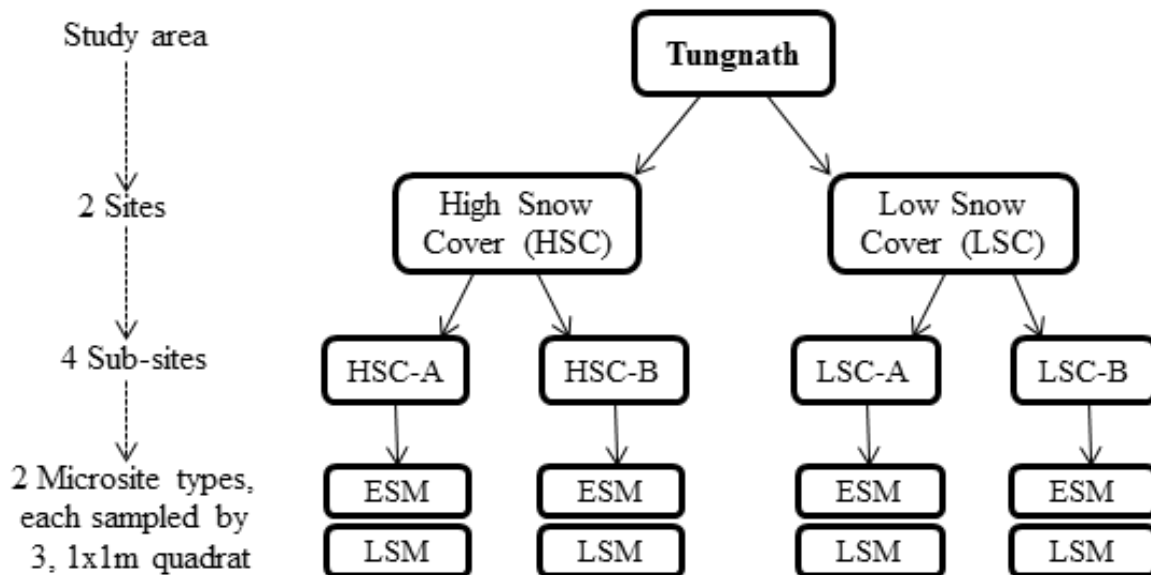
Study design

To determine the effect of snow on vegetation, we selected two slopes different in snow cover, as recorded on April 28, 2017, when we could reach the site for the first time after the winter snow fall. We observed that the site with high snow cover had 70–80% area under snow cover with thickness up to 1.2 m. On that day, the branches of krummholz were

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

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

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

**Fig. 2.** Schematic representation of sampling design. LSC: Low snow cover, HSC: High snow cover, ESM: Early snowmelt, LSM: Late snowmelt.

sheltered and concave surfaces. The difference in snowmelt time between ESM and LSM microsites was generally of 3–5 days in LSC site, while in HSC site it was 10–15 days. A plot (50 × 50 m) was identified in each HSC and LSC sub-site (with two

microsite types ESM and LSM, respectively). In each microsite, 3 permanent quadrats (1 × 1 m; Fig. 3) at an average distance of 10 m were laid for vegetation composition and phenology monitoring during the growth period (May–October, 2017).



Fig. 3. View of study area as on 19-02-2017 (top), early snow melt (left, with more plant cover) and late snowmelt (right, still with bare soil surfaces) microsites as on 27-05-2017.

Types and forms of plants

The species were divided into following categories with regard to their life span: annuals, plants which live for one growing season; perennials, plants which grow and bloom over spring/summer season and die every autumn/ winter and grow again from their root stock, and biennials, plants which complete life cycle in two years; in this plants germinate, grow and survive through winters, and next year grow more, bloom and die.

Growth form

The direction and extent of growth and branching of the main-shoot axis or axes determine the growth form of a plant. It may be largely

associated with eco-physiological adaptation, such as maximizing photosynthetic production, sheltering from severe climatic conditions, and resistance to grazing by optimizing the height and positioning of the leaves and rosettes and prostrate growth forms are associated with heavy grazing. Here, plants were classified based on Pérez-Harguindeguy *et al.* (2013) as semi basal herbs, short basal herbs, erect leafy herbs and tussock-forming grasses, dwarf shrubs and climbers.

Life form and nativity

Species occurring in treeline area were divided into Raunkier's life form (Raunkier 1934) to develop life form spectrum.

The place of origin/first record of the species,

Table 2. Various stages, their names and description as per BBCH scale (Hess *et al.* 1997).

Stage	Code	Code details	Code description
Germination/sprouting	0	Germination/sprouting/bud development	From dry seed till leaf breaks the soil
Vegetative/growth phase	1	Leaf development (main shoot)	First leaf to nine or more leaves/whorls development
	2	Formation of side shoots/ tillering	First side shoot/tiller to nine or more shoot/tiller visible
	3	Stem elongation/shoot development (Main shoot)	Beginning of stem elongation to nine or more nodes
Flowering/vegetative propagation	4	Vegetative propagation/ booting (Main shoot)	Development of propagation organ to first awl visible
	5	Inflorescence emergence (Main shoot)/heading	Inflorescence/flower bud visible to full emergence
	6	Flowering (Main shoot)	First flower till the end of flowering when fruiting begins
Fruiting and Maturation	7	Development of fruit	Fruit begins to develop till maturity for species and location
	8	Ripening or maturity of fruit and seed	The beginning of ripening or fruit colouration till fully ripe
Senescence	9	Senescence or beginning of dormancy	Plant dead or plant resting or dormant

where it occurs naturally 'indicates the nativity of the species (Anonymous 1883–1970), and the species introduced in an area where it did not occur previously through anthropogenic activities are called 'Non-Native'. We used *Index Kewensis Plantarum Phanerogamarum* (Anonymous 1883–1970) to know the nativity of a species.

Species richness and diversity

Species richness was taken as a count of a total number of species in a particular area. The index of diversity was calculated after Shannon & Wiener (1949). If p_i is the proportion of individuals (from the sample total) of species i.e. then diversity (H') is,

$$H' = - \sum_{i=1}^s (P_i)(\ln P_i)$$

Where, P is a proportion (n/N) of individual of one particular species found (n) to a total number of individuals found (N), \ln is a natural log, \sum is sum of the calculations, and s is a number of species.

Sorenson Similarity Index (I_s) between different sites was calculated following Sorenson (1948).

$$I_s = \frac{2C}{A+B} \times 100$$

Where, I_s the Sorenson Index of Similarity; C the common species to both comparable sites; A the

total number of species in site A and B , the total number of species in site B .

The contribution of each species to the dissimilarity (%) between the two groups was calculated from the Bray-Curtis dissimilarity matrix through SIMPER analysis in PAST between ESM and LSM microsites.

Beta-diversity, a measure of species compositional change along environmental gradients within an area was calculated as the ratio of total species to the mean number of species per sample (Whittaker 1975) among months and sites. We performed the non-parametric test because data did not follow central tendency. To check the variance in density between months, sites and microsites Kruskal-Wallis test was performed.

Phenological observations

The phenological changes were observed visually to monitor how the species respond to climate variations at a monthly interval. Therefore, records of various phenophases such as growth initiation, vegetative phase, flowering, fruiting, seed formation and senescence, of each species were taken from May to October in 2017 following Biologische Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) scale (Table 2; Hess *et al.* 1997). The existence of a particular phenophase was considered if 5% of the individuals showed

that phenophase. Based on growth initiation time, the plants were divided into two categories, early growth species (up to mid-May) and late growth species (mid-May to June).

To find out the changes in phenology of study plants caused due to change in climatic conditions over a time period, we have compared present phenological observations of thirteen common species with the studies conducted in past at Tungnath by Sundriyal *et al.* (1987) for *Anaphalis royleana*, *Anemone obtusiloba*, *Bupleurum longicaule*, *Danthonia cachemyriana*, *Geranium wallichianum*, *Oxygraphis polypetala*, *Pedicularis pectinata*, *Taraxacum officinale* and *Trachydium roylei*, Nautiyal *et al.* (2001) for *Selinum vaginatum* and a similar alpine site of west Himalaya i.e. Dyara (Bijalwan *et al.* 2013) for *Geum elatum*, *Parnassia nubicola* and *Potentilla atrosanguinea*. Since the frequency of phenological observation was long (1 month), the comparison gives only a rough estimate of change.

Results

Plant growth period (period from the beginning of growth to the time when about 80% of plant shoots had senesced) was about 5–6 months from about mid-April to mid-October. Soil moisture values (47–50%) during the peak growing period (July) were similar for ESM and LSM microsites, soil moisture was never a limiting factor for plant growth. The number of snow fall days during 2016–2017 winter (December to April) was 38 days.

Plant forms and growth cycle

In total, 86 plant species were encountered in quadrat sampling during the study period, of which the percentage of forbs was 90% and that of perennial species 90.6%, there were only few annuals (8.2%) and biennials (1.2%). Growth forms of the species in the present study were in the order: semi basal = short basal (32.9% each) > erect leafy (28.2%) > dwarf shrub (2.4%) > climber, shrub and tussock (1.2% each). A majority of species had a long growth cycle (64%), followed by intermediate growth cycle (31%) and short growth cycle (5%). Tall forbs were 34%, medium size forbs 23% and short forbs 34%, while the rest were climbers, shrub, undershrub, grasses and sedges (10%). The life form was dominated by hemicryptophytes (84%).

Species richness and diversity

Even within a short growing period, the growth

initiation in species was staggered. The ESM and LSM microsites were similar in total species number (74 and 72 species, respectively) and numbers by growth forms (semi-basal 26 and 24 species and short basal 25 and 24 species, respectively). The total species number in the study area increased as the growth period progressed from 44 in May to 80 in September. Generally, species number in a month was markedly higher in ESM than LSM microsites, the difference being particularly large at HSC-B sub-site (38 in ESM and 27 in LSM microsite) in July (Fig. 4). Two-way ANOSIM was applied to test for significant variations in species richness between sub-sites and across months. It showed significant differences ($R = 0.93$ and $R = 0.91$, respectively).

At the peak of species richness, 60% species were common to both ESM and LSM microsites. The species richness (species number m^{-2}) generally peaked in July and ranged between 15.0–20.7 in LSM and 19.7–24.0 in ESM microsites across four sub-sites. In LSC site plant density was significantly high for ESM microsite than LSM microsite, while such difference was not obvious for HSC site, possibly because of the shorter growing period due to longer stay of snow. The Shannon-Weiner diversity index was relatively higher in ESM microsites (2.832 ± 0.055) than LSM microsites (2.775 ± 0.048 ; Fig. 5). It seems that early snowmelt allowed basal leaf forms (*Ranunculus*, *Fragaria*, *Oxygraphis*, *Trachydium*) to express themselves prominently.

The β -diversity (calculated across quadrats used to sample species richness) between sites was higher in HSC (2.59) than LSC (2.28), among sub-sites it was higher in HSC-A (2.09), followed by LSC-A (1.88), HSC-B (1.86) and then LSC-B (1.83); between microsites it was higher in LSM (2.78) than ESM (2.42). The β -diversity across months was higher in LSM (1.9–2.3) than ESM (1.7–1.9).

Species similarity among sub-sites and microsites

The overall similarity in species context between ESM and LSM microsites was 82%, however, the similarity between ESM and LSM microsites within each sub-site was much lower (LSC-A 32%, LSC-B 31%, HSC-A 31%, and HSC-B 38%). The similarity between ESM microsites of HSC and LSC was 70%, while between LSM microsites of HSC and LSC was 53%. However, the similarity between HSC and LSC sites was 88%. SIMPER (Similarity Percent) analysis showed 72% and 67% dissimilarity, respectively, among LSM

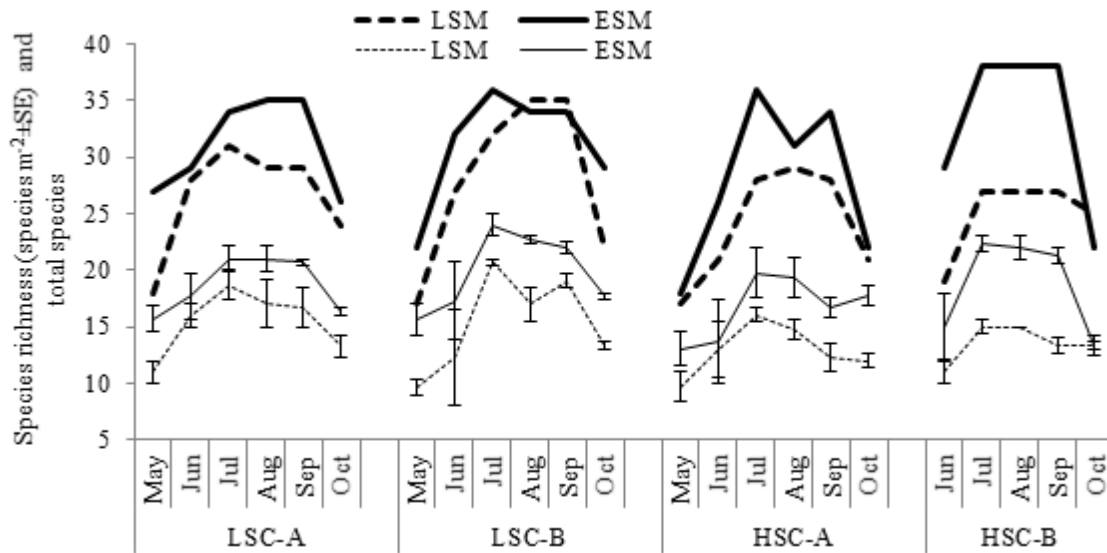


Fig. 4. Herb species richness across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath treeline in Garhwal Himalaya. Total species depicted in thick line and average species richness (number m^{-2}) in thin line. LSC: Low snow cover, HSC: High snow cover.

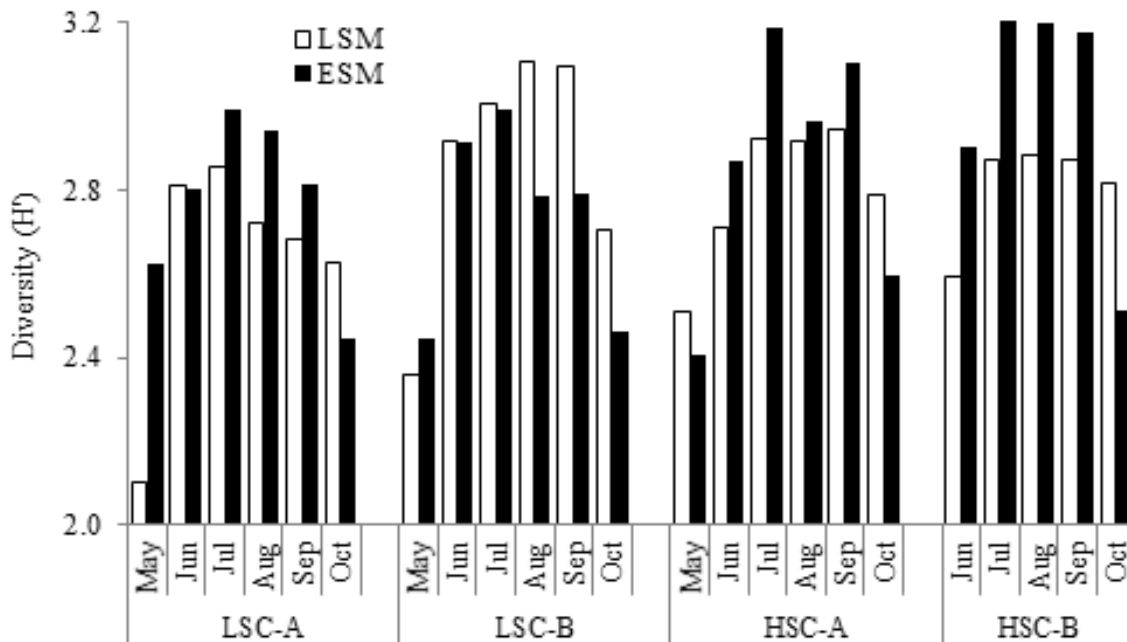


Fig. 5. Patterns of species diversity (H') across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath treeline in Garhwal Himalaya. LSC: Low snow cover, HSC: High snow cover.

and ESM microsites. The major species which contributed to dissimilarity in descending order were *Fragaria*, *Ranunculus*, *Polygonum*, *Carex*, *Bistorta*, *Trachydium*, *Anemone*, *Poa*, *Circaea* and *Potentilla* for LSM microsites and *Ranunculus*, *Trachydium*, *Carex*, *Oxygraphis*, *Fragaria*, *Anaphalis*, *Prunella*, *Polygonum* and *Anemone* for ESM microsites.

Habitat preference of plant species

Bistorta amplexicaulis, *Fragaria nubicola*, *Geranium wallichianum*, *Potentilla atrosanguinea* and *Viola biflora* were present in all quadrats. The species which were present in all LSM microsites were *Myriactis wallichii* and *Veronica cana* (both

erect leafy), while *Anaphalis nepalensis*, *Kobresia*, *Selinum vaginatum* (all semi-basal), *Oxygraphis polypetala*, *Polygonum filicaule*, *Potentilla lineata* and *Potentilla polyphylla* (all short basal) occurred in all ESM microsites. *Aster albescens*, *Corydalis cornuta*, *Cynoglossum glochidiatum*, *Gaultheria trichophylla*, *Gentiana argentea*, *Gentiana tubiflora*, *Gerbera gossypina*, *Goodyera repens*, *Ligularia sibirica*, *Morina polyphylla*, *Persicaria nepalensis*, *Primula reidii*, *Rumex nepalensis* and *Swertia auriculata* were present in ESM microsites only, while *Arisaema propinquum*, *Aster methodrus*, *Clematis barbellata*, *Galium asperifolium*, *Halenia elliptica*, *Hemiphragma heterophyllum*, *Ligularia amplexicaulis*, *Parochetus communis*, *Smilacina purpurea*, *Thalictrum foliolosum*, *Trillium govianum* and *Viburnum glanduliflorum* were present only in LSM microsites.

On the basis of monthly average density the dominant species by sites and sub-sites were as following:

LSC-A:

ESM: *Ranunculus hirtellus* (70.2 ± 9.1 individuals m^{-2}) followed by *Trachydium roylei*, *Oxygraphis polypetala* and *Fragaria nubicola* (56.8 ± 3.7 , 48.1 ± 2.2 and 38.7 ± 6.2 individuals m^{-2} , respectively)

LSM: *Fragaria nubicola* (53.2 ± 13.0 individuals m^{-2}) followed by *Carex setosa* (22.5 ± 2.0 individuals m^{-2}).

LSC-B:

ESM: *Ranunculus hirtellus* (97.9 ± 6.1 individuals m^{-2}) followed by *Carex setosa*, *Trachydium roylei* and *Oxygraphis polypetala* (61.7 ± 12.1 , 42.1 ± 6.9 and 35.5 ± 4.0 individuals m^{-2})

LSM: *Fragaria nubicola* (20.9 ± 3.9 individuals m^{-2}) followed by *Trachydium roylei* and *Bistorta amplexicaulis* (20.1 ± 1.4 and 16.7 ± 4.2 individuals m^{-2} , respectively).

HSC-A:

ESM: *Anaphalis nepalensis* (24.6 ± 2.2 individuals m^{-2}) followed by *Carex setosa* and *Polygonum delicatula* (16.4 ± 3.3 and 15.7 ± 4.0 individuals m^{-2} , respectively)

LSM: rapid changes in species dominance was seen where no two months had same dominance in terms of plant density, as the majority of species (*Bistorta amplexicaulis*, *Fragaria nubicola*, *Polygonum delicatula*, *Polygonum filicaule* and *Potentilla polyphylla*) contributed similarly (10.2 – 14.0 individuals m^{-2}).

HSC-B:

ESM: *Ranunculus hirtellus* (39.1 ± 0.2 individuals m^{-2}) followed by *Fragaria nubicola* and *Lysimachia prolifera* (18.3 ± 1.9 and 16.5 ± 4.2 individuals m^{-2} , respectively).

LSM: *Ranunculus hirtellus* (41.1 ± 1.9 individuals m^{-2}) followed by *Poa annua*, *Polygonum filicaule* and *Bistorta affinis* (22.3 ± 2.4 , 19.1 ± 2.3 and 17.1 ± 2.7 individuals m^{-2} , respectively)

The average plant densities were markedly higher in LSC (313.7 ± 30.3 individuals m^{-2}) than HSC (187.6 ± 13.6 individuals m^{-2}) sites. Similarly, the plant densities were higher in ESM microsite (325.2 ± 30.4 individuals m^{-2}) than LSM (182.1 ± 12.0 individuals m^{-2}) microsite (Fig. 6). The plant density was significantly higher in ESM (441.8 ± 30.2 individuals m^{-2}) microsite than LSM (196.3 ± 15.2 individuals m^{-2}) microsite of LSC, but ESM (208.5 ± 18.7 individuals m^{-2}) and LSM (166.7 ± 18.6 individuals m^{-2}) microsite of HSC site did not differ significantly (Fig. 6). The difference in densities was tested through Kruskal-Wallis test (non-parametric one way ANOVA), which were highly significant across months ($F = 17.69$, $df = 146.6$, $P < 0.001$), sub-sites ($F = 13.06$, $df = 322.5$, $P < 0.001$) and microsites ($F = 9.896$, $df = 205.3$, $P < 0.001$).

Phenology at microsite level

In general, phenophases were observed in more advanced stages in ESM than in LSM microsites.

At community level as indicated by species number, the vegetative phase peaked in June, flowering and fruiting in August and senescence phase in October in both ESM and LSM microsites (Fig. 7). Because observations were taken at a monthly interval, differences between ESM and LSM could not be detected with regard to phenology at the community level. In the initial months of growth period i.e. May and June the species number was high in vegetative phase (26–32 in ESM and 31–34 in LSM microsites).

The ESM microsites supported the vegetative as well as the reproductive growth of plants even after the rainy season and no difference was observed in fruiting and seeding phase between ESM and LSM microsites. The flowering phase peaked in August with 40 species in ESM and 38 in LSM microsites. Senescence started during June and July in ESM and LSM microsites, respectively and more species were senescing during September in LSM (36) microsites than ESM (31) microsites. The senescence was more rapid in ESM microsites than LSM microsites (Fig. 7).

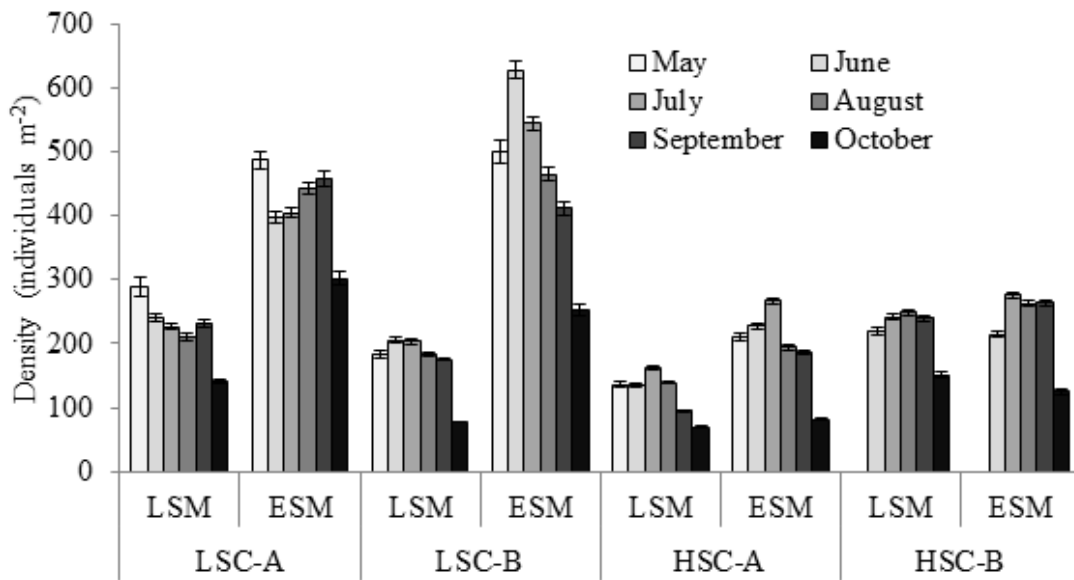


Fig. 6. Plant density (individuals m^{-2}) at different sites across months at treeline in Tungnath region, Garhwal Himalaya. LSC: Low snow cover, HSC: High snow cover, ESM: Early snowmelt, LSM: Late snowmelt.

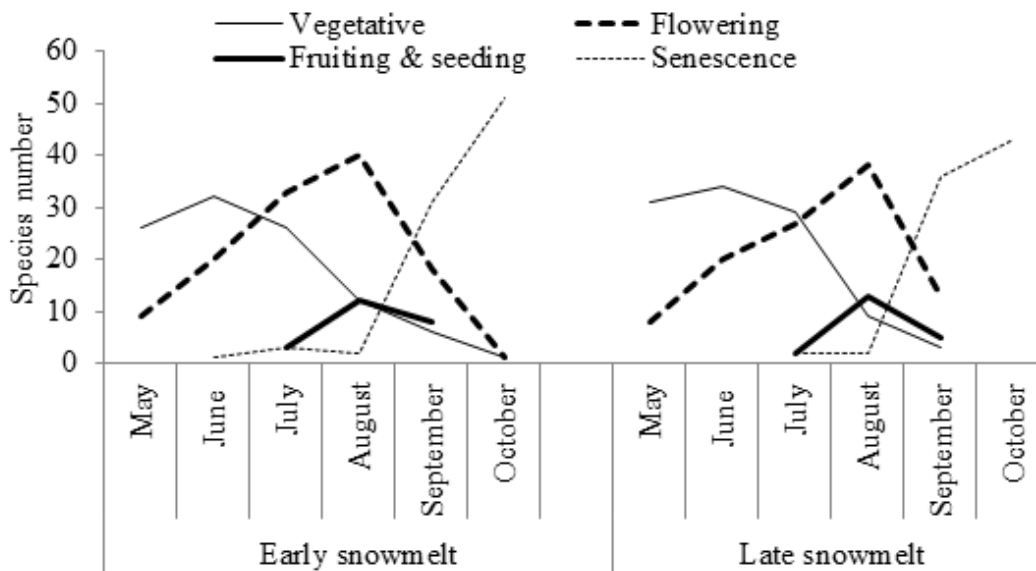


Fig. 7. Number of species across months in different phenophases in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath.

Change in phenology based on comparison with past studies

As compared to past studies, in our study the flowering advanced for *Anaphalis* (3 weeks), *Pedicularis* and *Anemone* (2.5 weeks), *Potentilla* and *Taraxacum* (2 weeks), *Bupleurum* and *Geum* (1 month). The flowering phase in the present study was shorter by a week in *Trachydium* and

delayed in *Selinum* by 2 weeks as compared to Sundriyal *et al.* (1987; Table 3). The flowering phase was extended in *Selinum*, *Parnassia* and *Geum* by one month period and in *Danthonia* and *Potentilla* by 2 weeks as compared to that of Sundriyal *et al.* (1987). *Oxygraphis* flowered twice, the first flowering phase was delayed by 1 week and the second by 3 weeks; the length of flowering duration increased by

Table 3. A comparison of timing and length of plant phenophase of the present study with those past studies conducted at the same and similar areas, Tungnath and Dyara. VP: Vegetative phase, FP: Flowering phase, FrP: Fruiting phase and SP: Senescence phase.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
Comparison with the study conducted by Sundriyal <i>et al.</i> (1987) in 1984 in Tungnath region				
<i>Anaphalis royleana</i>	VP	May to mid-June	May to early August	Extended more than 2 months
	FP	mid-June to mid-July	July to late September	Advanced by 3 weeks
	FrP	July last to August	September	Delayed by a month
	SP	September and October	October	Delayed by a month
<i>Danthonia cachemyriana</i>	VP	May to mid-June	May to July	Extended by a month
	FP	late-June to early August	August	Delayed by 1.5 months and extended 2 weeks
	FrP	early August to Mid-September	last week of August	Confined to a week
<i>Oxygraphis polypetala</i>	SP	mid-September to October	September-October	Advanced by 2 weeks
	VP	early May (2 weeks)	May to August	Extended by 3.5 months
<i>Oxygraphis polypetala</i>	FP	late May (2 weeks)	late May to mid-June and early to last August	Shown 2 growing cycles, delayed by 1 week and extended by 2 weeks in the first stage and 3 weeks in later stage and length of the period was more in a later stage
	FrP	June to mid-August	late May to June and late August to September	Shown 2 growing cycles; advanced by a week and length of phase was slightly more in later part
	SP	mid-August to October	October	Delayed by 1.5 months
<i>Pedicularis pectinata</i>	VP	up to mid-June	May to August	Extended by 3.5 months
	FP	mid-June to July	Late May to July	Advanced by 2.5 weeks
	FrP	August to early September	July	Advanced by a month
	SP	early September to October	September to October	Advanced by a week
<i>Trachydium roylei</i>	VP	May to mid-June	May to mid-June	No change
	FP	mid-June to early August	Mid-June to July	Reduced by a week
	FrP	early August to late September	August to mid-September	Advance by a week and reduced by 2 weeks
	SP	late September to October	mid-September to October	Advanced by 2 weeks
Comparison with the study conducted by Bijalwan <i>et al.</i> (2013) in 2008 in Dyara				
<i>Anemone obtusiloba</i>	VP	May	May to September	Extended 4.5 months
	FP	June-July	mid-May to July	Advanced by 2.5 weeks
	FrP	August	Absent	Not seen, may be for a short period
<i>Bupleurum longicaule</i>	SP	September - October	October	Delayed by a month
	VP	mid-June to mid-August	mid-June to mid-July	Reduced by a month
	FP	mid-August to mid-September	mid-July to late August	Advanced by a month
	FrP	September later half	late August to September	Advanced by 3 weeks
	SP	October	October	Reduced by a week

Contd...

Table 3. Continued.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
<i>Geranium wallichianum</i>	VP	May to mid-July	May to late August	Extended by a month
	FP	mid-July to late August	early June to September	Advanced by a month and extended by a month
<i>Taraxacum officinale</i>	FrP	late August to September	September to mid-October	Reduced by a week and extended by 2 weeks
	SP	October	September - October	Advanced by a month
	VP	May to mid-July	May-June	Reduced by 2 weeks
	FP	Mid-July to early September	July to early September	Advanced by 2 weeks
	FrP	September	Mid-July to September	Advanced by almost 2 months
	SP	October	October	No change
Comparison with the study conducted by Nautiyal <i>et al.</i> (2001) during 1988-1998 in Tungnath				
<i>Selinum vaginatum</i>	VP	May to mid-July	May to early September	Extended by 1.5 month
	FP	Mid-July to August	August - September	Delayed by 2 weeks and extended by a month
	FrP	September	Absent	Not seen, may be for a short period
	SP	October	October	No change
Comparison with the study conducted by Sundriyal <i>et al.</i> (1987) and Bijalwan <i>et al.</i> (2013)				
<i>Geum elatum</i>	VP	May to early June/May to mid-June	May-June	Extended by 4 and 3 weeks from 1984 and 2008, respectively
	FP	Early June to early July/mid-June to Late July	June to early August	Advanced by 1 and 2 weeks and extended by a month and 2.5 weeks, respectively from 1984 and 2008
	FrP	Early July to August/late July to September	July to early September	Advanced by 1 and 3 weeks and extended by 1 week and reduced by 3 weeks from 1984 and 2008, respectively
	SP	September-October/October	September-October	Similar to 1984 and advanced by a month from 2008
<i>Parnassia nubicola</i>	VP	mid-May to early July/mid-May to late August	Early June to mid-August	Extended by 3.5 weeks from 1984 and 2008, extended by 3 weeks and advanced by a month from 1984 and reduced by 3 weeks from 2008
	FP	early July to mid-August/Late August	July to mid-September	Advanced by 1 week and 1 month and extended 1 month and 3 weeks from 1984 and 2008, respectively
	FrP	mid-August to mid-September/September	September	Delayed by 2.5 weeks and extended 2 weeks from 1984 and similar with 2008
	SP	mid-September to October/October	October	Delayed by 1 and 2 weeks from 1984 and 2008, respectively

Contd...

Table 3. Continued.

Species	Phase	Time period		Changes over a period
		Earlier study	Present study	
<i>Potentilla atrosanguinea</i>	VP	May to early July in 1984 & 2008	May to late August	Extended by 1.5 months
	FP	early July to mid-August/early July to early September	July-August	Advanced by 2 weeks from both and extended by 2 weeks from 1984 and reduced by a week from 2008
	FrP	mid-August to mid-September/early September to early October	Late July to Late September	Advanced by 3.5 weeks and 1 month and 2 weeks from 1984 and 2008, respectively reduced 2 weeks from 2008 and extended by 1 week from 1984
	SP	mid-September-October/October	Early September to October	Advanced by 2 weeks and 1 month from 1984 and 2008, respectively

about two weeks. In the present study, the duration of flowering was extended by 2.5 weeks for *Geum* and 3 weeks for *Parnassia* and it was shortened by a week for *Potentilla* as compared with those reported by Bijalwan *et al.* (2013; Table 3).

The fruiting was delayed in *Anaphalis* by a month and in *Parnassia* by 2.5 weeks and advanced in *Pedicularis* by one month. The length of fruiting duration was shortened in *Trachydium* and *Geum* (1 week) and *Potentilla* (3.5 weeks), and extended in *Parnassia* (2 weeks) and *Potentilla* (1 week) as compared to Sundriyal *et al.* (1987; Table 3). The fruiting in *Danthonia* was confined to a week and it was not observed in *Selinum* and *Anemone*. The flowering phase was advanced in *Bupleurum* (3 weeks) and *Taraxacum* (2 months) and the length of duration increased in *Geranium* (2 weeks) as compared to that of Bijalwan *et al.* (2013). The senescence was delayed by 1 month in *Anaphalis*, 2 weeks in *Oxygraphis* and 1 week in *Parnassia* (as compared to Sundriyal *et al.* 1987) and by 2 weeks in *Parnassia* (as compared to Bijalwan *et al.* 2013). The senescence advanced by 2 weeks in *Danthonia* and *Trachydium* and by 1 week in *Pedicularis* as compared to Sundriyal *et al.* (1987) and by 1 week in *Guem* and *Potentilla* as compared to Bijalwan *et al.* (2013) However, no change was observed in *Selinum* (as compared to Nautiyal *et al.* 2001) and *Geum* (as compared to Sundriyal *et al.* 1987) from the past studies.

Discussion

Our study shows that the advancement of snowmelt affects species diversity, growth and phenology of herbaceous species in the Himalayan treeline ecotone.

Comparison between early and late snowmelt microsites

The t-test indicated that the means of species richness between sites (HSC and LSC) and between microsites (ESM and LSM) were significantly different ($P = 0.007$ and 0.0001 , respectively) at the 95% confidence interval. The monthly peak of species richness in ESM microsites (average 21.8 ± 0.4 species m^{-2}) was significantly higher than in LSM microsites (average 17.6 ± 0.6 species m^{-2}), indicating the positive effect of longer and favourable growth period on species diversity. The plant growth in treeline and alpine areas is influenced by the timing of snowmelt, post snowmelt temperature and soil moisture (Winkler *et al.* 2018). In Tungnath temperature is getting warmer due to global change over a long growth period (5–6 months) and soil moisture is constantly high during this period (Joshi *et al.* 2018; this issue). Sites, where snowmelt occurs earlier, are more productive and species-rich than where snowmelt is delayed (Kudo 1991; Stanton *et al.* 1994; Litaor *et al.* 2008).

Species richness is not entirely dependent on macro-climate, it is also influenced by variations in soil water content and other variables related to topography (Nabe-Nielsen *et al.* 2017). This study (Nabe-Nielsen *et al.* 2017) also indicates that impacts of snow loss due to climate change could result in an increase in species richness. Early snowmelt results in a longer period of growth provided there are species to take this advantage. The higher diversity of ESM microsites contributed to the lengthening of phenophases and overall growth period. Warming-induced acceleration in species enrichment on mountain summits has been recorded at a continental scale in Europe largely because of the migration of the species from lower elevations (Pauli *et al.* 2012). In our study, we have not analyzed to what extent the higher species richness in ESM was because of the migration of species from lower elevations or free-ranging species. It would be interesting to investigate to what extent an early snowmelt facilitates the establishment of such species.

In the present treeline ecotone sites three types of species with regard to distribution occurred: wide-ranging species, such as *Fragaria nubicola*; largely alpine, such as *Oxygraphis polypetala*, *Carex setosa*, *Ranunculus hirtellus* and *Trachydium roylei*; and largely treeline and subalpine species such as *Poa annua* and *Viola biflora*. Early snowmelt may also promote the occupation of the sites by wide ranging species (Kudo & Hirao 2006; Sherwood *et al.* 2017).

The species richness across various alpine sites in western Himalaya is reported to range from 27 to 56 species (average 30.5 ± 8.3 species; Rawat 2007), thus the species richness in present study site (49.8 ± 5.5 species) is towards the higher side of this range. Our species density values (species number m^{-2}) are similar to that ($15\text{--}21$ species m^{-2}) reported for Zemu valley in Sikkim by Tambe (2007). It shows that in alpine herbaceous communities species richness does not differ between a Uttarakhand Himalayan site (Tungnath) and a Sikkim site, though in lower elevations Sikkim is far more species-rich than Uttarakhand.

The diversity values of present study are less than those reported for herb layer of timberline zone (3.06–3.25) by Rai *et al.* (2012), south and south-east facing slopes of the Greater Himalaya (3.01–3.30) by Rawat (2007) and treeline gaps (3.23) by Kala *et al.* (1998). However, our diversity values are higher than those reported by Rawat (2007, 2.1–2.4) for greater Himalaya as a whole, Kala *et al.* (1998, 2.47) for Valley of Flowers National Park, Singh (1999, 2.39) for Upper Tirthan Valley between 3200–3300 m and Tambe (2007, 1.44–2.48) for alpine landscape of Khangchendzonga National Park.

The turnover rate of species as indicated by β -diversity was higher in LSM than in ESM and between HSC and LSC sites it was higher in the former. The association of high turnover of species in communities where snow cover was more and snowmelt was delayed needs to be investigated. It could be related to shorter lifecycle duration of species and grazing activities.

As per Raunkiaers' life form spectra, hemicryptophyte (83.5%) dominated the study site (Tungnath), which is a common feature of the alpine meadows in Himalaya (Dad & Khan 2010; Kumar *et al.* 2016; Nautiyal 1996; Nautiyal *et al.* 2001; Rawat 2007; Sundriyal *et al.* 1987; Vashistha *et al.* 2011). A comparison with those of past studies indicates that the proportion of hemicryptophytes has increased in the study area. They are better adapted to grazing, trampling and other environmental factors viz. wind, heavy rainfall/erosion, and heavy frost than that of other life forms (Hanninen 2016; Sternberg *et al.* 2000). The studies conducted by Ram & Arya (1991) in Rudranath region, Pangtey *et al.* (1990) for Central Himalaya and Dhar & Kachroo (1983) in Yusmarg indicate the higher proportion of Chamaephytes (31, 47 and 46%, respectively), which could be due to their drier conditions. We recorded that about 70% species are native to the Himalayan region, 11% are of the Indian subcontinent and 8% Indian origin. A high number of native species indicates the high conservation value of Tungnath region, as also

Table 4. Change in phenophase duration and timing (initiation) based on comparison with past studies (Bijalwan *et al.* 2013; Nautiyal *et al.* 2001; Sundriyal *et al.* 1987). Number in parenthesis denotes species of the total common species (# 13). Duration and time period of phenophase: +, increase and–, decrease.

Phenophase	Vegetative	Flowering	Fruiting	Senescence
Change in the length of phenophase duration (d = days)	+55 d (11), –21 d (2)	+21 d (7)	+16 d (4), –25 d (2), 0 d (7)	-
Change in timing of initiation (d = days)	–2 d (1)	+22 d (9), –18 d (4)	+17 d (6), –15 d (5), 0 d (2)	+16 d (8), –26 d (5)

reported by Rana & Samant (2009) for Manali Wildlife Sanctuary.

Changes in timing and length of phenophase over time

Our analysis based on a comparison between present and past studies carried out at the same and similar sites indicate that the length of the vegetative phase has increased on an average by 40 days. This extension has occurred both because of early initiation and delayed termination of the vegetative phase. Evidently, conditions have become favourable because of warmer temperature and high soil moisture availability. Flowering has advanced and extended in the majority of species but not to the extent of vegetative phase. The timing of bud break both, vegetative and flowering is also dependent on whether the bud is preformed or not. In alpine vegetation, nearly 50% species have preformed buds (Winkler *et al.* 2018). The growth of such plants partly depends on the growth condition of the previous year (Körner 2003). In a number of species, fruiting has delayed and shortened. This indicates that in the past when temperature was low, species resorted to fruiting when under stress, while the present favourable conditions (warm and moist) have promoted vegetative growth at the expense of reproductive growth (Table 4). During the last 36 years, precipitation and minimum temperature have increased, indicating an increasingly warm and humid condition, which causes a change in phenological patterns for alpine species, in general.

Conclusion

Early snowmelt is already a major driver of community change in Himalayan treeline ecotones. ESM and LSM microsites indicate that early snowmelt leads to an increase in species richness and higher plant density. However, the impact of

early snowmelt on plant density is modified by snow cover. A thick snow cover seems to suppress the positive effect of early snowmelt on plant density. The higher number of species in ESM microsites could suggest the migration of some free-ranging species to treeline ecotones, as being observed in alpine communities of other parts of the world. This needs to be investigated in view of the fact that the Himalayan treeline growth period is already quite long; in other words, it is not much shorter than in lower mountain areas.

Comparison of our data with those of past studies conducted at the same or similar site (based on 13 common herb species) indicates that the duration of vegetative growth period has increased in 77% species and flowering in 69% species. As for fruiting, the effect of warming is mixed. Flowering has advanced in 69% species, but species behaviour varies with regards to fruiting and senescence. The vegetative phase has extended for particularly long period in alpine-restricted species namely *Oxygraphis* and *Pedicularis* (3.5 months), *Anaphalis* (2 months), *Selinum* and *Potentilla* (1.5 months), *Geum* (3–4 weeks) and *Parnassia* (3 weeks).

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