



Snowmelt influence on phenological events of herbaceous plants in alpine region of West Himalaya

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Received: 10 January 2023 / Revised: 28 June 2023 / Accepted: 11 September 2023 / Published online: 7 October 2023
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Abstract

The snowmelt timing is a major factor controlling plant phenology in alpine regions. Presently, the warming is pushing forward snowmelt timing which may influence species' seasonal cycle throughout the alpine landscape of Himalaya. Nevertheless, very few studies have studied the response of species' phenology to advanced snowmelt in the Himalayas. The present study investigated different alpine species' responses to early snowmelt present in different alpine communities. Five communities were identified and two sites were selected in each community (early snowmelt: ES, late snowmelt: LS) with a 50 × 50 m plot marked permanently for species monitoring. The observations for phenophase initiation and durations of all species were recorded fortnightly. Kruskal–Wallis test was performed to examine species-specific differences in phenophase durations. Pairwise differences were tested with Dunn's post hoc test. The present study hypothesized early snowmelt advances and lengthens phenophases timing and duration in all alpine species. The results showed that phenophases initiations and duration were earlier and longer in ES sites for the majority of species but no significant relationship was found between snowmelt timing and species' phenophase duration. Many species showed two distinctive phenophases (reproductive and fruiting). The divergence was higher in the reproductive phenophase than in other phenological stages. Hence, it seems that the early snowmelt is an important driver influencing the early spring phenology of herb species, the species-specific effects of already happening phenological adjustment for higher reproductive success in the current warming of alpine meadows points towards other limiting factors too that remain to be better understood.

Keywords Climate change · Growth forms · Himalaya · Phenophase · Treeline

1 Introduction

Early seasonal warming and changes in precipitation regimes, leading to earlier snowmelt, have significant implications for alpine systems (Ernakovich et al. 2014). Warming trends in alpine regions show elevation and geographic-dependent effects on snow regimes, with regional trends deviating from global trends (Theurillat and Guisan 2001; Rangwala and Miller 2012; Zhang et al. 2007; Stocker

et al. 2013) emphasizing local topographic influence on the direction and magnitude of changes, especially concerning snow persistence, melt pattern, growing season, plant production, etc. These changes expose alpine ecosystems to faster climate change, affecting species redistribution, richness, growth, and phenology (Korner and Hiltbrunner 2021; Palaj and Kollar 2021; Steinbauer et al. 2018; Adhikari and Kumar 2020; Fazlioglu and Wan 2021) on or near mountain summits, resulting in group extinction of range-restricted species (Sonntag et al. 2022).

Snow plays a crucial role in controlling micro-climate and plant growth in alpine regions (Berauer et al. 2019). Its duration determines the beginning of the growth season, influencing composition, richness, and phenology of alpine communities globally (Aalto et al. 2018; Fazlioglu and Wan 2021), while its impact on temperature sums determines when germination takes place. Alpine plants have evolved cold resistance and phenology regulation as adaptations (Korner et al. 2016), making them highly sensitive to environmental changes,

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including alterations in plant phenology (Pervey et al. 2017; Kudo 2020).

Long-term monitoring studies have shown that warming events can advance plant reproductive phenology, but early snowmelt without temperature increase may not consistently advance phenology and can lead to false growth season initiation and negative ecological impacts (Wolkovich et al. 2012; Gehrman et al. 2021; Reyes-Fox et al. 2014) including false growth season initiation, increasing frost damage because of early dehardening, and may alter the functional attributes of alpine communities by increasing productivity at the cost of depleting nutrient reserves in alpine soils. Responses to warming events vary among species with some species neither advancing nor delaying the timing of spring events (Reyes-Fox et al. 2014), while other experiments show advance and delay in species phenology of species in the same habitat under changes in snowmelt regime (Adhikari et al. 2018, 2020), causing phenological mismatches and affecting survival (Jerome et al. 2021), reproductive synchrony, and pollinator interactions (Mémott et al. 2007; Liu et al. 2011). These changes can also limit suitable habitats for endemic and cryophilic species (Dirnbock et al. 2011).

The Indian Himalayan Region (IHR) is one of the most threatened non-polar regions, with projected significant temperature rise and precipitation increases (Singh and Negi 2018). Studies on alpine plant phenology in the Western Himalayan alpine landscape are limited (Sundriyal et al. 1987; Ram et al. 1988; Negi et al. 1992; Nautiyal et al. 2001; Vashistha et al. 2009, 2011; Bijalwan et al. 2013; Bisht et al. 2014), with few focusing on species' seasonal cycle and phenological responses to climate change or advanced snowmelt (Adhikari et al. 2018; Adhikari and Kumar 2020). This knowledge gap constrains our understanding of alpine ecosystem dynamics in the rapidly changing environment of the IHR.

Given the unique eco-climatic conditions and spatial variations in the Himalayan alpine landscape, species may exhibit broader phenological responses, distinct from manipulation experiments. Therefore, this study focuses on the response of various alpine species to changes in natural snowmelt timing, particularly their phenology behaviour and adaptation strategies being adopted to tackle warming in the Himalaya. The present study aimed to determine alpine species' response to early snowmelt in alpine meadows, which may act as baseline information for future studies as the phenology is strongly dependent on the snowmelt timing and temperature.

2 Material and methods

Study area – The study was conducted at and around the Tungnath region (30° 29' 12.26" N Lat. and 79° 13' 16.13" E Long.) lies in upper catchment of Alaknanda and Mandakini

ivers in Uttarakhand, West Himalaya, forms a part of Kedar-nath Wildlife Sanctuary (Fig. 1). Four distinct seasons are discernible in the study area viz., short summer (May–June), monsoon (July to mid-September), autumn (mid-September–October), and long winter (November–April). The period with total snow cover is usually between 4–5 months and melts during April–May marking the arrival of favourable conditions for plant growth. The mean annual temperature (MAT) ranged between -8.9 (January) and +25.6 °C (May) with an average of 6.7 ± 0.7 °C at timberline ecotone (3300 m) in 2008–2010 (Adhikari et al. 2012). The mean temperature of the warmest month was 12.6 ± 1.2 °C in July. The annual precipitation was 2410.5 ± 432.2 mm, of which 90% was recorded during rainy season (June–September). An increase in relative humidity, dew/frost point, maximum and minimum temperature, and annual rainfall over a period of over 30 years (1981–2017) were observed by Adhikari et al. (2018).

Selected communities – The phytosociological study was conducted in the alpine meadow at and around Tungnath region and five major herbaceous communities, viz. *Trachydium*, Mixed Herbaceous, Mixed *Danthonia*, *Polygonum*, and *Danthonia* were identified (Kumar and Adhikari 2023). Due to the physiognomy of the region, alpine meadows are interspersed with krummholz and form a natural boundary between some communities in alpine meadows.

All the species present in each community were selected for the phenological study. The recorded species were divided into different growth forms following Pérez-Harguindeguy et al. (2013), namely semi-basal herbs, short basal herbs, erect leafy herbs and tussock-forming grasses, dwarf shrubs and climbers; as the growth form of a species is largely associated with the eco-physiological adaptations, 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, thus playing a significant role in species phenology behaviour.

Study design – The area of alpine meadows is finite resulting in small communities. To determine the effects of natural snowmelt on species phenology, two sites were selected within each community on basis of snow cover as recorded on 28 March 2017, when the sites were for the first time accessed after a winter snowfall. Based on orography, the thickness of snow cover varies in each community ranging from 0 m (no snow) to 0.3 m in low snow cover regions (hereafter referred to as early snowmelt site or ES) and up to 1 m in high snow cover region (hereafter referred as late snowmelt site or LS), based on measurements at 10 random locations within each community, which is good enough to

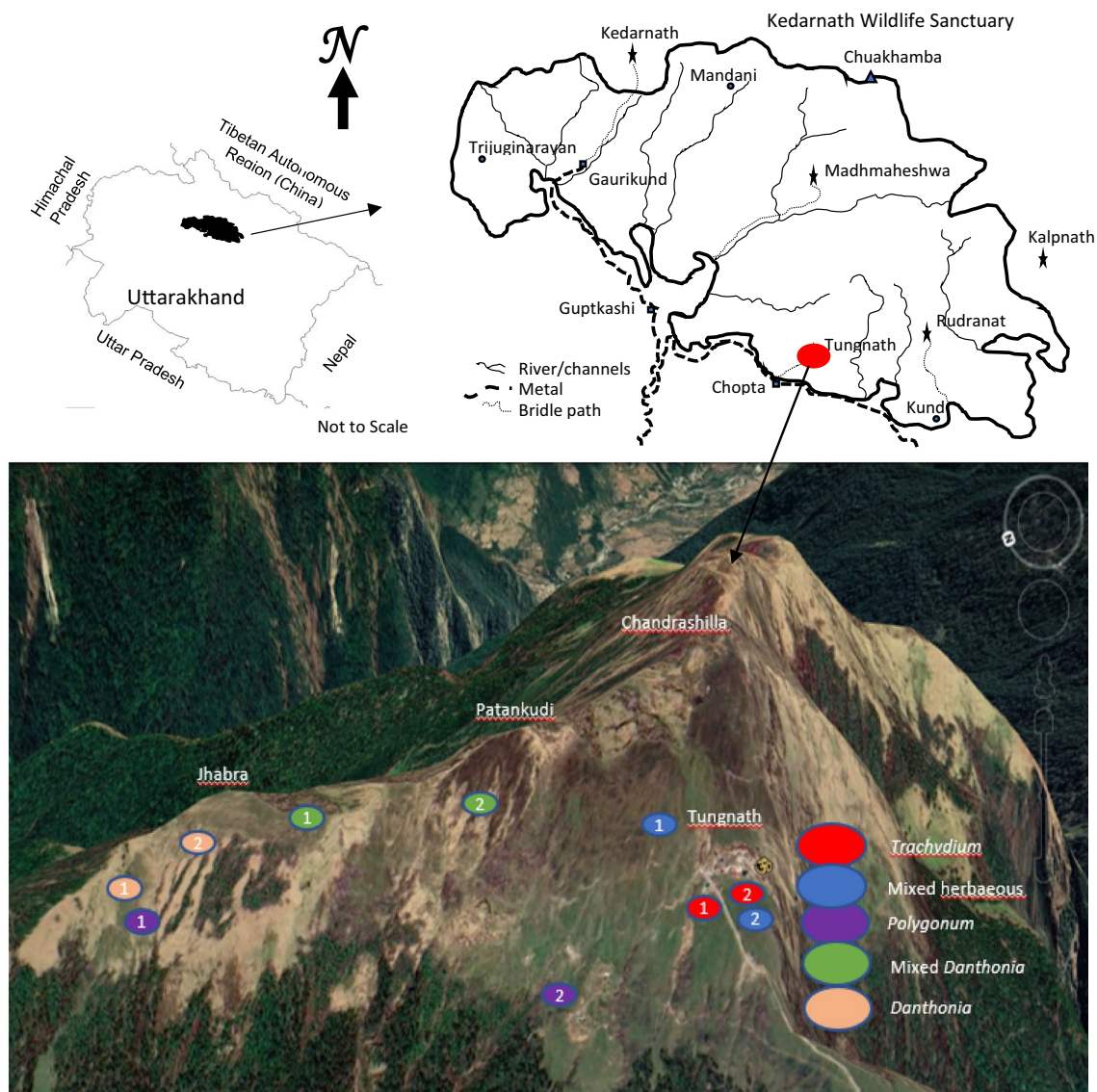


Fig. 1 Location of the study area in Kedarnath Wildlife Sanctuary at and around Tungnath region and Study design. 1: Early Snowmelt 2: Late Snowmelt

indicate two sites differed in snow cover. The snow cover duration in different communities in ES sites was 57–74 days and for LS sites 67–88 days.

Due to the habitat specificity of plant species, communities were interspersed and based on snow cover duration, ES and LS sites were randomly selected for each community. Subsequently, a difference of 7 to 14 days' snowmelt time was observed between ES and LS sites in individual communities. A 50 × 50 m plot was permanently marked in the ES and LS sites of each community. Twenty-five (1 × 1 m) random quadrats were laid in each site, fortnightly, to record the abundance and phenophase of the species. The focus of the study was to record all major phenophases with

corresponding principal stages for all species within quadrats for the growing season (May–October 2017).

Phenology observations – The phenological stage of each species was recorded through a modified Biologische Bundesanstalt Bundessortenamt und Chemische Industrie (BBCH) following Adhikari et al. (2018). BBCH scale is a detailed observation key providing uniform coding primarily to phenological criteria instead of differentiating analogous stages. It depends on the frequency distribution of population phenophase so the presence is not required at the beginning; however, in alpine herb species, it is often difficult to pinpoint the dominant secondary phenophase stages,

and sometimes even primary stages as per the BBCH scale. Since the growing period in the alpine is short (6–7 months), there are many herbaceous species with a short life cycle (<2 months to 2–4 months). These species may skip some primary stages depending on the micro-climate. Oftentimes, it was observed that the species individuals/population growth was fast enough between recorded observations that some primary stages were not recorded leading to the illusion of herb species skipping primary stages depending on micro-climate. Therefore, for ease of data recording, the ten primary phenophase stages (code 0–9) of the BBCH scale were modified (Adhikari et al. 2018) and enumerated into four principal stages viz. vegetative stage (0–4), reproductive stage (5–6), fruiting stage (7–8), and senescence stage (9).

The abundance of individual species and phenophase in a quadrat was recorded fortnightly. Since species population showed different primary stages at the same temporal point (sampling day), therefore, to avoid phenophase overlapping and to decrease noise, the existence of a particular stage was considered if, in a quadrat, more than 5% of the individuals showed that primary stage; if more than 20% quadrats showed the particular stage in a plot; and if more than 30% plots showed the particular stage in a site. The principal phenophase initiation for a species was considered on the day when its corresponding lowest primary phase was recorded in at least one plot for both ES and LS sites. Its end was the day when the next principal phenophase was recorded or when species individuals in that principal phenophase were recorded less than 5% after its initiation. The principal phenophase duration was calculated from the day of phenophase initiation to the day of phenophase end.

Statistical analysis – The Kruskal–Wallis test, a nonparametric equivalent of analysis of variance (ANOVA), was used to compare species phenophase duration between ES and LS sites and between different growth forms. Pairwise differences from the Kruskal–Wallis test were tested with the Dun post hoc test to determine the significant differences. The average duration of principal phenophase for different species and growth forms in different sites (ES and LS) was calculated by averaging the phenophase duration of species growth forms. Data were first tested for parametric assumptions such as normality and homogeneity of variance prior to using nonparametric analysis. Analysis was completed using PAST (PAleontological Statistics) software.

3 Results

The growth period in alpine meadow lasted for 6 months from mid-April to mid-October. Overall, eighty species were recorded during the study period, of which 36 species were common to both ES and LS sites (Fig. 2, 3, 4

and 5). In the present study, 22 species were common to all communities, 8 species each were common to 4 and 3 communities, 13 were common to two communities, and 29 were unique to a single community, respectively (See Kumar and Adhikari 2023). Twenty species of these common species, namely *Anaphalis nepalensis* (Spreng.) Hand.-Mazz., *Bistorta affinis* (D. Don) Greene, *Bistorta amplexicaulis* (D. Don) Greene, *Carex setosa* Boott, *Danthonia cachemyriana* Jaub. & Spach, *Gaultheria trichophylla* Royle, *Gentiana argentea* (Royle ex. D. Don), *Gerbera gossypina* (Royle) Beauverd, *Geranium wallichianum* D. Don ex Sweet, *Geum elatum* Wall. ex G. Don, *Kobresia duthiei* C. B. Clarke, *Oxygraphis polypetala* Hook. f. & Thomson, *Pedicularis hoffmeisteri* Klotzsch., *Plantago ovata* Forssk., *Ranunculus hirtellus* Royle, *Rumex nepalensis* Spreng., *Saussurea taraxacifolia* (Lindl. ex Royle) Wall. ex DC., *Sibbaldia cuneata* Edgew., *Sibbaldia parviflora* Willd., *Taraxacum officinale* F. H. Wigg., and *Trachydium roylei* Lindl., contributed most to the abundance in both ES and LS sites.

Plant communities composition – Kumar and Adhikari (2023) have studied the phytosociological characteristics of plant communities at Tungnath in detail and the gist is presented. Forbs were the major contributor (90%) in all the communities. The pattern of growth forms was in following order: short basal (31) > semi-basal (26) > erect leafy (20) > dwarf shrub, climber, and tussock (1 each). The species mostly exhibited an intermediate growth cycle and primarily characterized by hemicryptophytes (70%). The species count was similar between the ES and LS sites for *Trachydium*, *Polygonum*, and *Danthonia* communities; however, the Mixed Herbaceous and Mixed *Danthonia* communities exhibited greater variation in species count between ES and LS sites.

The species richness for the communities ranged between 4.5 and 21.8 species m^{-2} throughout the growing period, maximum with Mixed Herbaceous community (8.9–21.8 species m^{-2}) and minimum with *Polygonum* community (4.5–13.3 species m^{-2}). The diversity was generally higher in LS sites (1.46 to 3.21) than in ES sites (1.02 to 2.83) in all communities, except for specific months and communities where ES sites showed higher diversity. Based on density, *Trachydium roylei* was the dominant species in the *Trachydium*, Mixed Herbaceous and Mixed *Danthonia* communities, while *Ranunculus hirtellus* and *Danthonia cachemyriana* dominated the *Polygonum* and *Danthonia* communities, respectively.

Phenophase response to snowmelt – Among common species, the onset of three principal phenophases viz. vegetative, reproductive and fruiting in a majority of species responded strongly to early snowmelt. The vegetative and reproductive phenophases were observed in the early growth

period (May and June), while senescence was observed from September onwards. In both ES and LS sites, the vegetative phase dominated in June, the reproductive phase in August, and the senescence phase in late September and October. As per the BBCH scale, the maximum species were in different primary stages of the vegetative phase during May and June (76.3 and 60.0%, respectively), while the majority of species flowered between June (33.3%) and September (30.8%) with a peak in August (76.8%).

Growth form and species response to early snowmelt –

Overall, the average vegetative phase duration for ES sites was less than LS sites for erect leafy species and short basal species, while it was longer for semi-basal species. The reproductive phase duration was much more in ES sites than LS sites in all growth forms, while the fruiting phase duration was marginally higher in ES sites for erect leafy and semi-basal species, but was longer in LS sites for short basal species. The duration of senescence was shorter in ES sites for erect leafy and short basal species, while it was much longer in ES sites for semi-basal species (Table 1).

To see the influence of snowmelt timing on phenophase duration, the Kruskal–Wallis test was conducted for different phenophases and growth forms. Between sites (ES and LS), no significant differences were observed for phenophase duration between individual stages of vegetative, flowering, fruiting and seeding stages. Similarly, the Kruskal–Wallis test was also conducted between growth forms, where no significant differences were observed for phenophase duration between individual stages of vegetative, fruiting and senescence stages but a significant difference was observed for the reproductive stage ($p < 0.04$). Dun post hoc test showed reproductive phase duration differed significantly between erect leafy species and short basal species ($p < 0.01$).

Erect leafy growth form – Of the total 20 erect leafy species, 10 species were common to both ES and LS sites, while 5 species each were unique to ES sites and LS sites (Fig. 2). Among common species, the vegetative phase started in early May for 7 species (*Bistorta affinis*, *B. amplexicaulis*

(D.Don) Greene, *Gaultheria trichophylla* Royle, *Ranunculus diffuses* DC., *R. hirtellus*, *Rumex nepalensis* Spreng., and *Tanacetum dolichophyllum* (Kitam.)) in both ES and LS sites, while remaining species (*Bupleurum candollei* Wall. ex DC., *Euphrasia himalayica* Wettst., and *Polygonum polystachyum* Wall. ex Meisn.) started in June.

Among common species, germination and vegetative phase was first recorded in ES sites for all species, except *Bupleurum candollei* and *Polygonum polystachyum* where the germination was initially in LS sites (Fig. 2). The reproductive phase was initiated first in ES sites, except in *Bistorta affinis*, *Polygonum polystachyum* and *Rumex nepalensis*, which were recorded first in LS sites. *Ranunculus hirtellus* and *R. diffuses* showed two distinct reproductive phases, first in May–June and second during August. The fruiting phase was recorded in only 6 common species. It initiated early in ES sites than LS sites in *Gaultheria trichophylla* and at the same time in ES and LS sites in *Rumex nepalensis*. It was recorded only in 3 species (*Bupleurum candollei*, *Euphrasia himalayica* Wettst., and *Ranunculus hirtellus* Royle) in ES sites and only in one species (*Bistorta affinis* (D.Don) Greene) in LS sites. The senescence phase was initiated early in LS sites (Fig. 2).

Among 10 species unique to ES and LS sites, the early-growing species (germination before June) only showed vegetative phase, except *Veronica cana* Wall. ex Benth., which completed its life cycle. The reproductive phase was recorded in all unique species except *Pimpinella diversifolia* DC. and *Aconitum heterophyllum* Wall. ex Royle. The fruiting phase was only recorded in *Veronica cana* in ES sites and *Phlomis bracteosa* Royle ex Benth. and *Prunella vulgaris* L. in LS sites. Among late-growing unique species (germination after May), the senescence was not recorded for *Bistorta macrophylla* (D.Don) Sojak, while it was present in remaining species (Fig. 2).

Semi-basal growth form – Eleven, out of 26 semi-basal species were common in both ES and LS sites, while 5 species were present only in ES and 10 species in LS sites (Fig. 3). Among common species, 6 species (*Anaphalis nepalensis* (Spreng.) Hand.-Mazz., *Carex setosa* Franch. & Sav., *Dactylorhiza hatagirea* (D.Don) Soo, *Kobresia duthiei* S.R.Zhang, *Pedicularis hoffmeister* Klotzsch, and *Saussurea taraxacifolia* (Lindl. ex Royle) Wall. ex DC.) germinated in May, 2 species (*Geranium wallichianum* D.Don ex Sweet and *Poa annua* L.) in June, and 3 species (*Geranium collinum* Stephan ex Willd., *Goodyera repens* (L.) R.Br., and *Selinum vaginatum* (Edgew.) C.B.Clarke) in July. The germination and vegetative phase happened simultaneously in both ES and LS sites for both early and late-growing species, except *Geranium wallichianum* and *Goodyera repens* (Edgew.) C.B.Clarke, which germinated first in ES sites (Fig. 3). The reproductive phase was initiated first in *Anaphalis*

Table 1 Phenophase duration (Average days) of different species growth forms (ES: Early Snowmelt; LS: Late Snowmelt)

Growth Form	Site	Vegetative	Reproductive	Fruiting	Senescence
Erect Leafy	ES	43.9 ± 17.8	51.9 ± 23.1	9.6 ± 10.3	19.2 ± 12.12
	LS	53.9 ± 30.2	43.6 ± 12.1	8.1 ± 5.8	22.0 ± 7.7
Semi-Basal	ES	47.8 ± 22.1	39.2 ± 22.2	11.6 ± 13.2	26.4 ± 11.5
	LS	38.0 ± 20.6	34.1 ± 17.4	9.1 ± 4.7	16.9 ± 13.2
Short Basal	ES	35.4 ± 20.0	35.4 ± 22.7	13.5 ± 18.8	20.8 ± 14.5
	LS	42.7 ± 23.5	32.4 ± 20.3	17.0 ± 26.7	24.9 ± 10.1



Fig. 2 Major phenophases (vegetative: dark olive, reproductive: dark red, fruit/seed development and maturation: orange accent, and senescence: dark grey) of different erect leafy growth form species in early (E) and late (L) snowmelt sites

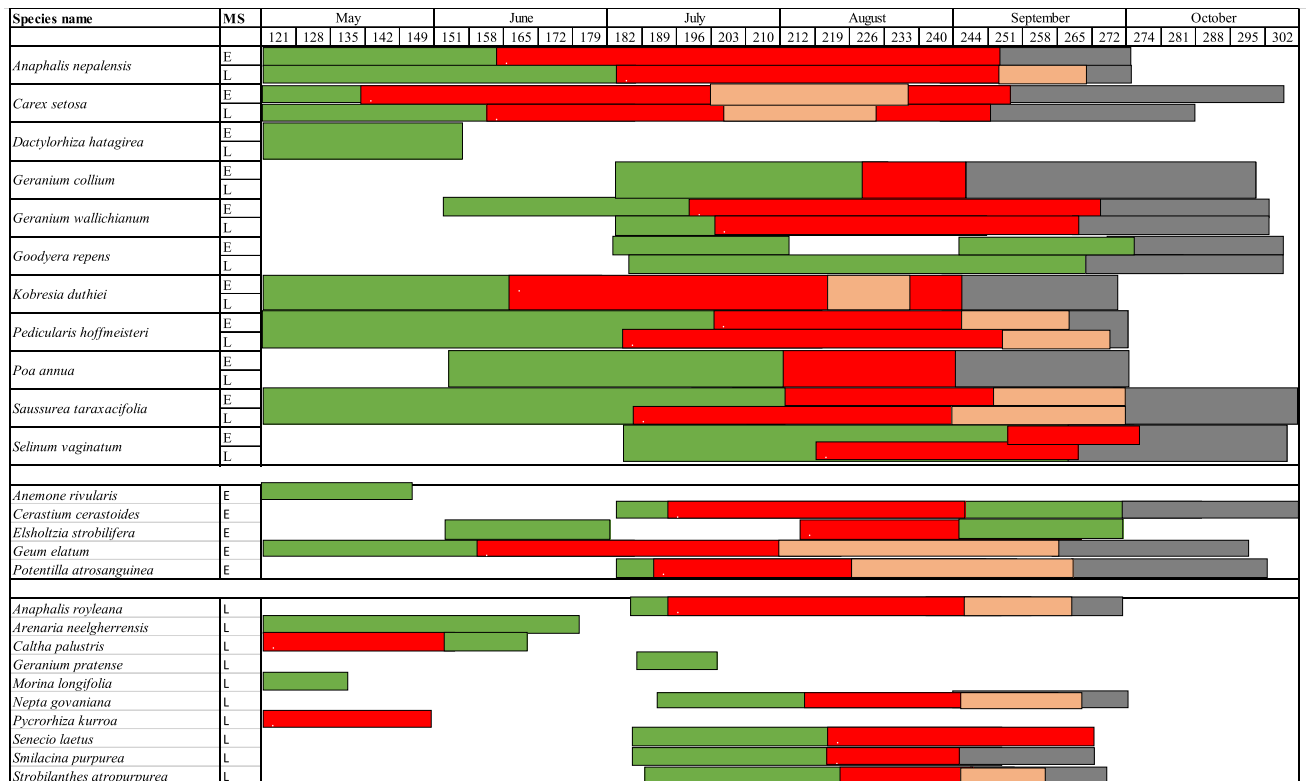


Fig. 3 Major phenophases (vegetative: dark olive, reproductive: dark red, fruit/seed development and maturation: orange accent, and senescence: dark grey) of different semi-basal growth form species in early (E) and late (L) snowmelt sites

nepalensis, *Carex setosa* and *Geranium wallichianum* in ES sites and in *Pedicularis hoffmeisteri*, *Saussurea taraxacifolia*, and *Selinum vaginatum* (Edgew.) C.B. Clarke in LS sites. The reproductive phase was initiated at same time in both ES and LS sites in *Kobresia duthiei* and *Geranium collinum*, while it was not recorded for *Goodyera repens*. The fruiting phase was recorded early in *Carex setosa* and *Pedicularis hoffmeisteri* in ES sites and in *Kobresia duthiei* at the same time in both ES and LS sites. In *Saussurea taraxacifolia*, the fruiting was recorded first in the LS site, while in *Anaphalis nepalensis*, it was recorded only in the LS site, respectively. The senescence phase was initiated in both ES and LS sites at the same time or early in LS sites for all common species (Fig. 3).

Among 15 species unique to ES and LS sites, the 6 early-growing unique species only showed either vegetative phase or reproductive phase or both with only one species (*Geum elatum* Wall. ex G. Don) in the ES site completing its' life cycle. The majority of late-growing unique species in ES and LS sites completed their life cycle, except *Elsholtzia strobilifera* (Benth.) Benth. and *Geranium pratense* L. Among 9 late-growing species, the reproductive phase was recorded in all except *Geranium pratense*, while the fruiting phase was recorded only in 2 ES unique species and 3 LS unique species. Among species unique to ES or LS sites, the senescence was recorded for only eight species (Fig. 3).

Short basal growth form – Of the total 31 short basal species, 14 species (*Cyananthus lobatus* Wall. ex Benth., *Fragaria nubicola* (Lindl. ex Hook.f.), *Gentiana argentea* (Royle ex D. Don) Royle ex D. Don, *Gerbera gossypina* (Royle) Beauverd, *Jurinea dolomiaea* Boiss., *Oxygraphis polypetala* Hook.f. & Thomson, *Plantago ovata* Forssk., *Polygonum vacciniifolium* Wall. ex Meisn., *Potentilla lineata* Trevir., *Sibbaldia cuneata* Edgew., *S. parviflora*, *Taraxacum officinale* F.H. Wigg., *Trachydium roylei* Lindl. and *Viola biflora* L.) were common to both ES and LS sites. By comparison, 10 and 7 species were present only in ES or LS sites, respectively (Fig. 4).

Among common species, 8 species were early-growing species, of which 3 germinated before May and 5 in May (*Fragaria nubicola* (Lindl. ex Hook.f.) Lacaita, *Plantago ovata*, *Sibbaldia cuneata*, *Taraxacum officinale* and *Trachydium roylei*), while 6 species were late-growing with 3 species (*Cyananthus lobatus*, *Polygonum vacciniifolium* and *Potentilla lineata* Trevir.) germinating in June and 3 species (*Gerbera gossypina*, *Jurinea dolomiaea* and *Viola biflora* L.) in July (Fig. 4). The species germinated first in ES sites; therefore, the vegetative phase started first in ES sites in all species. *Gentiana argentea*, *Oxygraphis polypetala* and *Sibbaldia cuneata* started germination immediately after snowmelt before the start of the growing season (May), therefore their vegetative phase in the early-growing season was not

recorded. The reproductive phase was first initiated in either ES sites or simultaneously in ES and LS sites in all common species, except *Fragaria nubicola* as it disappeared in ES sites by end of May, and only showed vegetative phase. *Fragaria nubicola* and *Oxygraphis polypetala* showed two distinctive reproductive phases in both ES and LS sites, first in May–June and second during August–September, while *Sibbaldia parviflora* showed two distinct reproductive phases only in ES sites, first in May and second during June–July. Of 14 common species, the fruiting phase was recorded for only 9 species, of which 5 species initiated early in ES sites, simultaneously in 2 species in both ES and LS sites and only in ES sites for *Trachydium roylei* and in LS sites for *Fragaria nubicola*, respectively. For most of common species, the senescence phase was first recorded in ES sites except in *Jurinea dolomiaea* and *Taraxacum officinale*, which senesced first in LS sites (Fig. 4).

Among 17 unique species, 4 were early-growing species and 13 were late-growing species. The early-growing species only showed vegetative phase and then disappeared by May end except *Potentilla anserina* L. which reappeared early July completing its life cycle, but did not show fruiting phase. The majority of late-growing unique species in ES and LS sites entered the reproductive phase. Two distinctive reproductive phases were recorded in *Polygonum delicatulum* Meisn., a unique species to ES sites, first in July and second in August–September. The fruiting phase was recorded for 4 and 3 unique species for ES and LS sites, respectively. Among species unique to ES or LS sites, the senescence was recorded for only 13 species (Fig. 4).

Other growth forms – *Danthonia cachemyriana* Jaub. & Spach (a tussock) was present in both ES and LS sites. The germination took place in early and mid-July in ES and LS sites, respectively. The reproductive phase started in early August in both ES and LS sites. The fruiting phase was not observed and senescence started in mid-September. *Cassiope fastigiata* (Wall.) D. Don (dwarf shrub) was present only in ES sites for a month (August) and showed only the vegetative phase. *Codonopsis rotundifolia* Benth. (climber) germinated in early July, flowering lasted from mid-July to mid-August and senescence by late August (Fig. 5).

Changes in herbaceous phenology over a period – To understand changes in the herbaceous phenology of wide-ranging species with respect to snowmelt timing in the study area, the phenophase of common species in the present study is contrast with the study conducted by Adhikari and Kumar (2020) for treeline herbaceous species. The timberline region became snow-free by about two weeks before the alpine region. Fifty-two species were common in both studies. Among these species, 20 species were common to both ES and LS sites at treeline and alpine zones, while 10 species



Fig. 4 Major phenophases (vegetative: dark olive, reproductive: dark red, fruit/seed development and maturation: orange accent, and senescence: dark grey) of different short basal growth form species in early (E) and late (L) snowmelt sites

Species name	Site	May					June					July					August					September					October				
		121	128	135	142	149	151	158	165	172	179	182	189	196	203	210	212	219	226	233	240	244	251	258	265	272	274	281	288	295	302
<i>Cassiope fastigata</i>	E																														
<i>Codonopsis rotundifolia</i>	E																														
<i>Danthonia cachemyriana</i>	E																														
	L																														

Fig. 5 Major phenophases (vegetative: dark olive, reproductive: dark red, fruit/seed development and maturation: orange accent, and senescence: dark grey) of different growth forms (dwarf shrub, climber and tussock) species in early (E) and late (L) snowmelt sites

were common in treeline but ES sites only in alpine, 13 species were common in treeline but LS only in alpine, 4 species were in ES only in treeline but common in alpine, 2 species were in ES only in both treeline and alpine and 3 species were in LS only in both treeline and alpine zones (Table 2).

In contrast to treeline, the average initiation and duration of phenophase of 52 common species in alpine communities showed a delay and shortening of 21.3 and 21.2 days for the vegetative phase, 8.7 and 13.1 days for the reproductive phase, advances in initiation of fruiting and seeding

and senescence phases (11.4 and 3.6 days) and shortening of duration by 2.8 and 14 days for fruiting and seeding and senescence phases, respectively. However, based on the majority of species contributing to the abundance in communities throughout the growing season, the phenophase initiation advanced for all phenophases in alpine communities, while the duration was shortened for vegetative, fruiting and seeding and senescence phases and lengthened only for the flowering phase (Table 2).

Table 2 Comparison of phenological events of species in alpine with treeline (Adhikari and Kumar 2020) in Tungnath region

Species	Sites\Phenophase	Vegetative		Reproductive		Fruiting and Seeding		Senescence	
		A/D	E/S	A/D	E/S	A/D	E/S	A/D	E/S
Erect Leafy									
<i>Bistorta affinis</i>	ES/ LS	0	- 30	24	29	28	28	- 14	- 14
<i>Bistorta amplexicaulis</i>	ES/ LS	0	- 21	21	28	0	0	- 7	- 30
<i>Gaultheria trichophylla</i>	ES/ LS	0	0	- 8	0	64	0	- 21	
<i>Polygonum polystachyum</i>	ES/ LS	14	0	23	30	0	0	14	- 28
<i>Ranunculus hirtellus</i>	ES/ LS	0	0	- 14	0	Present 28		28	- 5
<i>Impatiens scabrida</i>	ES	-31	- 26	0	- 21	0	0	21	- 14
<i>Myriactis wallichii</i>	ES	-42	- 35	7	- 21	0	0	14	- 7
<i>Pimpinella diversifolia</i>	ES	5	- 51	Absent					
<i>Veronica cana</i>	ES	21	0	- 28	- 56	7	- 21	21	
<i>Epilobium royleanum</i>	LS	- 60	- 35	- 30	- 19	Absent0- 14		28	28
<i>Prunella vulgaris</i>	LS	- 68	- 50	- 7	- 7	0	8	0	- 13
<i>Swertia ciliata</i>	LS	- 53	- 32	- 21	- 39	Absent0- 14		17	- 21
Semi-Basal									
<i>Anaphalis nepalensis</i>	ES/ LS	0	- 35	27	5	21	- 7	30	0
<i>Carex setosa</i>	ES/ LS	0	- 7	7	0	0	- 23	7	0
<i>Geranium wallichianum</i>	ES/ LS	- 21	- 13	28	- 25	Absent- 40		7	0
<i>Goodyera repens</i>	ES/ LS	38	- 33	Absent				21	0
<i>Kobresia duthiei</i>	ES/ LS	0	- 20	7	14	- 7	- 33	7	- 23
<i>Pedicularis hoffmeisteri</i>	ES/ LS	60	23	35	37	21	15	- 7	- 30
<i>Poa annua</i>	ES/ LS	- 30	- 5	- 21	0	Absent- 38		14	- 14
<i>Selinum vaginatum</i>	ES/ LS	- 62	- 35	0	- 30	0	0	16	0
<i>Anemone rivularis</i>	ES	No change		Absent					
<i>Cerastium cerastoides</i>	ES	28	- 28	0	0	0	0	- 35	0
<i>Geum elatum</i>	ES	0	- 29	30	7	30	- 23	14	0
<i>Potentilla atrosanguinea</i>	ES	- 60	- 67	7	- 7	14	7	7	0
<i>Anaphalis royleana</i>	LS	- 63	- 56	- 7	- 29	Present 28		21	- 14
<i>Arenaria neelgherrensis</i>	LS	0	- 8	Absent					
<i>Caltha palustris</i>	LS	0	- 21	Absent					
<i>Morina longifolia</i>	LS	7	- 29	Absent					
<i>Nepeta govaniana</i>	LS	- 33	0	- 80	- 50	Present 29		- 33	- 41
<i>Senecio laetus</i>	LS	27	- 7	14	7	0	0	7	- 21
<i>Smilacina purpurea</i>	LS	- 30	7	- 7	- 36	0	0	31	0
Short Basal									
<i>Cyananthus lobatus</i>	ES/ LS	21	28	- 7	0	0	- 16	14	14
<i>Fragaria nubicola</i>	ES/ LS	0	7	- 21	- 22	- 21	- 45	- 7	0
<i>Gentiana argentea</i>	ES/ LS	No change		0	0	0	0	Absent	
<i>Gerbera gossypina</i>	ES/ LS	- 30	- 21	- 16	- 46	0	0	Absent	
<i>Oxygraphis polypetalata</i>	ES/ LS	No change							
<i>Potentilla lineata</i>	ES/ LS	- 30	- 35	- 14	0	8	- 21	23	- 10
<i>Sibbaldia cuneata</i>	ES/ LS	0	0	13	- 26	20	0	30	30
<i>Taraxacum officinale</i>	ES/ LS	0	26	28	0	0	0	14	14
<i>Trachydium roylei</i>	ES/ LS	0	0	12	33	17	15	14	10
<i>Viola biflora</i>	ES/ LS	- 37	- 22	- 24	- 31	7	37	- 30	- 7
<i>Corydalis cornuta</i>	ES	21	21	0	16	Present 16		21	- 15
<i>Euphorbia stracheyi</i>	ES	74	0	Absent					
<i>Polygonum delicatulum</i>	ES	- 45	- 22	- 17	- 9	Present 7		- 40	- 61
<i>Primula denticulate</i>	ES	- 63	- 48	- 74	- 25	0	0	0	- 20

Table 2 (continued)

Species	Sites\Phenophase	Vegetative		Reproductive		Fruiting and Seeding		Senescence		
		A/D	E/S	A/D	E/S	A/D	E/S	A/D	E/S	
<i>Hemiphragma heterophyllum</i>	LS	0	0	0	11	– 6	0	– 14	– 14	
<i>Lysimachia proliifera</i>	LS	– 63	– 18	– 66	– 36	0	0	– 22	– 20	
<i>Parnassia nubicola</i>	LS	– 14	7	– 18	0	Absent– 30		– 30	– 37	
<i>Polygonum filicaule</i>	LS	– 60	– 31	– 74	– 102	Present 37		– 30	– 37	
<i>Potentilla polyphylla</i>	LS	– 62	– 31	– 58	– 27	– 31	0	Absent		
<i>Primula edgeworthii</i>	LS	0	– 8	Absent						
Tussock										
<i>Danthonia cachemyriana</i>	ES/LS	– 65	– 57	7	14	0	0	– 7	– 7	

ES/LS: Common to early and late snowmelt sites in both alpine and treeline; ES: Early Snowmelt Site; LS: Late Snowmelt Site; A/D: Advance/Delay and E/S: Extension/Shortening in the alpine. A negative sign denotes Delay and Shortening of phenophases in the alpine region with respect to the treeline

4 Discussion

Snowmelt water is a precursor for initial plant growth in alpine regions during the early-growing season, which was received by the area in the form of snowfall (4 days during November–December in 2016 and 35 days during January to April in 2017). In the present study, the snowmelt in ES sites started by end of March 2017 and the sites became snow-free by the second week of April, while snowmelt in LS sites started in early April and all sites became snow-free by the last week of April. As per BBCH scale, the majority of species present directly transitioned to stage 3 from stage 0–1, as they showed rapid stem elongation/shoot development. The starting of vegetative phase in the present study was observed, but the end could not be discernible as per the BBCH scale. Similar findings were reported by Adhikari et al. (2020) for treeline herbaceous communities in Tungnath. Therefore, whenever species individuals reached up to 5% of the next stage, the termination of the previous stage was considered. The senescence showed an abrupt increase in ES and LS sites in September, especially in LS sites.

The timing of different phenophases, especially reproductive, varied between different communities, i.e. less variability was observed between communities like *Trachydium* and Mixed Herbaceous, Mixed *Danthonia* and *Danthonia* occupying similar habitats and more variability between communities occupying different habitats like *Polygonum* and Mixed *Danthonia*. This is expected as many authors (Körner 1999; Wipf et al. 2009; Bjorkman et al. 2015; Adhikari and Kumar 2020; Kudo 2020) also reported a strong correlation between flowering and snowmelt timing determined by local community assemblage, i.e. species organize themselves as per snow-depth (snowmelt timing) gradient across communities. Furthermore, the differences between phenophase initiation between communities can be further accredited to

different micro-climatic conditions including orography, as was observed by Nautiyal et al. (2001) in an alpine meadow.

Early snowmelt advanced phenology – The species in alpine communities showed a positive response to phenophase initiation in response to early snowmelt in the present study. The phenophases among a majority of species initiated in ES sites across the communities initially show the dominant effect of early snowmelt timing on vegetative phenology and reproduction. This result is consistent with many other active snow manipulation experiments (Dunne et al. 2003; Sherry et al. 2007; Wipf et al. 2009), which suggests snowmelt timing has a large influence on phenology, especially vegetative (Semenchuk et al. 2016) and reproductive (Wipf et al. 2009) phenophases. This is especially true in relation to the advancement of the first flowering day or flowering in general of early-growing species (Abeli et al. 2012; Bjorkman et al. 2015). Although the majority of species' phenophase initiation showed a positive response with snowmelt timing, the phenophase duration of species in present study did not show a significant relationship with early snowmelt. This suggests that the alpine species have high phenotypic plasticity in phenophase initiation with respect to snowmelt timing and at the same time they show conservation in duration, which is consistent with many other warming experiments (Price and Waser 1998; Semenchuk et al. 2016; Jabis et al. 2020). However, some long-term experiments done in alpine regions in the Tibetan plateau (Yu et al. 2010) and ITEX experiment (Oberbauer et al. 2013) showed changes (shortening and lengthening) in flowering duration (duration between the first and last flowering day) with respect to experimental warming, similar to temperate grasslands where experimental warming resulted in longer phenophase duration (Reyes-Fox et al. 2016).

The germination in multiple species (*Aconitum sp.*, *Bistorta sp.*, *Caltha palustris* L., *Gentiana argentea*, *Kobresia*

duthiei, *Lysimachia prolifera* Klatt, *Oxygraphis polypetala*, *Picrorhiza kurroa* Royle ex Benth., *Ranunculus* sp., *Trachydium roylei*) was initiated as soon as the area was snow-free by mid-April. The growth of these early-growing species was fast and some of them immediately entered into the reproductive phase in early May, e.g. *Carex setosa*, *Plantago ovata*, *Sibbaldia parviflora* and *Trachydium roylei* were recorded in the bud development stage, while *Caltha palustris* L., *Gentiana argentea*, *Oxygraphis polypetala*, *Picrorhiza kurroa*, *Trachydium roylei* and *Gaultheria trichophylla* Royle in the flowering stage. This is probably due to an increase in soil moisture and microhabitat temperature, however, the role of soil moisture in advance or cessation of flowering is still debatable as some studies found that it has a minimum role in flowering (Dunne et al. 2003; Sherry et al. 2007). However, Dorji et al. (2013) reported its immediate negative influence on reproductive initiation in lieu of soil dry down due to warming. Gehrman et al. (2021) reported the early snowmelt without an increase in temperature. Most of the early-growing species with short growth cycle (less than 3 months) flowered early for reproductive success, thereafter building reserve for next season (Kimball et al. 2014). Early flowering in early-growing species may also decrease competition with long growth cycle species (more than 4 months) for reproductive success as they avoid early spring initiation to avoid damages from freezing events (Gezon et al. 2016).

Oftentimes, frost damage was also recorded simultaneously with germination in ES sites forcing the individuals to senescence resulting in false growth start before May. It was interesting to note that although these early-growing species started flowering before May in both ES and LS sites, none of the above species showed fruiting before May and did not enter fruiting phenophase at all. This was because although early snowmelt initiates early growth, it also exposes plants to extreme temperatures resulting in frost damages with drastic consequences for early-growing alpine plants including reduced leaf growth, survival and individual flowering (Baptist et al. 2010; Kawai and Kudo 2018) and at same time affecting individual reproductive success (Inouye 2008; Tonin et al. 2019). Therefore, early-growing species may take advantage of early snowmelt due to warming resulting in early flowering, they are at a risk of reduced reproductive potential/success (Wipf et al. 2009; Cooper et al. 2011; Gezon et al. 2016) than late-growing species as is evident from no to minimum fruiting recorded in these species.

Altitudinal difference in species phenology – With a change in altitude, the wide-ranging species search for apt habitats to take roots in adjusting their phenological events suited with the environment. To understand these changes, the species phenology of alpine species was compared with some common species of treeline (Adhikari and Kumar 2020). A

majority of common species showed advancement in the phenophase initiation, as well as shrinkage in phenophase durations in the present study. This is probably due to temperature exerting main control on the pre-flowering and flowering period with snowmelt timing and soil moisture also playing a secondary role as the trees and krummholz at timberline may provide a blanket effect for underlying herb species. In last few decades, the temperature of tree-lines is increasing across the globe (Tian et al. 2022), which can induce moisture stress and have negative influence on plant growth (Wu et al. 2019) as is observed in arctic tundra (Buntgen et al. 2015). However, in treeline, melt water from upslope region (snowmelt in alpine) may have curbed the above-mentioned negative influence making favourable conditions (warm and moist) for vegetative growth and simultaneously delaying reproductive phenophase. This is consistent with multiple manipulation experiments (Smith et al. 2012; Dorje et al. 2013; Jabis et al. 2020), which correlated high soil moisture with delay in flowering onset and termination.

The flowering period of plant species is controlled by snow cover (Krenová et al. 2022) only in early-growing species, while in late flowering plants flowering period is controlled by photoperiod (Schuchardt et al. 2021), thus determining reproductive success (Prieto-Benítez et al. 2021). This is evident from multiple early flowering species which showed only vegetative phenophase in the alpine, while they completed or showed at least two phases in treeline (Adhikari and Kumar 2020). Similarly, *Anaphalis royleana* Hook.f., *Corydalis cornuta* Royle, *Polygonum filicaule* Wall. ex Meisn, *Nepeta govaniiana* (Wall. ex Benth.) Benth. and *Ranunculus hirtellus* showed fruiting and seeding phase in alpine, while it was absent in the treeline. Contrary to this it was absent in *Epilobium royleanum* Hausskn., *Parnassia nubicola* Wall. ex Royle, *Swertia ciliata* (D.Don) B.L.Burt in alpine, but present in treeline (Adhikari and Kumar 2020). This may be due to the absence of overhead canopy cover which might result in not enough heat retention in alpine communities, thus affecting the growth of these plants in their respective alpine habitats.

Overtime, the alpine communities have developed complementary phenological strategies by spreading individual species' peak across the growing season (Sherry et al. 2007), which resulted in better resource utilization. However, in the study area, the temperature is getting warmer and soil moisture is constantly high. Over the period, an obvious change in environmental parameters (relative humidity, frost point, rainfall, temperature, decrease in diurnal range) has been reported (Adhikari et al. 2020). These rapid changes coupled with individual species sensitivity and adaptation strategies may give advantage to some species and disadvantage to others. Considering early snowmelt (by March) and less temperature variation (minima and maxima) during

the peak growth period in the past few years', multiple species have started their growth in early April (Adhikari et al. 2018; Adhikari and Kumar 2020). At the species level, phenological modifications in multiple species was also recorded, especially with respect to phenophase' onset and duration. This can be seen from the comparative shrinkage and delay of vegetative and reproductive phase duration, respectively, and the advancing of the senescence phase in alpine communities. Many workers have also suggested positive growth responses and advances in phenophase initiation with advances in snowmelt and temperature (Gehrmann et al. 2021; Schuchardt et al. 2021). The flowering and fruiting phenophases has also seen an advance/extension for initiation/duration in treeline compared to the alpine (Adhikari et al. 2018; Adhikari and Kumar 2020) and past studies (Sundriyal et al. 1987; Nautiyal et al. 2001; Vashistha et al. 2009, 2011). But multiple species have also shown delay/shortening in phenophases initiation/duration in timberline and ES sites, probably due to need of higher temperature requirement coupled with early snowmelt (Gehrmann et al. 2021) or these species may be showing a lagging effect to rise in temperature as reported by Mulder et al. (2017) and need detailed further study.

Two distinctive reproductive periods were recorded in 11 species either in ES or LS or both sites in alpine zone, of which *Fragaria nubicola*, *Oxygraphis polypetala*, *Prunella vulgaris*, *Ranunculus hirtellus* and *Trachydium roylei* also showed two reproductive periods in treeline zone (Adhikari and Kumar 2020), but were absent in past (Sundriyal et al. 1987; Nautiyal et al. 2001). The breaking of reproductive phase may indicate species resort to fruiting under stress (dominantly temperature), while favourable conditions (warm and moist) promote vegetative growth at the expense of reproductive growth (Adhikari and Kumar 2020). This may end up influencing individual species fitness and population dynamics within communities, causing migration, and changing interspecific interactions leading to changes in community structure as is reported by multiple studies (Parmesan 2006; Elzinga et al. 2007). The above phenological responses, if persistent for longer period, may alter reproductive success of species by either, disrupting plant-pollinator synchrony or by shortening of reproductive duration synchrony (Memmott et al. 2007; Liu et al. 2011), or increased synchrony between co-flowering species (Forrest et al. 2010). This may result in development of new assemblage patterns of plant communities over time.

The present study is an attempt to highlight the phenological behaviour of alpine herbaceous species in the west Indian Himalayan Region (IHR). The present study suggests that the early snowmelt (without any manipulation) greatly advances phenophase initiation in early growth species (between timberline and alpine and as well as ES and LS sites) while late growth species (germinating after June) are

not much influenced by snowmelt timing as they probably depend on temperature sums for triggering specific phenophase events. The study also finds phenophase duration to be conserved especially in late growth species, indicating less capitalisation on warmer seasons. These findings are consistent with most of the manipulation experiments conducted in the temperate or boreal forests with inconsistencies in experimental settings, as these experiments are mostly in-situ. The growing season duration in the alpine Himalaya is much longer (~6 months) than in other regions across the globe (3–4 months), therefore, the species responses may not comply with the findings of studies conducted in temperate or boreal alpine. The species modification of their phenophase across alpine communities already suggests a complex community response to climate change, with many species already splitting and modifying their reproductive phenophase to either avoid peak warming or to facilitate neighbour recruitment to maintain synchrony and reproductive success. These changes (advance flowering) if persistent, could affect reproductive success by altering plant-pollinator relationships in alpine communities, especially if pollinator phenology responds in a different manner to the changing environment. This may result in a different response across lifeforms, especially anthesis of herb species across different functional groups, which will result in completion and final adjustment between species for the resource (pollinators). This will ultimately affect community composition resulting in changes in assemblage patterns across sites. Furthermore, considering the wide elevation treeline range in IHR (~2000 m) and increasing temperatures across the globe. Therefore, there is a need to study the phenological sensitivity of herbaceous species in alpine across the IHR as species populations may show different responses under similar conditions due to orography as well as in context to snowmelt influence on community phenology especially introducing spatial variation across IHR, as the temporal relationship of plants (overlapping of anthesis, etc.) will evolve.

Acknowledgements The authors would like to thank Director and Dean, Wildlife Institute of India (WII) for providing necessary facilities and Uttarakhand Forest Department for granting permission to conduct field work in Kedarnath Wildlife Sanctuary. We also thank Prof. S. P. Singh for his suggestions. We would also like to thank Sachin MH and Manish Bisht for their help during the field work.

Author contributions Conceptualization was done by RK and BSA. Data curation, formal analysis, and writing were done by RK. Methodology was done by BSA and RK. Supervision and review were done by BSA.

Funding This study was funded by the National Mission on Himalayan Studies, MoEF & CC, New Delhi.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors have declared that no competing interests exist.

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