PATTERNS OF STRUCTURAL AND FUNCTIONAL ATTRIBUTES OF ALPINE MEADOWS AT TEMPORAL SCALE IN TUNGNATH, WESTERN HIMALAYA

A THESIS

Submitted by

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For the award of the Degree of

DOCTOR OF PHILOSOPHY

IN

WILDLIFE SCIENCES

Under the guidance of

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June - 2023

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CERTIFICATE

This is to certify that the thesis by Mr. Rahul Kumar entitled "**Patterns of Structural and Functional Attributes of Alpine Meadows at Temporal Scale in Tungnath, Western Himalaya**" is an original and independent research work submitted to the Saurashtra University, Rajkot (Gujrat), for the award of the degree **of Doctor of Philosophy in Wildlife Science**.

Mr. Rahul Kumar has put more than six semesters of research work embodied in this thesis under my guidance and supervision. The work presented in this thesis has not been submitted to any other University or Institute for the award of any degree, diploma or distinction.

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DECLARATION

I hereby declare that the work conducted under the thesis entitled "**Patterns of Structural and Functional Attributes of Alpine Meadows at Temporal Scale in Tungnath, Western Himalaya**", is a record of original research work, done by me and subsequently submitted for the award of the degree of doctor of Philosophy in Wildlife Science to Saurashtra University, Rajkot. This research work has been carried out under the guidance and supervision of Dr. Bhupendra Singh Adhikari, Scientist-G, Wildlife Institute of India, Dehardun. This work has not formed the basis for the award of any other degree, diploma, or any other qualification. I also declare that the thesis embodies my own work, analysis, observation and understanding and the particulars given in it are true to the best of my knowledge.

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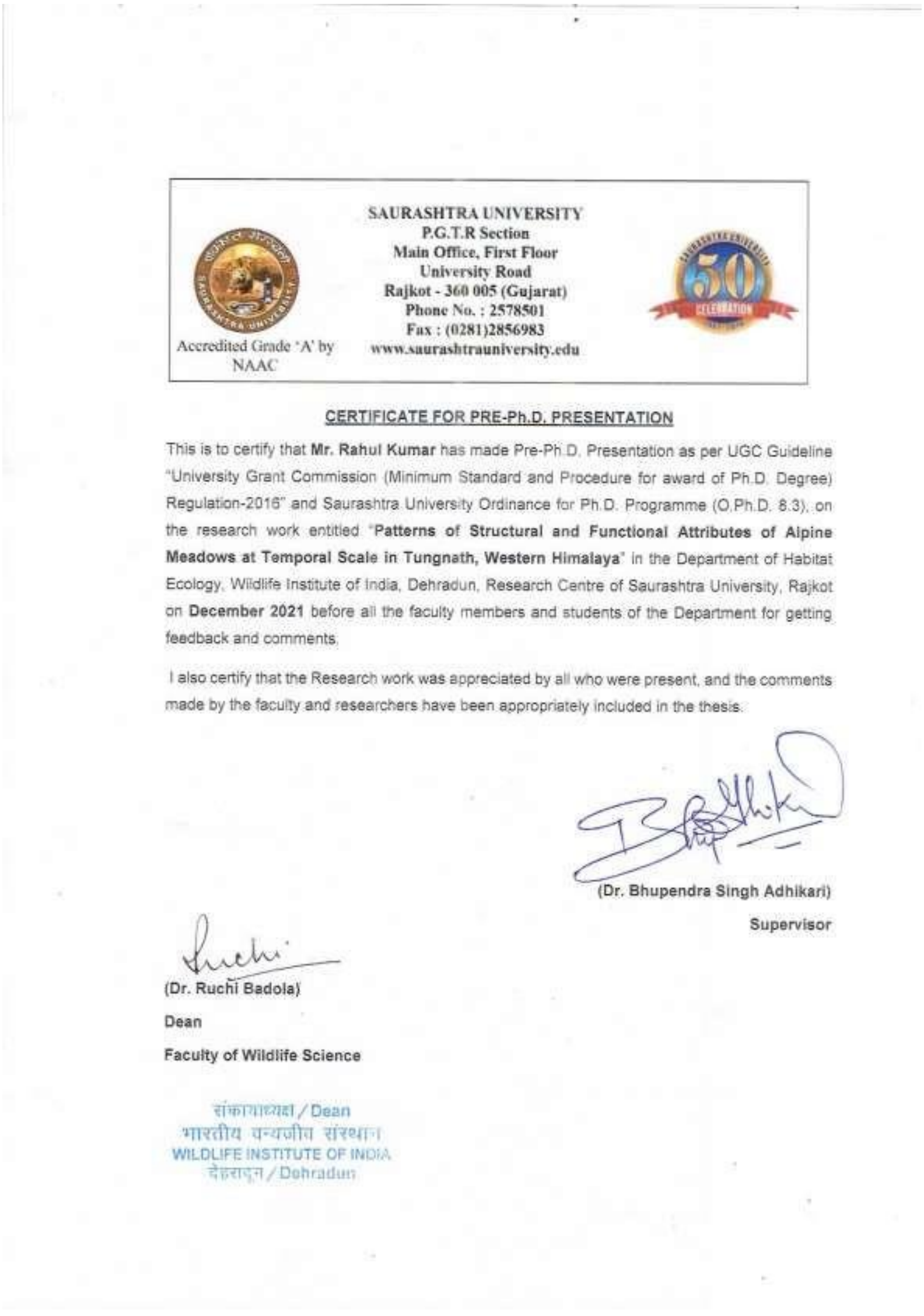

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I also certify that the Research work was appreciated by all who were present, and the comments made by the faculty and researchers have been appropriately included in the thesis.

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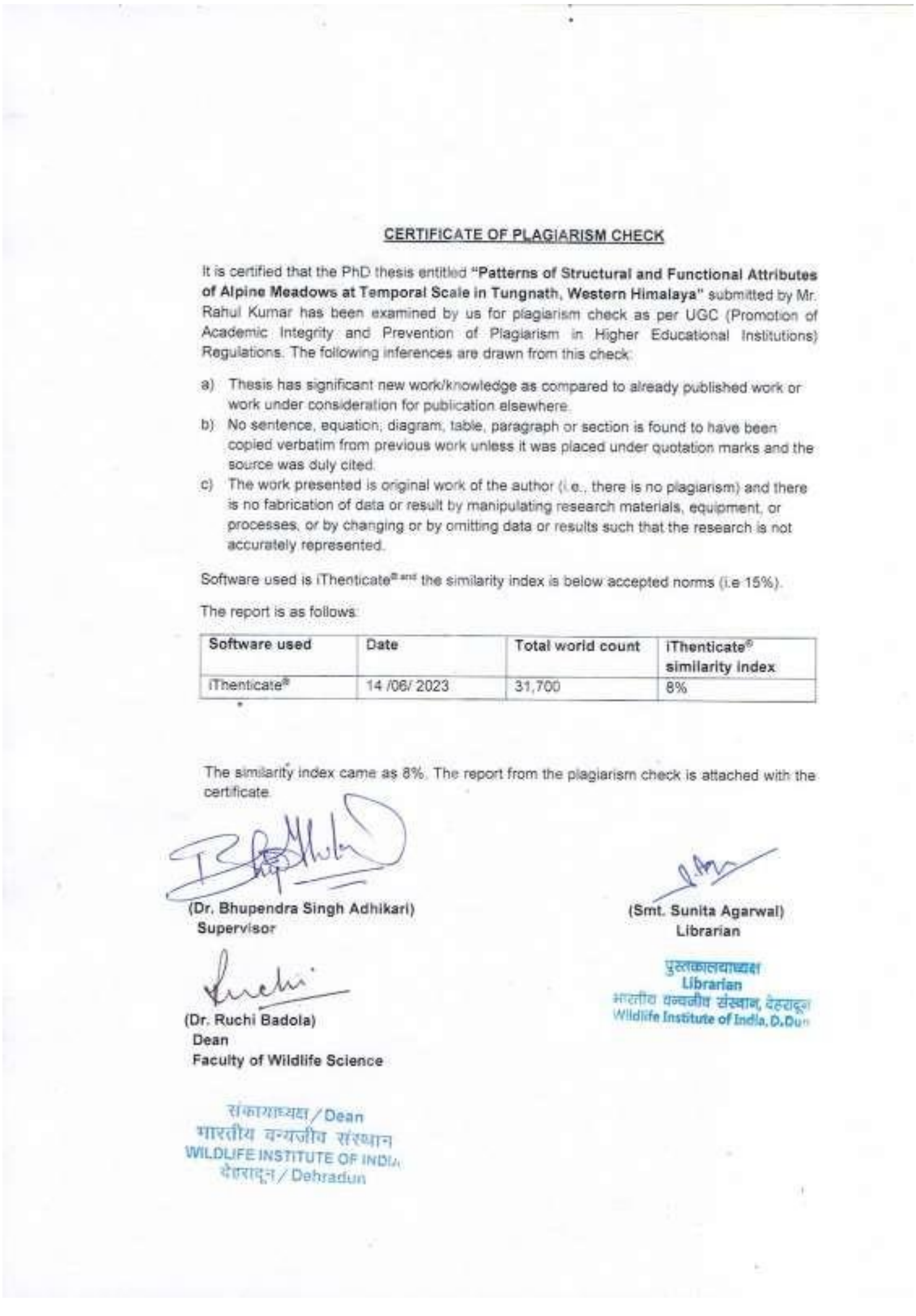

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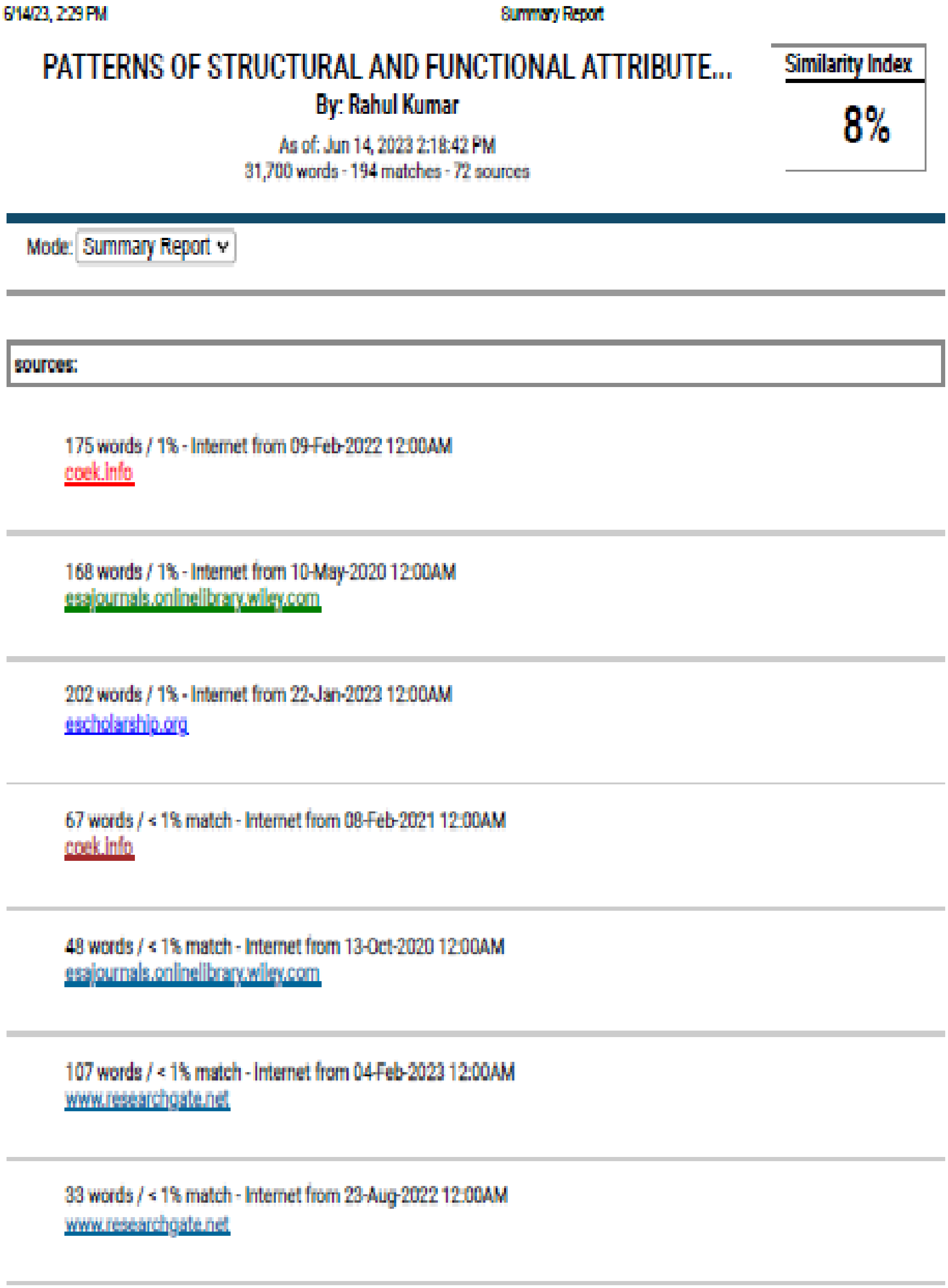

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The completion of the present study, "**Patterns of Structural and Functional Attributes of Alpine Meadows at Temporal Scale in Tungnath, Western Himalaya**," required immense dedication, countless hours of sampling, observations, and extensive computer work. It commenced in the small meadows of the southern part of Kedarnath Wildlife Sanctuary in the Western Himalaya, where I found myself deeply concerned about the uncertain future of range-restricted alpine plants due to climate change and anthropogenic pressures. However, this final work owes its realization to the invaluable inspiration, commitment, and guidance provided by my advisor, Dr. B.S. Adhikari, as well as the assistance of numerous individuals who contributed to the preparation and completion of this study.

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I would like to acknowledge that this thesis is part of a larger project entitled "Influence of micro-climatic variables on herbaceous plant communities at the timberline ecotone of Western Himalaya," under the supervision of Dr. B.S. Adhikari. This project is part of the broader umbrella project titled "Indian Himalayan Timberline Project," led by Prof. S.P. Singh of the Central Himalayan Environment Association and funded by the "National Mission on Himalayan Studies" by the Ministry of Environment, Forests, and Climate Change.

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Rahul Kumar

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Executive Summary

The current ongoing and projected warming trends across the globe have become a source of great concern for scientists and land managers. This calls for prioritizing studies for providing a solid understanding of the complex environmental changes, especially in relation to ecological processes. These changes can be easily studied and monitored in mountains, as climate change rapidly with an increase in altitude, heterogeneity of climatic and non-climatic factors over a short spatial scale reflects humongous variations, especially in floral diversity. This is especially true for alpine communities as the plant communities are present towards the mountaintops and are especially sensitive to associated changes in temperature and precipitation. The alpine zone covers a very small area globally, and the microenvironmental conditions govern spatial heterogeneity of alpine habitats as they are influenced by topography, climate, altitude, aspect and herbivory, resulting in high heterogenicity in neighboring alpine communities in the same mountain region. They are ecologically sensitive and easily interpretable indicators of biological diversity. Presently the high mountain alpine ecosystems are under threat such as biodiversity loss, habitat destruction and landscape modification as they are sensitive to climate variables, species pool and biogeographical region. Given global trends showing an expected upward shift of treelines and timberlines towards the alpine zone across the globe in both elevation and latitudes, it becomes imperative to study the effect of warming on ecological processes, especially understanding the dynamics of alpine communities and coupling with biosphere components to develop climate change indicators and mitigating strategies.

Although Indian Himalayan Region (IHR) is the youngest mountain ecosystem in the world, its strong altitudinal gradient, varied climatic conditions and diverse floral and faunal composition make it more susceptible to warming conditions. Furthermore, in IHR alpine regions the local communities have an intimate association with alpine grasslands in terms of cultural (local medicines), religious and economic points of view. The IHR alpines also have ecological significance as they are home to a large number of high-value medicinal, aromatic, and threatened plants. Several questions pertaining to the conservation and ecology of alpine

meadows in Himalaya remain, especially in relation to patterns of species diversity and richness and factors influencing them, and the response of different plant functional groups/communities to major or minor environmental variables. However, compared to studies done across the globe, especially in Europe and China, the studies focusing on Himalayan Alpine are pitiful low which is quite surprising. There are limited studies available on floristic linkages, patterns of diversity and functional aspects in various vegetation communities and landforms available. This is especially true for biotic and abiotic interactions to understand the underlying dynamics of alpine ecosystems in IHR.

The present study was carried out to understand the temporal changes in structural (richness, diversity, of alpine communities, above and belowground biomass, net biomass accumulation/productivity, and carbon density) and functional attributes (Phenology of species recorded) of different alpine plant communities of alpine meadows. This research work has not only generated information on baseline ecological characteristics of species and communities but also provides valuable management implications. The study is summarized in the following paragraphs.

The major objectives of the study are:

1. To study temporal changes in composition, structure, and functional attributes across various herbaceous communities,
2. To study the phenological patterns of dominant plant species across various communities in relation to abiotic parameters (rainfall/snowfall and temperature),
3. To assess the patterns of biomass production, carbon storage and sequestration in various communities and temporal dynamics of soil nutrients

The study was carried out in Tungnath region of Western Himalaya which lies on outer fringe of Kedarnath Wildlife Sanctuary in the upper catchment of the river Mandakini, a major tributary of the Alaknanda, which finally join the river Ganga at Devprayag. 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) in general and snowmelts during April-May between 3200-3300 m. The mean monthly temperature range between -5.5 in January and +31.3 °C in May, with an average of 4.8±1.8 °C during 2018 and the mean temperature of the warmest month July was 13.7±0.2°C in alpine meadows (3200-3600 m) in Tungnath. The study area falls under sub-alpine forest and alpine scrubs. The study area is categorized into four major zones based on vegetation type namely subalpine forest (up to 3200 m), timberline (3200-3300 m), treeline ecotone (3300-3400 m) intersperse with alpine zone, and alpine meadows (3300-3600 m). The intensive study area selected was alpine meadows present at and around Tungnath temple (ca. 2 km^{-2}), with krummholz layer formed by *Rhododendron campanulatum*, while ground layer consists of cushionoids herbs, grasses, sedges, and tussock, forming different communities based on microhabitat characterstics viz. embedded rocks and deep soil. Five communities namely *Trachydium*, Mixed Herbaceous, Mixed *Danthonia*, *Polygonum*, and *Danthonia* were selected and within each community three sites differing in the timing of snowmelt (7-14 days) were marked. In each site, a permanent plot of 50x50m was marked and 25, 1x1m quadrats were randomly laid in each microsite to record data on abundance and phenology of species fortnightly. The phenological changes in the species were monitored visually at fortnight interval following "Biologische Bundesanstalt, Bundessortenamt and CHemischeIndustrie"(BBCH) scale.

A total of 80 species were recorded across the sites of which 43 species each were present in Trachydium and Mixed Herbaceous communities, 46 in Mixed Danthonia, 54 in Polygonum and 51 in Danthonia respectively. Overall, the communities were dominated by forbs (90%) and perennial species (91.25%). Short basal (36.3%), semi basal (31.3%) and erect leafy (25%) growth forms of the species dominated in the study area. Most of the species had intermediate growth cycle (growth between 3-4 months, 48.8%) while hemicryptophytes (70%) were dominant life forms overall in the alpine communities. At the peak of species richness, 32.4% species were common to all communities. The species richness for communities across growing period ranged between 4-28 species m^{-2} while the total number of species ranged between 9-36 species in the sites across growing period and years. The total species in communities peaked between July and September in all communities during study period. The average plant density was higher for *Trachydium* and Mixed Herbaceous communities than other communities. The total plant density ranged between 52.4-894.8 individuals m^{-2}. In general, the diversity increased as growing season progressed in all communities and then declined. Out of total 80 species recorded, 24 species were present in all communities, 11 species were common to 4 communities, 9 to 3 communities, 10 to 2 communities and remaining 26 were unique to a single community.

On average all communities were 70% similar to each other. The average dissimilarity between sites in different communities was 32%, respectively with 20 species contributing about 70 % dissimilarity in all communities. In *Trachydium* community 3 species were responsible for more than 50% dissimilarity between sites, in Mixed Herbaceous and *Danthonia* communities 5 species, in *Polygonum* community 8 species, and in Mixed *Danthonia* community 7 species, respectively. To understand the role of edaphic factors in community and species distribution in the study area PCA and CCA analysis was conducted and it was found that soil texture and moisture content play a significant role in the distribution of communities, while snowmelt water, pH, and soil chemical properties do not. The overall semi-basal growth form species showed positive interaction with edaphic factors, while majority of short-basal growth forms showed their distribution dependence on available Potassium. Erect leafy growth forms however showed positive interaction to snowmelt, Nitrogen%, and Silt respectively.

The variance of species richness between communities was significant ($p < 0.05$) indicating microhabitats playing a significant role in richness and diversity of herbaceous plants in alpine meadows. The species diversity was significantly higher in early snowmelt sites than in late snowmelt sites in all communities. Over the period it is interesting to note that the percentage of hemicryptophytes (87.5%) have increased considerably in alpine region of the study area compared to the past might be due to better adaptation to grazing, trampling and other environmental factors. The warming-induced acceleration in species enrichment on mountain summits has been recorded at a continental scale in Europe and species richness, changes in community composition due to warming have also been observed over time and experimental treatments. The grazing and anthropogenic pressure is another leading component in alteration of species composition overtime as it encourages clonal growth of perennial grasses, low growing forbs and mat forming herbs. There is an obvious increase in relative humidity, frost point, rainfall, the maximum and minimum temperature and decrease in diurnal temperature in study area which not only increases the productivity of meadows but, with increase in anthropogenic pressure and grazing, also opens up them for an invasion by lower elevation species ultimately creating pressure on alpine species for upward migration.

Phenological modifications are one of the most serious warming impacts on, be it up land or lowland, alpine systems. The long-term monitoring already suggests advance of plant phenophase initiation during early spring and lengthening of phenophases in mid or late growing season with multiple studies reporting species specific interannual variations of reproductive phenophase in response to warming. This will lead to a long growing season with increased primary production and may have cascading effects on reproductive synchrony, pollinator interactions and birds and mammals depending on vegetative matter or seeds further limiting suitable habitat for endemics and cryophilic species Most studies in alpine and arctic ecosystems are manipulation experiments that either shows an advance in flowering phenology in response to warming via change in temperature or an advance in snowmelt while some shows delay in phenology due to increase in snow and additional warming.

At a community level as indicated by species number, during the study period (2017-2019), in general, the vegetative phase peaked in June for *Trachydium* and Mixed Herbaceous community and July for remaining communities, Mixed *Danthonia, Polygonum* and *Danthonia*. The flowering peaked in all communities in August while the fruiting peaked during September in *Trachydium* and Mixed Herbaceous communities and in August in Mixed *Danthonia Polygonum*, and *Danthonia* communities. It is important to note that the species common to more than two communities, their phenological behaviour varied depending on the prevailing micro-climatic conditions in the communities. Sometimes they showed all phases in all communities or sometimes a phenophase was absent in one community but present in other community. Some species initiated germination immediately after aboveground snowmelt and then disappered by July. The average vegetative and fruiting phase duration was longest in erect leafy growth form while fruiting duration was longest in short basal species.

The vegetative phase has extended for longer period particularly in few of the species, *Oxygraphis, Pedicularis, Anaphalis, Selinum* and *Potentilla*. It seems in alpine region; early snowmelt influences early spring phenology of herb species and may continue to influence overall phenology of species for entire season. Furthermore, some species have already advanced and lengthened their vegetative and flowering phenophases, especially those germinating during and immediately after beginning of snowmelt, could be due to warming of meadow and less difference in diurnal changes in temperature. Tungnath region in general has higher maximum and minimum temperature and precipitation which might be influencing extension and delayed termination of vegetative and flowering phases. The less variation in temperature (minima and maxima) during the peak growth period i.e., July-August might be helping species to remain in different phenophases for a longer period. Comparing community phenophase progression to the past studies in Tungnath, the vegetative phase duration has extended compared to past while fruiting and senescence has delayed and advanced respectively. In Tungnath, over a period (from 1984 to 2019) the duration of vegetative phenophase has increased from 2 months in 1984 to 5 months in the present study. The increasing warming temperature is also influencing species phenophase. Comparison of 13 species with past records indicates that phenophases duration of species have increased (especially vegetative growth period in 77% species and flowering in 69% species). Although the phenophase behavior of different species to the past varies, some species, especially alpine restricted, shows extended phenophases namely *Oxygraphis, Pedicularis, Anaphalis, Selinum, Potentilla, Geum* and *Parnassia*.

The alpine vegetation biomass and productivity (Above and Belowground) are major contributors to organic matter and has an important function in global carbon cycle. Due to colder climate alpine systems have slower decomposition rate and biochemical transformations, resulting in more liable soil organic matter and more soil carbon than lower elevations. The soil moisture availability and texture play a vital role in vegetative growth thus affecting biomass accumultion. The warming may alter soil organic matter depending on the type of alpine systems as warmer soils increase soil respiration. The small changes in soil organic carbon (SOC) stock pools in high altitude can have large implications for atmospheric CO_2 concentrations. But early snowmelt may cause disturbances in the necessary microbial communities causing intensification in microbial activities via changes in freeze thaw cycle, soil pH or moisture, leading to changes in edaphic conditions, thus changes in moisture regimes and summer precipitation in alpine may ultimately shifting alpine ecosystems into carbon sources or may cause changes in mineralization and nutrient pools. However, in the context of Western Himalaya there is a lack of baseline studies for temporal changes in biomass, productivity and carbon stock density as well as their response to warming climate in alpine regions. Therefore the present study deals with temporal changes happening in biomass, productivity, soil carbon and soil macronutrient in w*et al*pine meadows in Tungnath.

During the study period the conditions were similar and seasonal periodicity for growth and biomass accumulation did not vary significantly. In general, the aboveground biomass (AGB) increased from May to September in all communities, after which it declined sharply, whereas the belowground biomass (BGB) decreased from May to July after which a sharp increase was recorded in all communities. The live shoot biomass increased till August and September, the total standing dead biomass increased August onwards, and the litter mass declined till July after which it started increasing subsequently and a sharp increase was recorded in October for all communities. There was lack of litter mass in May in all communities which shows that dead attached shoots of previous growing season did not transfer to litter component in winter due to snow fall. The BGB to AGB ratio varied between 0.37:1 and 5.1:1 during study period. It decreased as growing season progressed, after which it increased sharply from September to October. Among communities, 75% of AGB was accumulated by July end and average accumulated BGB was 60 % of the total biomass. The higher per cent accumulated biomass in BGB is similar to reported by multiple authors for alpine meadows in Himalaya.

The aboveground net production was lowest for *Polygonum* community and highest for Mixed Herbaceous community during study period while there was no fixed pattern for below ground productivity. The above and belowground carbon stock density followed same pattern as AGB and BGB of communities. To calculate the carbon sequestered by the communities the monthly aboveground and belowground net primary productivity (NPP) of communities was first converted into gram carbon m^{-2} and total carbon sequestered by the community was determined by summation of monthly sequestered carbon stock (CS) at the end of growing season. The highest carbon sequestered was by *Trachydium* community (480 g m^{-2}) and minimum was by *Polygonum* community (122.6 g m^{-2}), respectively.

Among communities, a general pattern of increase in soil pH as the growing season progressed, was observed in *Trachydium,* Mixed Herbaceous and Mixed *Danthonia* communities, while a decrease was recorded for *Polygonum* and *Danthonia* communities. The highest and lowest soil pH was recorded in Mixed Herbaceous community. Among communities the Nitrogen content (N%) was highest in *Polygonum* community (0.64%) and lowest in *Trachydium* community (0.44%). The available Phosphorus (P%) was highest in Mixed *Danthonia* (0.52%) and lowest in Mixed Herbaceous (0.28%) community. The potassium was highest in Mixed *Danthonia* and *Danthonia* communities (0.20%) and lowest in Mixed Herbaceous (0.12%) community. The higher per cent of N in *Polygonum* community is due to presence of community in marshy soil. Also, the community is used by locals as a livestock camp. Soil organic carbon (SOC %) increased as the growing season progressed in the *Trachydium* community and a constant decrease in the Mixed *Danthonia* community. In *Polygonum* and *Danthonia* communities SOC % first increased till the early and mid-growing season and declined afterwards, while an opposite trend was recorded for the Mixed Herbaceous community. The soil organic carbon stock followed same trend as SOC %. The highest soil organic carbon was recorded in Mixed *Danthonia* (359.5 t ha^{-1}) and lowest carbon stock was in *Danthonia* community (119.7 t ha^{-1}).

Increasing global temperature affects species richness, distribution, phenology, and physiology, posing a major threat to floral ecosystems and biodiversity. Phenological observations in present study revealed advances and lengthening of vegetative and flowering phases in response to warming which is similar to recent studies showing that species have been advancing and prolonging their growth and flowering phases due to climate warming and snow cover and depth playing a crucial role in preserving soil nutrients and microbial function. Also, the average AGB recorded in present study is higher than Greater Himalaya as whole, Rudranath, Bedni – Ali, Tapovan, Nandanvan, Pawalikantha, Bhojbasa, and Gaumukh, and similar to studies conducted in Valley of Flowers National Park while the peak community BGB values were higher than that reported for Rudranath, Bedni-Ali, and lower than Tapovan, Nandanvan, Bhojbasa, and Gaumukh. Previous studies have not specifically examined carbon stock density in alpine ecosystems of the Himalayas, but similar research has been conducted in the Qinghai-Tibetan plateau. The above-ground carbon stock in the present study is higher than that in alpine meadows of northern China grasslands, while the below-ground carbon stock is higher than northern China grasslands but lower than Tibetan meadows. Soil organic carbon (SOC) stock in high altitude ecosystems plays a significant role in the global carbon cycle and is sensitive to climate warming. Alpine soils have more easily decomposable organic matter, and even small changes in the SOC pool can have significant implications for atmospheric CO2 concentrations. High altitude warming is expected to increase litter decomposition rate accelerating carbon turnover which could be mitigated by change in community composition or early snowmelt, as decrease in decay rate have been observed in early snowmelt sites leading to higher carbon content.

Climate change particularly endangers organisms with fragmented habitat distribution, especially those with narrow ecological ranges, which may lead to extinction. Cold-adapted species are especially vulnerable in high alpine meadows due to rapid warming, potentially exceeding their adaptive capacity. The alpine zone covers 9 % of the total area in Greater Himalaya. In Uttarakhand, there are 5 protected areas encompassing alpine region namely Nandadevi National Park (NP), Valley of Flowers NP, Govind Pashu Vihar NP, and Wildlife Sanctuary (WS), Kedarnath WS and Askot WS of which except Nandadevi NP and Valley of Flowers NP, others are heavily exploited leading to habitat degradation. Exploitative practices such as unsustainable pastoralism, excessive extraction of medicinal plants, pilgrimage pressure, and poorly planned developmental projects are major challenges faced by alpine ecosystems in the Greater Himalaya. Therefore, it is crucial to understand species and community ecology to identify stress mechanisms and develop effective conservation strategies in Greater Himalaya. Numerous studies have shown correlations between temperature, precipitation, productivity, plant interactions, spatial patterns, and species richness in alpine ecosystems outside of the Himalayas. However, knowledge about the Himalayan alpine regions is limited due to their micro-topographic variations, altitudinal gradient, temperature range, and precipitation patterns, which make it challenging to isolate specific variables responsible for environmental-species relationships. These issues can lead to smaller population sizes, habitat degradation, and local extinctions, putting immense stress on alpine meadows. To address these challenges and conserve alpine meadows, it is essential to study sustainable land use practices adopted by local communities and develop conservation plans tailored to specific sites and species.

1. General Introduction

1.1 Introduction

Mountains are rugged structures difficult to delineate in a landscape, but defining “mountain terrain” is crucial for the assessment of plant species diversity and their response to climate warming. Different inventories of mountain terrain use criteria such as ruggedness and rapid changes in elevation over short distances. Consequently, a terrain may be classified as a mountain in one definition while being considered a hill in another. To encompass the *spatial* extent of mountainous areas, various definitions have been proposed over the years by Meybeck et al. (2001), Sayre et al. (2018), and Price et al. (2019). Presently, the most commonly applied approaches for delineating mountains are those provided by Kapos et al. (2000) for the United Nations Environmental Program (UNEP) under the World Conservation Monitoring Centre (WCMC), defining 24% of the land surface as mountains (Fig. 1.1); Korner et al. (2011, 2017) for the Global Mountain Biodiversity Assessment (GMBA), serving as a reference for global biogeographic comparisons in mountains, defining 12.5% of the land surface as mountains (Fig. 1.1); and Karagulle et al. (2017) for the United States Geological Survey (USGS), following the concept developed by Hammond (1954), which identifies 30% of the land surface as mountains excluding Antarctica. Regardless of the specific definition used, the interaction between land structure (topography) and climate factors (solar radiation, wind, snow distribution) in mountainous regions creates a diverse habitat that contributes to the richness of plant species found in mountains (Korner, 2004). Ruggedness and rapid elevation changes, which lead to variations in climate, have repeatedly been identified as key determinants of the impact of climate change on mountain biota (Loarie et al., 2009; Scherrer and Korner, 2011).

Mountains are unique as climate rapidly changes with increase in altitude over a short horizontal distance, along with vegetation and hydrology. They show high heterogeneity of climatic and non-climatic factors over a short spatial scale which reflects in variation of diversity for both flora and fauna. Mountain ecosystems are rich in biodiversity especially due to varied climatic and geographic contrasts within short geographic distance, with half the human population depending upon them for basic necessities, water and cultural values (Korner *et al*. 2017). With the projected rise in global temperatures caused by increasing CO_2 levels, and considering the sensitivity of high-altitude mountain ecosystems to global temperature changes (Korner, 1998; Paulsen *et al.* 2000; Korner and Paulsen 2004; Danby and Hik, 2007; Korner, 2012), it is anticipated that alpine timberlines and treelines will migrate to higher altitudes and latitudes in the coming years. This upward shift poses a potential risk to alpine ecosystems situated at mountain peaks. Mountains are unique areas to detect, assess and understand climate change and related impacts (Beniston,2003). It is widely acknowledged that climate change is not just about averages, but also of extremes. The scientists and land managers have become concerned about ongoing and projected effects of current warming trends and its potential threats to biodiversity and ecosystem services.

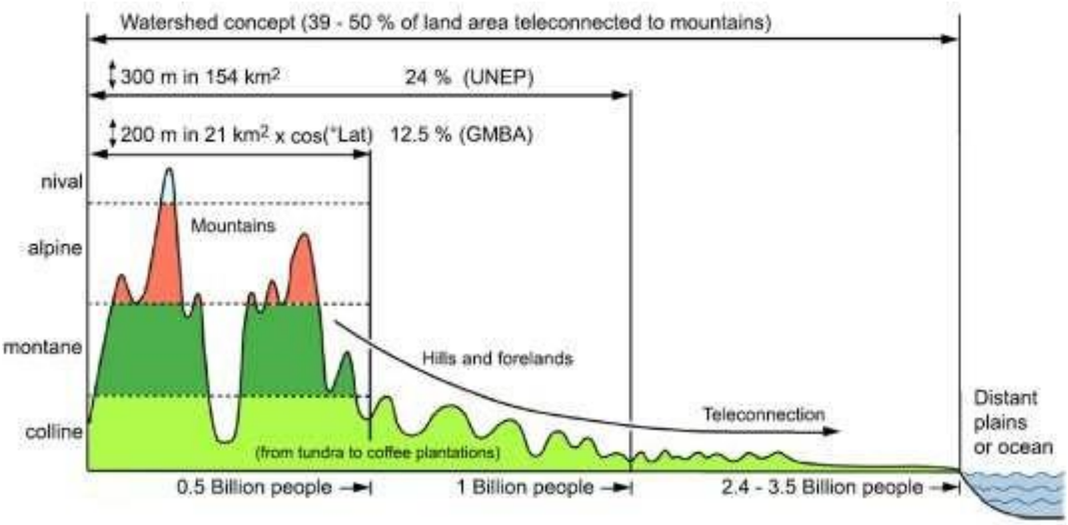


Figure 1.1. The pictoral representation of definitions provided by UNEP and GMBA for mountainous terrain based on ruggedness (Courtesy: Korner et al. 2021)

1.2 The Alpine Zone

Globally, the alpine life zone covers a small land fraction (2.6%) outside Antarctica (Korner, 2007), a terrain including lot of barren land or glaciated areas with actual plant cover less than two percent globally.

The term "*alpine*" originates from the Latin word "*albus*," which means white, and originally referred to the peaks of the Alps in Northern Italy (Love,1970). It is now commonly used to describe the region above the natural treeline in high mountains. While the physical characteristics of alpine ecosystems vary depending on factors such as proximity to the equator, slope, aspect, topography, solar radiation, and patterns of summer and winter precipitation, the term "*Alpine*" is commonly in use for “the treeless areas above a low-temperature determined treeline in the high reaches of mountains”. These areas are characterized by low temperatures, limited rainfall, blizzards and snowstorms, strong winds, and high levels of ultraviolet (UV) radiation (Malik and Nautiyal, 2016). The physiognomy of the vegetation, species composition, and species richness vary across alpine regions.

Microenvironmental conditions govern spatial heterogeneity of alpine habitats resulting in high heterogenicity in neighboring alpine communities in same mountain region or even within same mountain site (Amagai et al. 2018).

The distribution of plant species within the alpine region is primarily influenced by climate or ecological factors associated with climate. The alpine plant communities composition, similar to many other ecosystems, is shaped by a combination of biotic (living organisms) and abiotic (non-living) elements (Cavieres *et al*. 2014). In the alpine environment, extreme abiotic conditions such as prolonged periods of snow cover, strong winds, large temperature fluctuations, limited soil development, early and late frosts, and dry-down of soil moisture during the growing season play a significant role (Jabis, 2018) in communities’ composition. Organisms in this environment must possess adaptations to thrive in the short growing season and highly fluctuating seasonal conditions to emerge, grow, and reproduce successfully.

Alpine plant communities predominantly consist of perennial species interlinked to the challenging environmental conditions. However, across most alpine areas, there is a commonality in the vegetation structure, characterized by dwarf shrubs, tussock or mat-forming grasses, cushion and rosette-forming herbs, succulents, forbs, and low-lying shrubs

(Rawat, 2007). Due to the harsh climate, plants in these regions have developed specific adaptations, resulting in dwarfed, stunted, woolly, or spiny characteristics, and creating a mosaic of different life forms (Walker et al., 1994). The structure and composition of alpine communities exhibit seasonal fluctuations and are adjusted to the synchronization of periodic phenomena among individual plants (Kershaw, 1973). Although alpine species are highly adapted to their environment, their response to climate change remains uncertain.

1.3 The Himalayan Alpine

The Indian Himalayan Region (IHR) is youngest mountain ecosystem in the world, with its alpine landscape lined as islands on high mountains, separated from each other by deeply incised traverse valleys with diverse vegetation. The alpine zone is the uppermost vegetated area in the Himalaya with either distinct or diffusedly demarcated treeline towards its lower elevation (3200±200m in Western and 3800±200 in eastern Himalaya, Rawat, 2007). At treeline, tree species can be observed growing as shrub-shaped, low, prostrate, or stunted individuals commonly referred to as ‘krummholtz’ which allows them to benefit from self-protection and moderate heat retention within dense branches. As one moves further towards the alpine zone, these shrub-shaped trees gradually transition into alpine vegetation, which consists of closely intertwined mats of shrubs, bogs, fell-fields, and herbaceous meadows depending on orography of the region.

The Himalayan alpine zone is known for its rich diversity of both flora and fauna, aesthetics, biological and cultural values. The alpine vegetation is of considerable interest to ecologist on account of presence of many rare plants and their different adaptation patterns to differing extreme conditions (Rawat, 2007) but remoteness, lack of resources, difficult terrain and underdeveloped infrastructure puts strain on extent of research conducted in the region. Thirty three percent of Himalayan region comes under alpine landscape, of which 25.8% is vegetated and remaining 7.2% is perpetual snow (Lal *et al*. 1991). Forty eight percent of the total geographical area of western Himalaya falls in alpine zone and forms 90% of Indian alpine region (Rawat, 2007). This alpine zone proportion is 24.11% of the total geographical area of the Uttarakhand state, which is less than its other western Himalayan states of Himachal Pradesh, Jammu & Kashmir and Ladakh (Rawat, 2007).

The Garhwal Himalaya, which constitutes a significant portion of the Himalaya range, is particularly susceptible and fragile in the face of local, regional, and global climate changes. Given its pronounced altitudinal variations, diverse climatic conditions, and rich array of plant and animal species, this region experiences heightened impacts from climate change. Many studies in the latter half of twentieth century has seen extensive survey of Garhwal Himalaya (Adhikari *et al*. 2012), but the literature is quite sparse for alpine zones in Garhwal Himalaya. The alpine zones below 'nival' region are known as "Bugyals" or alpine meadows in the local dialect and exhibit either gradual or steep slopes characterized by the prevalence of herbaceous or graminoid vegetation. These grasslands have an intimate association in terms of cultural (local medicines), religious and economic (used as summer grazing ground by local and migratory herders) point of view for local communities. Additionally, these meadows possess high ecological significance, harboring a diverse array of highly valuable medicinal, aromatic, threatened and endangered plant species (Hamilton and Radford, 2007).

There have been numerous studies conducted on the flora and ecology of various regions in the western Himalayas, however, there is a noticeable scarcity of research focused on comprehending different aspects of alpine ecology. While several studies have investigated the floral and ecological aspects of timberline vegetation in the Garhwal Himalayas (Adhikari, 2004; Adhikari *et al*. 2012, 2018; Rawal and Pangtey, 1994; Rawal and Dhar, 1997; Maikhuri *et al*. 1998), there is a lack of research on the alpine landscape in the Himalayas. This gap in knowledge hinders our understanding of the dynamics of alpine ecosystems in the Indian Himalayan Region (IHR), as it lacks baseline data and comprehensive assessments of biotic and abiotic interactions.

One prominent possibility for alpine and subalpine ecosystems is that global climate change will lead to earlier snowmelt and the initiation of plant growth, flowering, and fruiting in angiosperms further bringing subsequent changes on biomass production and soil mineral cycling at high altitudes. Furthermore, these ecological and phenological events may impact plant communities by altering the relative success/fitness of species with different growth and reproductive strategies (Price and Waser, 1998).

1.4 Rationale of the study

Fluctuations in global surface temperature have already had discernible ramifications on diverse physical and biological systems across the globe. Should this rapid rate of temperature escalation persist, the repercussions could surpass initial predictions. The Garhwal Himalaya, an important component of the vast Himalayan mountain range, exhibits heightened sensitivity and vulnerability to shifts in the local, regional, and global climate. The region's pronounced variation in elevation, wide-ranging climatic conditions, and abundant biodiversity makes it highly susceptible to an intensified impact from climate change.

In Himalaya, the climate change may influence interspecific interaction, particularly mutualistic relations between animals and plants. Although research on this topic is not evenly distributed across taxa or geographical regions (Korner, 2009), there has been a growing number of publications focusing on alpine ecosystems in general, with a significant emphasis on the effects of climate change (Chen *et al*. 2014; Guisan *et al*. 2019; Halloy and Mark, 2003; Pickering *et al*. 2014; Rumpf *et al*. 2019). Most of these studies originate from Europe (Gottfried *et al*. 2012; Lamprecht *et al*. 2018; Lenoir *et al*. 2008; Parolo and Rossi, 2008; Pauli *et al*. 2007; Rumpf *et al*. 2018; Scherrer and Korner, 2011; Steinbauer *et al*. 2018), while North America contributes approximately 20%, and the rest of the world contributes less than 10%. The majority of research in this field concentrates on either alpine (Gottfried *et al*. 2012; Pauli *et al*. 2012) or treeline (Harsch *et al*. 2009; Holtmeier and Broll, 2005; Korner, 1998) vegetation.

However, there is a noticeable lack of studies discussing different facets of structural and functional attributes of alpine ecology in the Himalaya. In fact, it has been estimated that only 6% of total alpine ecological studies encompass Central Asia, including the Himalayas (Korner, 1999). Numerous questions regarding the conservation and ecology of alpine meadows in the Himalayas remain unanswered, especially in relation to patterns of species diversity and richness and factors influencing them, and the response of different plant functional groups to major or minor environmental variables. There is a need to study the response of various alpine species to changes in specific environmental factors especially in relation to their phytomass and phenology, species invasion, inter and intra species competition, and adaptation strategies being adopted to tackle warming.

Addressing these questions is crucial, as alpine communities are structured on relatively small scale compared to other ecosystems due to their existence on micro topographic relief. Furthermore, in temperate alpine systems, the multiple communities coexists in close vicinity due to slight variations of slope, aspect, depressions, snowmelt timing; producing dry meadow, wet meadow, or snow-bed communities in small perimeter. It is especially true for island like alpine meadows at mountain top, surrounded by timberlines. Therefore, there is a need for specific studies oriented towards baseline data development and underlying ecological processes and responses towards the structural and functional characteristics of the alpine ecosystems. Since Himalaya have broad orography in alpine zones with each region having unique eco-climatic conditions, therefore multiple studies are required to understand the influence of warming climate on temporal changes in phenology, biomass, and soil nutrients on the sensitive Himalayan alpine ecosystem, especially for developing management and conservation strategies for their protection.

The primary objective of the current study is to investigate the temporal changes in structural and functional attributes of different alpine plant communities of wet meadows of Tungnath, which is located on the fringe of Kedarnath Wildlife Sanctuary (KWLS). The study focuses on assessment of temporal patterns of species richness and diversity in selected alpine communities, temporal patterns of phenology of species recorded in alpine plant communities, temporal changes in above and belowground biomass and net biomass accumulation/productivity, temporal organic carbon fluctuation and sequestration potential of selected communities, and temporal dynamics of macronutrients (NPK) in selected communities of alpine meadows at and around Tungnath.

The major objectives of the study are:

1. To study temporal changes in composition, structure, and functional attributes across various herbaceous communities,
2. To study the phonological patterns of dominant plant species across various communities in relation to abiotic parameters (rainfall/snowfall and temperature),
3. To assess the patterns of biomass production, carbon storage and sequestration in various communities and temporal dynamics of soil nutrients

1.5 Organization of the Thesis

Chapter one describes the background, objectives, and literature review on the floristics, vegetation ecology, and structural and functional aspects of alpine meadows of IHR.

Chapter two covers the description and introduction of the study area including its location, topography, climate, geology, soil type, vegetation, flora, fauna, local community, and land use practice.

Chapter three deals with the first objective of the study. This chapter gives an elaborative account of temporal changes in structural attributes such as structure, community composition and other functional attributes (relationship between communities and soil chemical properties) across selected communities of alpine meadows.

Chapter four focuses on the second objective, to study the phenological patterns of dominant plant species across various communities in relation to abiotic parameters. This chapter gives an account of temporal changes in phenological behaviour of communities and herbaceous species.

Chapter five assess the patterns of biomass production, carbon storage and sequestration in various communities and temporal dynamics of soil nutrients. This chapter discusses temporal changes in biomass patterns, carbon stock, sequestration potential, and physico – chemical parameters (soil) of selected communities in the study area.

Chapter six discusses the major findings of the study.

2. Study Area

2.1 Introduction

The study was conducted in Tungnath region (latitude N 30°29'–30°30' and longitude E 79°12'–79°13') situated in the Western Himalaya, India (Fig. 2.1). Tungnath lies on outer fringe of Kedarnath Wildlife Sanctuary, in the upper catchment area of the Mandakini River, a tributary of the Alaknanda, which finally join the river Ganga at Devprayag. Akashkamini, a source of springwater from a small microwatershed of Chandeashila peak (3680 m) from the study area forms a tributary of river Mandakini. From the Chandrashila peak, on a clear day panoramic views of the Himalayan mountain range, including the snow-capped peaks of Nanda Devi, Panchachuli, Banderpoonch, Kedarnath, Chaukhamba, and Neelkanth on one side, while providing a glimpse of the Garhwal valley on the opposite side.

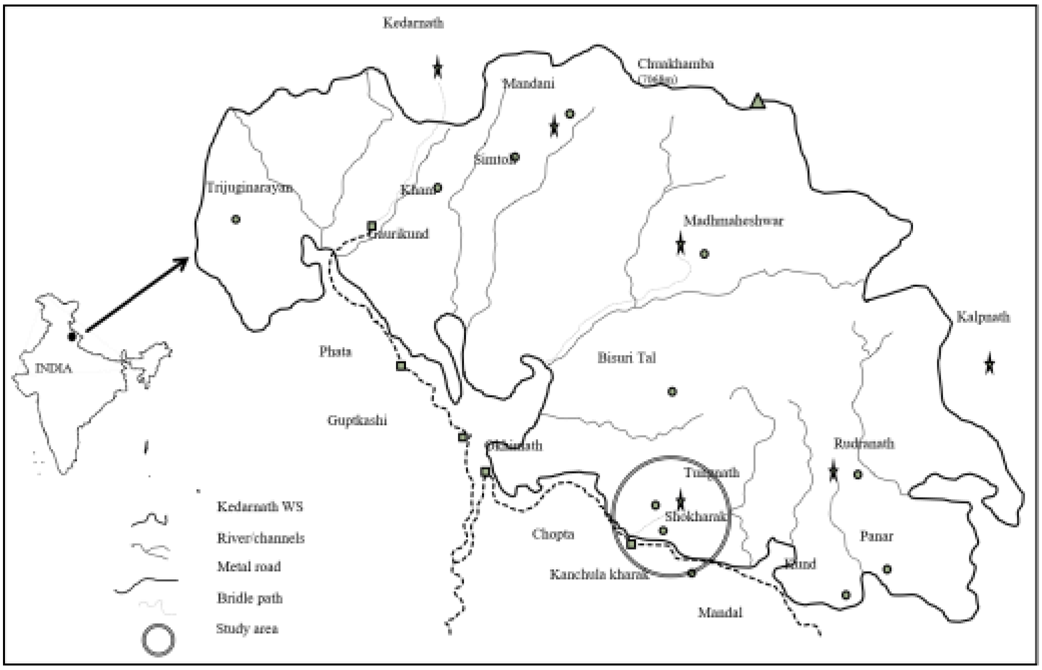


Figure 2.1. Map showing location of study area

2.2 Forest Types

The study site is located within the sub-alpine forest and alpine scrub vegetation zones, as classified by Champion and Seth (1968). The study area can be broadly categorized into four major zones based on vegetation type. These zones are as follows:

2.2.1 Sub-alpine forest

The subalpine forest in the study area starts from 2800 m upward and upto 3200m. It is characterized by dominant tree species such as *Abies* spp*., Quercus semecarpifolia*, *Acer* spp., while the understory canopy is mainly dominated by *Rhododendron arboreum* and *Rhododendron campanulatum* followed by *Viburnum erubescens* and *Sorbus* species. In the shrub layer, species such as *Rhododendron campanulatum, R. barbatum, Viburnum* spp., *Rosa sericea, Rubus niveus, Salix* sp. can be found while *Impatiens spp, Selenium, Ligularia, Rumex, Polygonum, Persicaria wallichii, Thamnocalamus spathiflorus* etc. represent the herb layer.

2.2.2 Timberline ecotone

Timberline ranges between 3200–3300 m and is characterized by specific tree species distribution. On north to north-west facing slopes, *Betula utilis* and *Abies spectabilis* are the dominant species, while *Q. semecarpifolia* and *R. arboreum* prevail on south to south-west facing slopes (Rai et al., 2012b). In areas with steep rocky slopes, the timberline consists of dwarf and stunted individuals of *R. arboreum*, which adapt to the harsh climatic conditions by exhibiting slow growth. The understory of timberline ecotone is inclusive of stunted individuals of *Rhododendron campanulatum* forming a '*krummholz*' layer. Other prominent shrub species within this zone encompass *Lonicera* spp., *Rubus niveus*, *Salix denticulata*, *Rosa sericea*, *Berberis jaeschkeana* and *Viburnum grandiflorum*. In drier slopes and rocky outcrops, *Cotoneaster microphylla* and *Juniperus indica* are prevalent. The timberline area also exhibits the presence of rare orchid taxa such a. *Cypripedium elegans, C. cordigerum, Neottia pinetorum* and *Platanthera leptocaulon* (Rai *et al*. 2012).

2.2.3 Treeline ecotone (Krummholz)

The “treeline ecotone” in Tungnath starts occurs betwween 3300 and upto 3400m intersperse with alpine zone. This ecotonal region is predominated by '*krummholz*' layer of *Rhododendron campanulatum*, a dominant small tree species of the region, interspersed with few individuals of *Sorbus, Abies, Acer* and *Betula* species. *R. anthopogon* and *R. lepidotum* are present as the dwarf shrubs in the ecotone are. The '*krummholz*' layer serves as a micro-habitat for varius herbaceous species as well as habitat to wild animals.

2.2.4 Alpine meadow

The ground layer vegetation of the meadow comprises cushion-like herbs, grasses, and sedges. It includes species such as *Acomastylis elata* (*Geum elatum*)*, Anaphalis* spp., *Anemone* spp., *Bistorta* spp., *Carex inanis, Danthonia cachemyriana, Gaultheris trichophylla, Trachydium roylei, Sibbaldia cuneata, Tanacetum longifolium* etc. This area also supports many high value medicinal and aromatic plants like *Potentilla spp.* (Bajradanti), *Dactylorhiza hatagirea* (Panchaule, Hatajadi), *Morina longifolia* (Himalayan whorlflower), *Primula* spp., *Rheum webbianum* (Rhubarb), *Aconitum heterophyllum* (Atis), *Rumax nepalensis* (Nepal Dock), *Jurenia dolomiaea* (Dhoop Lakkad), *Bistorta affinis* (Himalayan fleeceflower), *Picrorhiza kurroa* (Kutki), *Swertia chirayita* (Chirata), *Swertia speciosa* (Showy Swertia) and many more.

2.3 Faunal Diversity

The study area is rich in mammalian and bird diversity. The notable mammalian species includes the Himalayan musk deer (*Moschus chrysogaster*), Himalayan tahr (*Hemitragus jemhalicus*), Himalayan goral (*Nomorhedus goral*), Barking deer (*Muntiacus muntjak*), Wild pig (*Sus scrofa*), Rhesus macaque (*Macaca mullata*), Grey langur (*Semnophithecus entellus*), as well as omnivorous species like the Red foxRed fox (*Vulpes vulpes*), Himalayan yellow throated marten (*Martes flavigula*), Himalayan weasel (*Mustela sibirica*). Additionally, predatory species such as thecommon leopard (*Panthera pardus*) can also be found. Among the reptile species are the Himalayan pit viper (*Ancistrodon himalayensis*) and Boulenger’s keelback (*Amphiesma parallela*) and major avian species include Himalayan monal (*Lophophorus impejanus*), Khaleej (*Lophura leucomelana*), and Koklass (*Pucrasia macrolopa*).

2.4 Land Use Practice

griculture serves as the primary livelihood for the local community. Beside agriculture they depend on utilization of forest resources and non-wood forest produces for their secondary needs. Given the study region's status as a pilgrimage site, there is a substantial demand for fuelwood consumption in the area. The intensive study area faces extreme pressure in treeline and alpine meadows due to fuelwood collection and grazing. The local villagers migrate to this region for their livelihood by raising shops and livestock, respectively, from April to November.

2.5 Intensive Study Area

The intensive study area selected was alpine meadow present at and around Tungnath temple (ca. 2 km^{-2}), with krummholz layer formed by *Rhododendron campanulatum*, while ground layer consists of cushionoids herbs, grasses, sedges, and tussock, forming different communities based on microhabitat characterstics viz. embedded rocks and deep soil.

2.6 Geology and Soil

The bedrocks of Tungnath area are mainly comprised of mylonitized gneisses, augen gneisses, schists and granites which form the Munsiari formation (Agarwala, 1973). These rocks exhibit crystalline and metamorphic characteristics, with sedimentary deposits dating back to the Paleozoic era (Gupta, 1964). Due to the metamorphic and sedimentary nature of the parent materials, the soil texture in the area ranges from sandy loam (Rai et al., 2012) to loam (current study). The soil is acidic, with a pH range of 4.5 to 6.5, and appears as light to dark brown in color. The northern aspect of the region features meadows with a substantial soil cover, while the southern aspect typically consists of prominent rock spurs and crevices, some of which are barren or inhabited by a few lithophytes..

2.7 Climate

The study area experiences four distinct seasons: a brief summer from May to June, monsoon season from July to mid-September, autumn from mid-September to October, and a long winter lasting from November to April. The snow cover persists for approximately 4-5 months and typically melts during April and May, signaling the arrival of favorable conditions for plant growth. The growth period in the area is relatively short, lasting only about 5-7 months. In present study, the HOBO temperature data loggers were deployed at the alpine zone from August 2017 to October 2018. Air maximum and minimum temperature were recorded in May and January 2018 (31.31 and -5.45°C) while mean monthly temperature at the alpine zone (3300-3600 m) ranged between -3.95±0.31 (January) and +13.73±0.24°C (July) with an average of 4.97±1.85°C between August 2017 and October 2018 (Fig. 2.2).

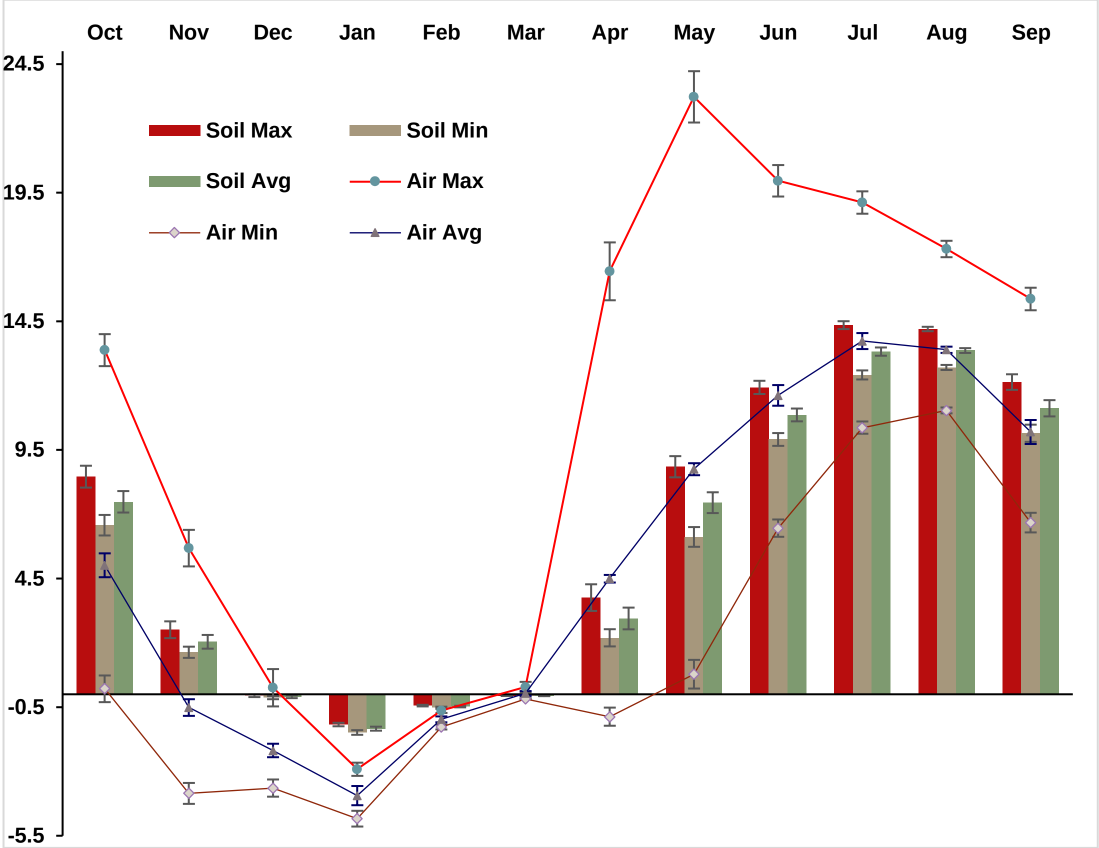


Figure 2.2. Air and soil temperature of alpine meadow of Tungnath (October 2017 to September 2018)

2.8 Study Design

A reconnaissance survey was conducted at and around Tungnath meadow and based on dominance of species, five communities namely *Trachydium*, Mixed Herbaceous, Mixed *Danthonia*, *Polygonum* and *Danthonia* were identified. To determine the effects of natural snowmelt on species present in communities three sites were selected in each community. These site selections were based on the recorded snow cover data from April 28, 2017, which marked the initial access to the sites after the winter snowfall.Each community had varying thickness of snow cover ranging from 0.1m to 0.3m in low snow region and up to 1m in the high snow cover region. These values are based on 10 random measurement samples in each community and provides sufficient evidence to demonstrate the contrasting snow cover between two sites. Due to the physiognomy of the area, alpine meadow is interspersed with krummholz makes the natural boundary between some communities in alpine meadow (Table 2.1).

The area of alpine meadow in Tungnath is finite resulting in smaller area for communities. Subsequently a difference of 7 to 14 days between different sites in all communities was observed. In each site, a permanent plot of 50x50m was marked and 25, 1x1m quadrats were randomly laid in each microsite to record data on abundance and phenology of species fortnightly.

Table 2.1. Characteristic features of selected communities at Tungnath Alpine

Site	***Trachydium***	**Mixed Herbaceous**	**Mixed *Danthonia***	***Polygonum***	***Danthonia***
Slope (°)	30-40	30-45	35-45	15-25	30-45
Aspect	North-West	North-West	North-West	North-West	North-West
Grazing	High	Moderate	Moderate	Low	High
Snow depth (m)	0.3-0.9	0.3-0.6	0.4-0.8	0.4-0.9	0.5-1
Snowmelt (Visual observation)	Early	Early	Late	Mid	Late
Total snow duration days	67	70	73	72	88

3. Temporal Changes in Alpine Communities

3.1 Introduction

Plant growth is influenced by various environmental factors and physiological processes, including light, water, oxygen, mineral nutrients, and temperature. These factors involve meteorological conditions such as light, photoperiod, temperature, precipitation, humidity, wind, and gases, as well as edaphic factors like topography, slope, exposure, and soil properties. Biotic factors such as pests, diseases, and competition also play a role (Menzel, 2002). The role of climate thresholds in determining the geographic boundaries of species was first highlighted by Grinnell (1917) and further explored by MacArthur (1972) and Walther et al. (2002).

The changing climate, particularly the warming of mountainous regions, is expected to have significant impacts on the structure and functioning of alpine ecosystems, particularly affecting plant species sensitive to changes in temperature and precipitation. Numerous studies have documented the upward shifts of treelines and the expansion of shrubs into alpine and subarctic regions (Butler et al. 1994; Kullman, 2002; Shiyatov, 2003; Peñuelas et al. 2007; Gehrig-Fasel et al. 2007; Devi et al. 2008; Sturm et al. 2001, 2005; Dullinger et al. 2003; Tape et al. 2006; Buras et al. 2012). Parmesan (2006) reported that species with limited ranges, particularly polar and alpine species, have been the first to go extinct in various mountain habitats due to recent climate change. Therefore, these species are highly sensitive and provide valuable insights into the impacts and predictions of climate change, especially in comparison to other ecosystems (Malik and Nautiyal, 2016). Biodiversity in a region is defined by the species richness and relative abundance (evenness) of living organisms and ecological complexes, and these indicators are ecologically sensitive and easily interpretable (Polyakov et al. 2008).

Currently, high mountain ecosystems are facing threats such as biodiversity loss, habitat destruction, and landscape modification. These ecosystems are particularly sensitive to climate variables, species pool, and biogeographical region (Körner, 2003; Bruun et al. 2006;

Beniston, 2003; Pauli et al., 2012). Evangelista et al. (2016) conducted a re-visitation study to investigate the long-term changes in the composition, ecology, and structure of high-mountain vegetation. They observed significant shifts in floristic composition, with an increase in nutrient-demanding vegetation in alpine mountain habitats within the Mediterranean region. In a short-term study spanning 7 years, Pauli et al. (2012) documented two different trends in the relationship between vascular plant species and climate warming. Similarly, Gottfried et al. (2012) identified a consistent thermophilization process occurring in high-mountain vegetation over a 7-year period. Several studies have described consistent changes in plant community composition, including species richness and diversity, as well as ecological shifts such as the upward movement of thermophilic plant species. These changes have been observed in both short-term studies of approximately 7-10 years (e.g., Pauli et al. 2007, 2012; Erschbamer et al. 2009, 2011) and long-term studies spanning approximately 50-100 years (e.g., Körner, 2003; Cannone et al. 2007; Holzinger et al. 2008; Parolo and Rossi, 2008; Vittoz et al. 2008; Britton et al. 2009; Grabherr et al. 2010; Engler et al. 2011; Matteodo et al. 2013).

The Indian Himalayan Region (IHR) faces significant threats compared to non-polar regions worldwide, as it is projected to experience a temperature increase of 5-6 °C and a precipitation rise of 20-30% by the end of the twenty-first century (Kohler and Maselli, 2009). Among the various regions within the Himalayas, the Garhwal Himalaya, which constitutes a significant portion of this mountainous system, is particularly susceptible and sensitive to climate change at the local, regional, and global levels. The diverse floral and faunal composition, coupled with the pronounced altitudinal gradient and varying climatic conditions, further contribute to the heightened impact of climate change in this region. Major floristic studies done in Western Himalaya are by Smythe (1939), Ghildiyal (1957), Rau (1975), Kachroo *et al*. (1977), Semwal *et al*. (1981), Chowdhery and Wadhwa (1984), Rawat (1984), Naithani (1984), Naithani *et al*. (1992), Samant (1993), Rawal and Dhar (1997), and Singh and Rawat (2000). But there is very scanty information on composition and diversity along with environmental relationships (Rikhari *et al*. 1992; Nautiyal *et al*. 1997, 2004; Arya, 2002; Chandrashekhar *et al*. 2003; Singh and Sundriyal, 2004; Gaur *et al*. 2005; Rana *et al*. 2011; Salick *et al*. 2014; Vashistha *et al*.

2011). In past few decades several authors have shown some major changes in timberline ecotone (vegetation composition and structure) of higher Himalaya (Adhikari, 2004; Adhikari *et al*. 2012, 2018; Rawal and Pangtey, 1994; Rawal and Dhar, 1997; Maikhuri *et al*. 1998) however, there is a lack of studies on Himalayan alpine landscape for both baseline data and biotic and abiotic interactions especially from ecological perspective done in alpine zones are significantly less which hamper the understanding of underlaying dynamics of alpine ecosystems in IHR.

Keeping in view abovementioned facts there is a need for amassing baseline information of fragile Himalayan alpine ecosystem. With this background the study is being carried out to understand temporal changes in composition and structure in different herbaceous communities of alpine ecosystems in Western Himalaya.

3.2 Methods

Five distinct communities, namely *Trachydium*, Mixed Herbaceous, Mixed *Danthonia*, *Polygonum*, and *Danthonia*, were identified. To investigate the impact of natural snowmelt on species within these communities, three sites were selected in each community based on the snow cover recorded on April 28, 2017, which was the first accessible time after winter snowfall. In each site, a permanent plot measuring 50x50 meters was marked, and 25 random 1x1 meter quadrats were placed within each site to gather data on species abundance and phenology. During the first year of the study period (2017), data was collected monthly intervel, which was then changed to fortnightly intervals for the remainder of the study period.

3.2.1 Types and forms of plants

The species were categorized based on their life span: annuals, which complete their life cycle within a single growing season; perennials, which grow and bloom during the spring/summer season, then die in autumn/winter and regrow from their root stock; and biennials, which undergo a two-year life cycle, germinating, growing, surviving through winters, and then growing, flowering, and dying in the following year.

3.2.2 Growth forms

The growth form of a plant is determined by the direction and extent of growth and branching of its main-shoot axis or axes. In this study, plants were classified into various growth forms according to Pérez-Harguindeguy *et al*. (2013), including semi-basal herbs, short basal herbs, erect leafy herbs, tussock-forming grasses, dwarf shrubs, and climbers.

3.2.3 Life form and Nativity

To develop a life form spectrum for the study area, the species occurring in the treeline area were categorized based on Raunkier's life form classification (Raunkier, 1934). Additionally, the nativity of each species was determined by identifying its place of origin or first recorded occurrence. Species naturally occurring in the area were considered "native" (Anonymous, 1883-1970), while species introduced through differnt activities to an area where they did not previously exist were classified as "non-native." The *Index Kewensis Plantarum Phanerogamarum* (Anonymous, 1883-1970) and the International Plant Name Index (IPNI) were used to ascertain the nativity of the species.

3.2.4 Species richness and diversity

Species richness refers to the total number of species in a specific area, while the index of diversity was calculated using Shannon and Wiener's method (1949). The diversity index (H') is calculated using the proportion (Pi) of individuals of a particular species (n) to the total number of individuals (N) in the sample, and applying the natural logarithm (ln) to each proportion as per following equation where, ∑ is sum of the calculations, and s is several species:

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

.

The Sorenson Similarity Index (Is) was calculated to measure the similarity between different sites based on common species, following Sorenson (1948). The formula for Is involves the number of common species (C) between two comparable sites, and the total number of species in sites A (A) and B (B).

$$Is = \frac{2C}{A + B} X\ 100$$

3.2.5 Statistical Analysis

Two-way analysis of variance (ANOVA) was conducted to assess the variance in richness, density, and diversity among months, communities, and years.

3.3 Results

The onset of growth is influenced by the quantity of snowfall during the previous winter and the beginning of snowmelt in the spring season. The growth invitation in the study area occurred between mid-April to early May and lasted till late September or early October during the study period (2017-2019) for about 5-6 months. The total snow fall days for year 2017-18 were 38 days, 2018-19 were 42 days and 2019-20 were 29 days respectively. The days were counted as snow fall days if the snow stayed after snowfall for at least a day.

A total of 80 species encountered in quadrat sampling within fixed plots across all the communities during the study period, of which 43 species each were present in *Trachydium* and Mixed Herbaceous communities, 46 in Mixed *Danthonia*, 54 in *Polygonum* and 51 in *Danthonia* respectively. In the year 2017, 80 species were recorded while in 2018 and 2019, 78 species were recorded.

3.3.1 Plant forms and Growth cycle

In general, the proportion of forbs constituted 90% of the species, while perennial species accounted for 93.75%, with only a small percentage (6.25%) being annuals and no biennials. The growth forms of the present species were categorized as follows: short basal (36.3%) > semi basal (31.3%) > erect leafy (25%) > dwarf shrub (2.5%) > climber and tussock (1.3% each). The majority of species exhibited an intermediate growth cycle, lasting between 3 to 4 months (48.8%), followed by long growth cycle species with a growth period exceeding 4 months (36.3%), and short growth cycle species with a growth period of less than 3 months

(15%). Hemicryptophytes were the dominant life forms, accounting for 70% of the alpine community (Table 3.1).

In *Trachydium* community, the percentage of forbs and perennial species was more than 93% each. Short and semi basal growth form contributed equally (34.9%) followed by erect leafy (25.6%) and dwarf shrub (4.6%) growth form. Majority of species had long growth cycle (growth period > 4 months, 53.5%) followed by intermediate growth cycle (growth between 3-4 months, 34.8%), and short growth cycle (growth period up to 2 months, 11.6%). Hemicryptophytes (86%) were the dominant lifeforms followed by therophyte (6.9%), chaemophyte (4.6%) and geophyte (2.3%).

In Mixed Herbaceous community, the percentage of forbs was more than 95% and 93% species were perennial. The percentage of short-basal species (46.5%) was largest followed by semi basal and erect leafy growth form contributing equally (25.6%) and dwarf shrub (2.3%) growth form. Most species had long growth cycle (58.1%) followed by intermediate growth cycle (37.2%), and short growth cycle (4.6%). Hemicryptophytes (88.3%) were the dominant lifeforms followed by therophyte and chaemophyte (4.6% each) and geophyte (2.3%).

In *Polygonum* community, the percentage of forbs was more than 96% while 92.6% species were perennial. The percentage of short-basal species (40.7%) was largest followed by semi basal (29.6%), erect leafy (27.8%) and dwarf shrub (1.8%) growth form. Most species either had long growth cycle (growth period > 4 months, 46.3%) or intermediate growth cycle (growth between 3-4 months, 44.4%), and short growth cycle (growth period <3 months, 9.3%). Hemicryptophytes (88.3%) were the dominant lifeforms followed by therophyte and chaemophyte (4.6% each) and geophyte (2.3%).

Table 3.1. Structural properties of different communities

		Trachydium	**Mixed Herbaceous**	***Polygonum***	**Mixed *Danthonia***	***Danthonia***
Life cycle	Perennial	40	40	50	43	47
	Biennial	0	0	0	0	0
	Annual	3	3	4	3	4
Growth Form (%)	Semi-Basal	34.88	25.58	29.63	32.61	29.41
	Short-Basal	34.88	46.51	40.74	36.96	39.22
	Erect Leafy	25.58	25.58	27.78	26.09	25.49
	Dwarf Shrub	4.65	2.33	1.85	2.17	1.96
	Tussock	0.00	0.00	0.00	2.17	1.96
	Climber	0.00	0.00	0.00	0.00	1.96
Raunkier Life Form (%)	Hemicryptophyte	86.05	88.37	87.04	91.30	88.24
	Chaemophyte	4.65	4.65	1.85	2.17	1.96
	Therophyte	6.98	4.65	7.41	4.35	5.88
	Geophyte	2.33	2.33	3.70	2.17	3.92
Ecologival Parametes	Density	276-894.8	162.2-627.7	52.4-264.8	105.12-341.4	73.4-202.72
	Species Richness (m^{-2})	5.9-25	8.9-21.8	4.5-23	9.3-19.4	5.5-19
	Total Species	43	43	54	46	51
	Diversity	1.28-2.83	2.07-2.79	1.68-2.91	2.24-3.5	1.02-3.21
Dominant Species		*Trachydium roylei, Oxygraphis polypetalae, Plantago ovate*	*Trachydium roylei, Carex setosa, Oxygraphis polypetalae*	*Rannunculus hirtellus, Polygonum polystachium, Trachydium roylei*	*Trachydium roylei, Anaphalis nepalensis, Oxygraphis polypetalae*	*Danthonia cashmerina*

In Mixed *Danthonia* community, the percentage of forbs was more than 95% and 93.5% species were perennial. The short-basal growth form (37%) was dominant followed by semi basal (32.6%), erect leafy (26%) and dwarf shrub and tussock (2.2% each) growth form respectively. Most of species had long growth cycle (growth period > 4 months, 54.4%) followed by intermediate growth cycle (growth between 3-4 months, 39%), and short growth cycle (growth period <3 months, 6.5%). Hemicryptophytes (91.3%) were the dominant lifeforms followed by therophyte (4.4%) and chaemophyte and geophyte (2.2% each) respectively.

In *Danthonia* community, the percentage of forbs was more than 94% and 92% species were perennial. The short-basal species (37%) were dominant followed by semi basal (32.6%), erect leafy (26%) and dwarf shrubs and tussock (2.2% each) growth form respectively. Majority of species had long growth cycle (growth period > 4 months, 54.4%) followed by intermediate growth cycle (growth between 3-4 months, 39%), and short growth cycle (growth period <3 months, 6.5%). Hemicryptophytes (91.3%) were the dominant lifeforms followed by therophyte (4.4%) and chaemophyte and geophyte (2.2% each) respectively.

3.3.2 Life form distribution

The species present in the quadrat at the study site were classified based on their life forms and biological spectrum. The life form analysis revealed that only four lifeforms are present in the studied communities with majority being Hemicryptophytes (He), followed by Therophyte (Th), Geophyte (Ge) and Chaemophyte (Ce) represented by 70, 5, 3, and 2 species respectively (Table 3.1).

3.3.3 Temporal changes in Structural properties

Within a short time, growth initiation of species staggered during early growing period. With the progress of growing period, the total number of species in the study area increased from 42 in May to 69 in September. Generally, the Mixed Herbaceous community had highest species richness (species m^{-2}), followed by Mixed *Danthonia*, while *Polygonum* community had lowest species richness (Fig. 3.1).

3.3.3.1 Species Richness

At the peak of species richness, 32.4% species were common to all communities. The total number of species ranged between 9-36 in the sites across growing period and years. The total species in communities peaked between July and September in all communities during study period. In *Trachydium* community a drop in species number was observed during May and June and in *Danthonia* it was observed in the month of May and August for the year 2018 and 2019, respectively. In *Polygonum* and Mixed *Danthonia* community an increase in total species number was observed in the month of June and August in 2018 and 2019 respectively. The species richness for communities across growing period ranged between 4-28 species m^{-2}.

In general, the species richness (species number m^{-2}) peaked in May for *Trachydium* and July for Mixed Herbaceous and Mixed *Danthonia* communities while peak was observed in *Polygonum* and *Danthonia* communities in August and September respectively (Fig. 3.1). Across the years, the drop was observed in peak species richness for all communities (2017-2019) except Mixed Herbaceous community, where richness increased, and in *Danthonia* community it decreased in 2018 and then increased in 2019. Similarly, the timing of peak species richness changed from September (2017) to July (2018, 2019) for Mixed Herbaceous and Mixed *Danthonia* communities and from May (2017) to August (2018, 2019) for *Polygonum* community while no change was observed in *Trachydium* and *Danthonia* communities (Fig.3.2).

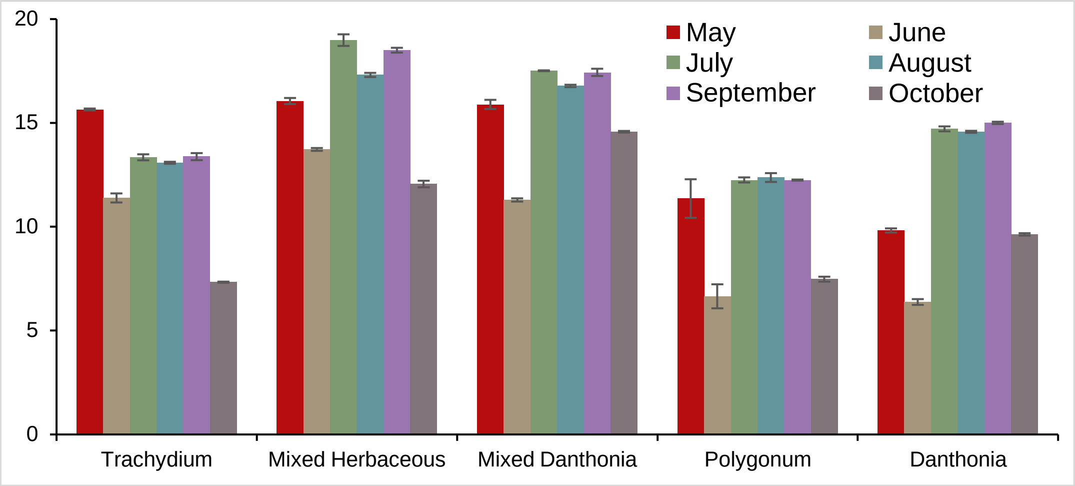


Figure 3.1. Species richness across months in different alpine communities (2017-2019)

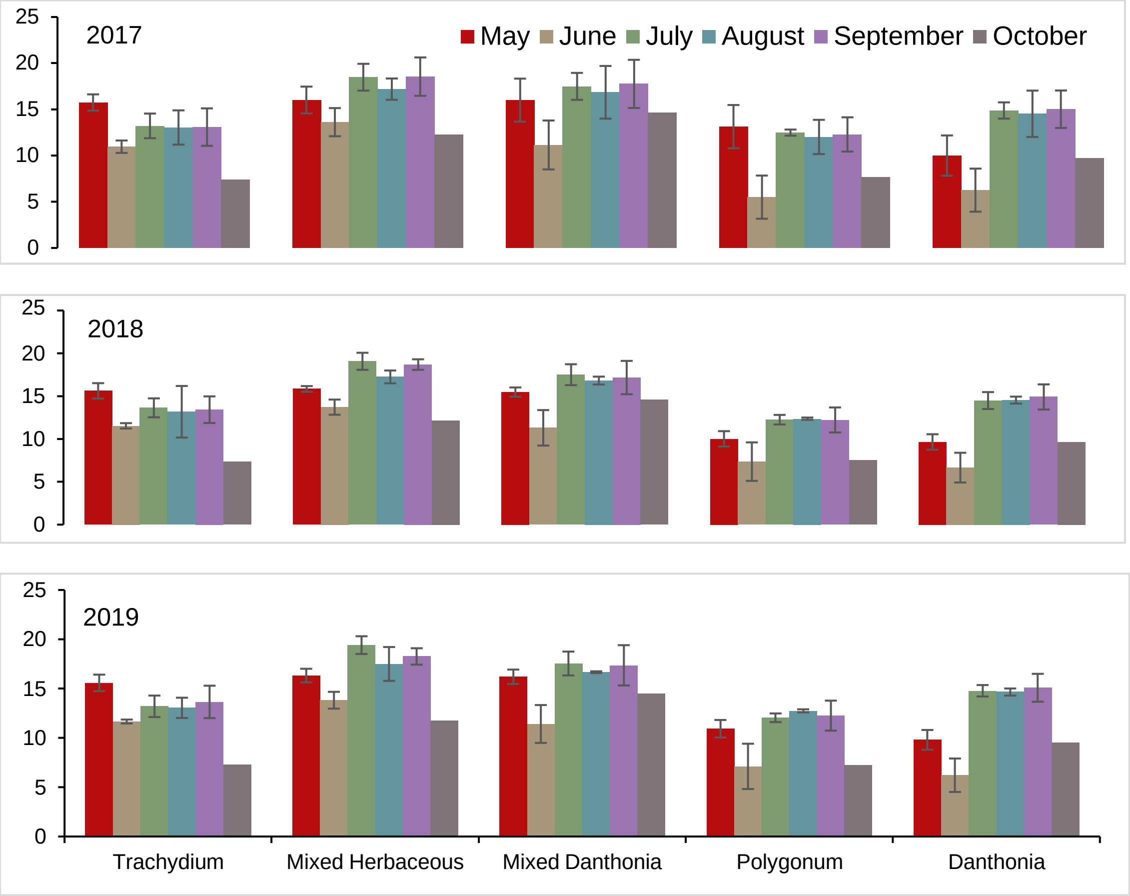


Figure 3.2. Temporal changes in species richness in different alpine communities

3.3.3.2 Density

In general, the average plant density was significantly higher for *Trachydium* and Mixed Herbaceous communities than other communities. The average peak density was recorded in May for *Trachydium* (821.2±57.7), Mixed Herbaceous (545.6±18.1), Mixed *Danthonia* (257.3±26.8), and *Polygonum* (191.5±33.5) communities and in September for *Danthonia* (172.7±14.1) community. However, the minimum density for *Trachydium* (366.5±58.0) and Mixed Herbaceous (209.3±8.1) communities was recorded in October while in Mixed *Danthonia* (132.5±23.7), *Polygonum* (74.5±11.5), and *Danthonia* (106.2±15.9) communities it was recorded in June (Fig. 3.3).

During study period (2017-2019), the average plant density was much higher for *Trachydium* (498.2±63.1) and Mixed Herbaceous (409.2±63.6) communities than Mixed *Danthonia*, *Polygonum*, and *Danthonia* communities. For the entire study duration, maximum density was recorded in the month of May for *Trachydium* (815.3±58.8 to 832.4±59.1), Mixed Herbaceous (534.5±21.9 to 558.2±19.1), Mixed *Danthonia* (227.5±26.8 to 277.9±28.5), and *Polygonum* (155.5±30.9 to 220.9±38.3) communities and in September for *Danthonia* (170.4±16.7 to 175.6±26.3) community (Fig. 3.4).

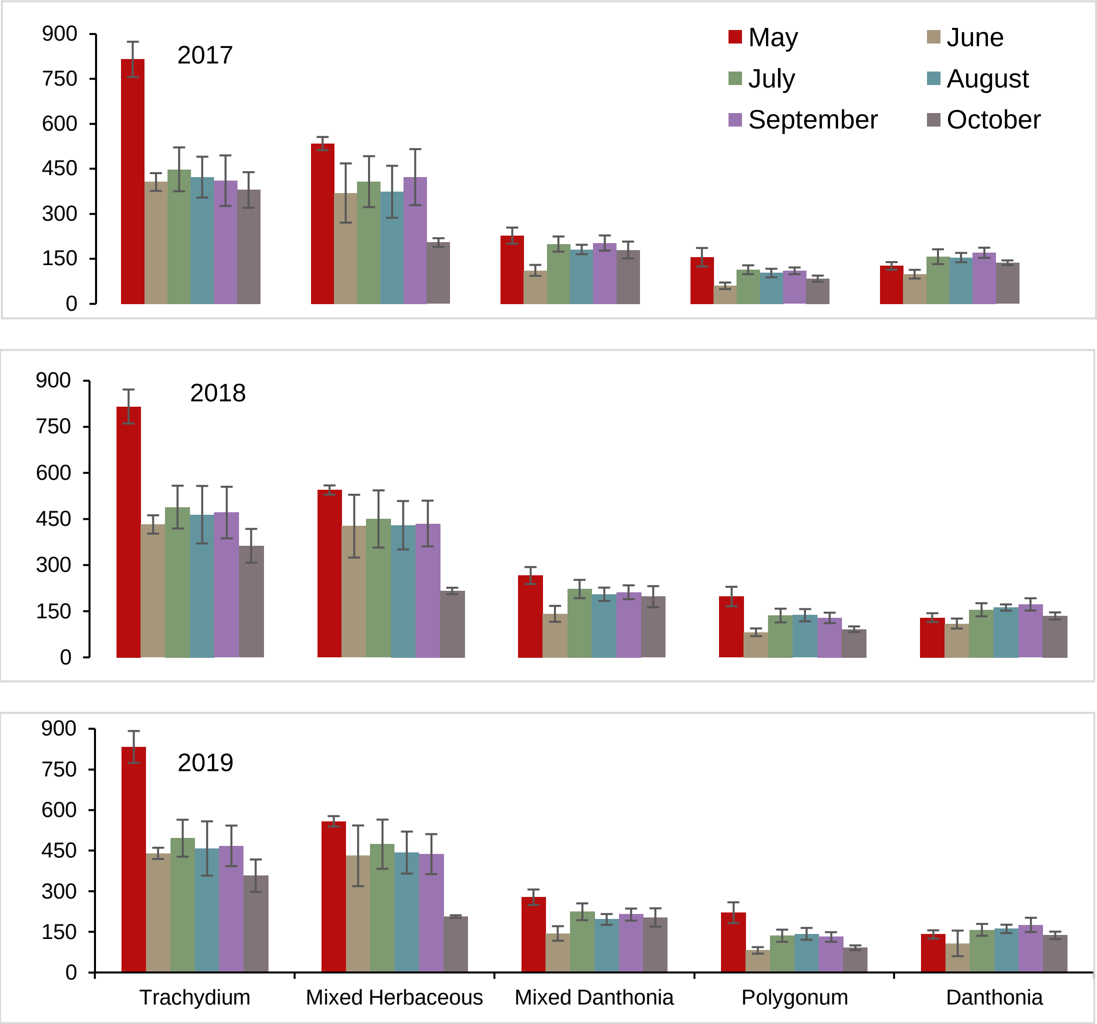


Figure 3.3. Temporal changes in species density in different alpine communities

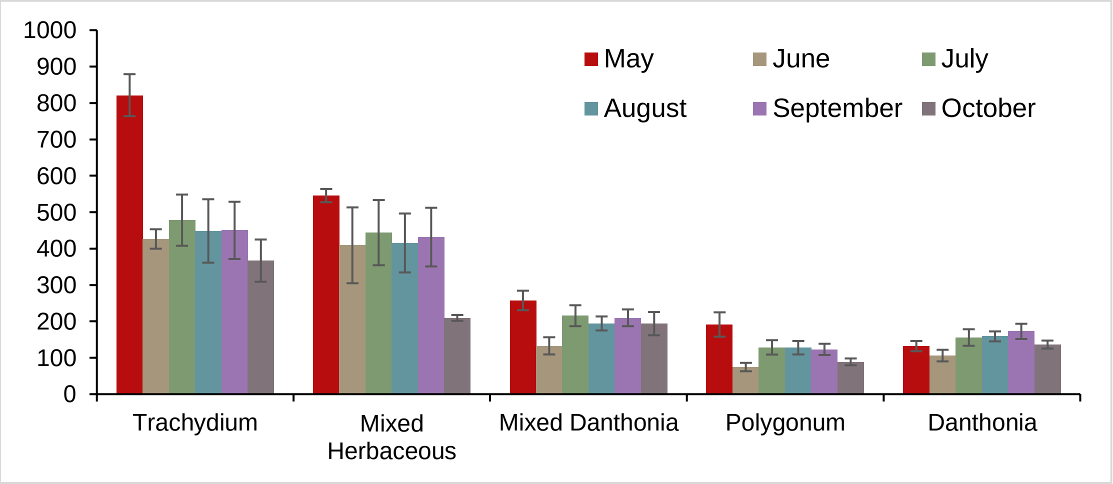


Figure 3.4. Species density across months in different alpine communities

3.3.3.3 Diversity

During peak the growing season, the Shannon-Weiner diversity index was relatively higher in *Polygonum* community (2.93±0.2), followed by Mixed *Danthonia* (2.92±0.2) and Mixed Herbaceous (2.73±0.1) communities in 2017 while in 2018 and 2019 diversity was highest in Mixed *Danthonia* (2.80±0.1) community followed by Polygonum (2.69±0.1) and Mix Herbaceous (2.66±0.1) communities (Fig. 3.5). The peak diversity was observed in July in *Danthonia* (2.59±0.5), *Trachydium* (2.11±0.1) and Mixed Herbaceous (2.73±0.1) communities in 2017, while in *Danthonia* (2.42±0.3) and *Trachydium* (2.03±0.1) communities in August and September respectively, for remaining study period (2018-2019). Similarly, diversity peaked in August in Mixed *Danthonia* (2.92±0.2) and *Polygonum* (2.93±0.2) communities in 2017 but peak diversity was observed in July in *Polygonum* (2.74±0.2) community for remaining study period while no change was observed in Mixed *Danthonia* community. Like the density, minimum diversity was observed in *Trachydium* and Mixed Herbaceous communities were observed in October, but in remaining communities the minimum diversity was observed in June (Fig. 3.5).

In general, the diversity increased as growing season progressed in all communities and then declined. In *Trachydium* community, the average diversity decreased from May to June and then increased and peaked in September (2.07±0.03). Similarly, in Mixed *Danthonia* and *Danthonia* communities the diversity decreased from May to June and then increased and peaked in August (2.84±0.04; 2.47±0.1) respectively. In Mixed Herbaceous and *Polygonum* communities, the diversity increased as growing season progressed and peaked in July (2.69±0.03) and August (2.78±0.1) respectively (Fig. 3.6).

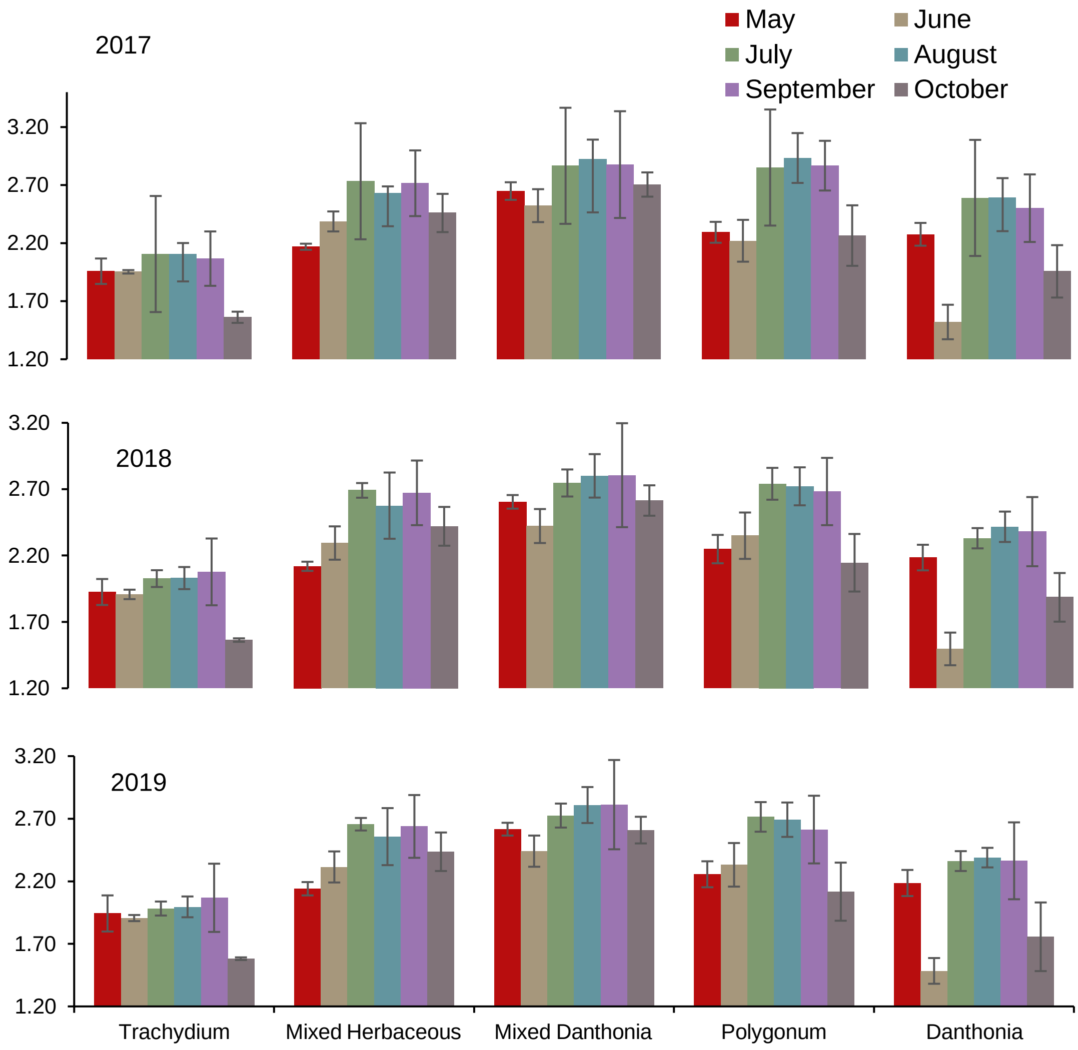


Figure 3.5. Temporal changes in species diversity in different alpine communities

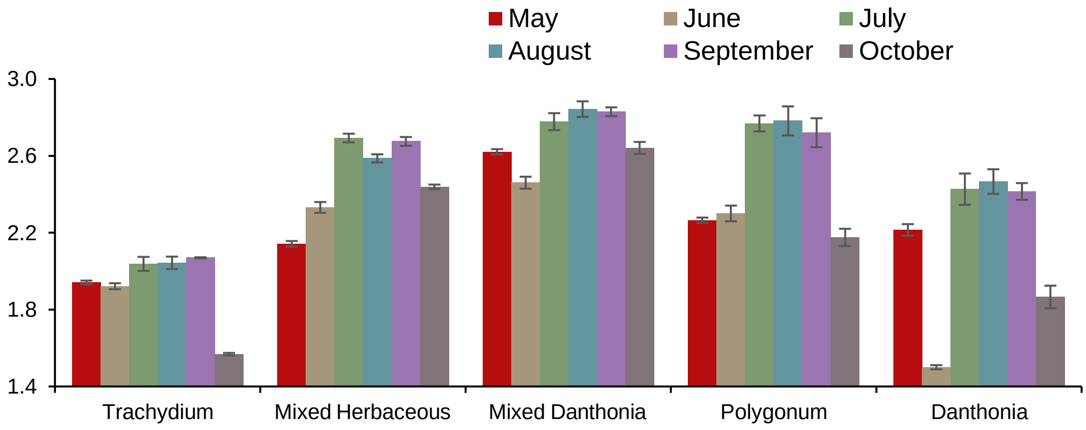


Figure 3.6. Species diversity across months in different alpine communities

3.3.4 Vegetative structure and species composition across different communities

Based on monthly average density, the dominance of species was calculated. During the study period (2017-2019), in each community a total of 2250 quadrat (1 x1 m) across three microsites and 6 months were sampled.

In *Trachydium* community 43 herb species were recorded. The density was recorded highest in *Trachydium roylei* (197.5±20.7) followed by, *Oxygraphis polypetala* (106.7±23.9), *Plantago ovata* (23.9±7.1), *Carex setosa* (19.8±9.8), *Bistorta affinis* (18.3±4.4), *Sassurea taraxacifolia* (14.2±3.8), *Taraxacum officinale* (12.0±1.9), *Anaphalis nepalensis* (11.7±2.6), *Geum elatum* (10.1±1.7), and *Pedicularis hoffmeisteri* (9.1±3.4). The frequency was recorded highest for *Trachydium roylei* (99.8%) followed by, *Taraxacum officinale* (84.2%), *Oxygraphis polypetala* (83.6%), *Bistorta affinis* (81.9%), *Sassurea taraxacifolia* (81.8%), *Plantago ovata* (81.3%), *Anaphalis nepalensis* (77.8%), *Pedicularis hoffmeisteri* (77.1%), *Carex setosa* (73.7%), and *Geum elatum* (71.6%; Table 3.2).

In Mixed Herbaceous community, a total of 43 herb species were recorded. The density was recorded highest in *Trachydium roylei* (106.1±16.3) followed by, *Oxygraphis polypetala* (64.8±16.8), Carex setosa (37.5±28.0), *Anaphalis nepalensis* (19.5±4.8), *Plantago ovata* (16.3±4.0), *Sassurea taraxacifolia* (15.9±4.1), *Kobresia duthieie* (14.9±6.4), *Geum elatum* (11.3±3.4), *Taraxacum officinale* (10.4±2.9), and *Cynanthus lobatus* (10.0±4.4). The frequency was recorded highest for *Taraxacum officinale* (98.9%) followed by, *Trachydium roylei* (96.2%), *Anaphalis nepalensis* (90.2%), *Tenacetum dolichophyllum* (86%), *Oxygraphis polypetala* (85.6%), *Geum elatum* (82.2%), *Sassurea taraxacifolia* (80.4%), *Sibbaldia parviflora* (80.2%), *Kobresia duthieie* (74.9%), and *Plantago ovata* (72.9%; Table 3.2).

In *Polygonum* community, a total of 54 herb species were recorded. The density was recorded highest in *Rannunculus hirtellus* (28.6±12.7) followed by *Polygonum polyastachium* (11.8±3.2), *Polygonum filicule* (7.7±3.1), *Poa annua* (7.0±2.7), *Trachydium roylei* (6.3±3.9), *Rumax nepalensis* (5.7±2.2), *Fragaria nubicola* (5.1±3.9), *Polygonum delicatula* (4.4±2.4), *Bistorta affinis* (4.1±1.4), and *Veronica canna* (4.1±2.1). The frequency was recorded highest for *Polygonum polyastachium* (74.2%) followed by *Polygonum filicule* (57.8%), *Bistorta affinis* (55.1%), *Bistorta amplexicaulis* (43.6%), *Poa annua* (42.4%), *Potentilla polyphyla* (41.9%), *Plantago ovata* (40.1%), *Fragaria nubicola* (39.1%), *Potentilla atrosanguinea* (36.4%), and *Geum elatum* (22.2%; Table 3.2).

In Mixed *Danthonia* community, a total of 46 herb species were recorded. The density was recorded highest in *Oxygraphis polypetala* (24.5±3.7) followed by *Danthonia cachemyriana* (24.8±2.5)*, Trachydium roylei* (21.3±6.7), *Anaphalis nepalensis* (21.0±6.2), *Sibbaldia cuneata* (9.6±2.1), *Geum elatum* (9.5±2.9), *Taraxacum officinale* (9.1±1.4), *Fragaria nubicola* (7.31±3.2), *Potentilla atrosanguinea* (6.6±1.7), and *Rannunculus hirtellus* (6.1±3.4). The frequency was recorded highest for *Geum elatum* (88.0%) followed by *Sibbaldia cuneata* (86.9%), *Anaphalis nepalensis* (82.9%), *Oxygraphis polypetala* (81.6%), *Potentilla atrosanguinea* (67.8%), *Danthonia cachemyriana* (65.3%), *Bistorta affinis* (63.1%), *Tanecetum dolichophyllum* (56.7%), *Fragaria nubicola* (51.3%) and *Bupleurum candollei* (50.1%; Table 3.2).

In *Danthonia* community, a total of 51 herb species were recorded. The density was recorded highest in *Danthonia cachemyriana* (53.8±6.0) followed by *Rannunculus hirtellus* (8.2±3.6)*,* *Trachydium roylei* (7.6±3.9), *Fragaria nubicola* (4.8±1.02), *Geranium wallichianum* (4.5±2.6), *Potentilla atrosanguinea* (4.1±1.4), *Anaphalis nepalensis* (4.1±1.5), *Sibbaldia cuneata* (3.9±1.7), *Oxygraphis polypetala* (3.8±2.9), and *Bistorta affinis* (3.7±1.1). The frequency was recorded highest for *Danthonia cachemyriana* (82.7%) followed by *Rannunculus hirtellus* (65.6%), *Geum elatum* (63.6%), *Potentilla atrosanguinea* (56.7%), *Bistorta affinis* (52.2%), *Fragaria nubicola* (51.1%), *Geranium wallichianum* (40.4%), *Bupleurum candollei* (37.3%), *Anaphalis nepalensis* (34.7%) and *Potentilla polyphyla* (34.7%; Table 3.2).

Table 3.2. Density (individuals m^{-2}) and Frequency (%) of the Dominant species across different communities in the study area. Fre: Frequency.

S.No.	**Communities**	***Trachydium***		**Mixed Herbaceous**		***Polygonum***		**Mixed *Danthonia***		***Danthonia***	
	Species	**Density**	**Fre**	**Density**	**Fre**	**Density**	**Fre**	**Density**	**Fre**	**Density**	**Fre**
1	*Anaphalis nepalensis*	11.8±2.6	77.9	19.5±4.8	90.2			21.0±6.2	82.9	4.1±1.5	34.7
2	*Bistorta affinis*	18.3±4.4	81.9			4.1±1.4	55.1		63.1	3.7±1.1	52.2
3	*Bistorta amplexicaulis*						43.6				
4	*Bupleurum candollei*								50.9		37.3
5	*Carex setosa*	19.9±9.8	73.8	37.5±28.0							
6	*Cynanthus lobatus*			10.0±4.4							
7	*Danthonia cachemyriana*							24.8±2.5	65.3	53.8±6.0	82.7
8	*Fragaria nubicola*					5.1±3.9	39.1	7.3±3.2	51.3	4.8±1.0	51.1
9	*Geranium wallichianum*									4.5±2.8	40.4
10	*Geum elatum*	10.1±1.7	71.6	11.3±3.4	82.2		22.2	9.4±2.9	88		63.6
11	*Kobresia duthieie*			14.9±6.4	74.9						
12	*Oxygraphis polypetala*	106.7±23.9	83.6	64.8±16.8	85.6			26.5±3.7	81.6	3.8±2.9	
13	*Pedicularis hoffmeisteri*	9.1±3.4	77.1								
14	*Plantago ovata*	23.9±7.1	81.3	16.3±4.0	72.9		40.9				
15	*Poa annua*					7.0±2.7	42.4				
16	*Polygonum delicatula*					4.4±2.4					
17	*Polygonum filicule*					7.7±3.1	57.8				
18	*Polygonum polyastachium*					11.8±3.2	74.2				
19	*Potentilla atrosanguinea*						36.4	6.5±1.7	67.8	4.1±1.3	56.7
20	*Potentilla polyphyla*						41.8				34.7

21	*Rannunculus hirtellus*					*28.6*±12.7		*6.1*±3.4		*8.2*±3.6	*65.6*
22	*Rumax nepalensis*					*5.7*±2.2					
23	*Sassurea taraxacifolia*	*14.2*±3.9	*81.8*	*15.9*±4.1	*80.4*						
24	*Sibbaldia cuneata*							*9.6*±2.1	*86.9*	*4.0*±1.7	
25	*Sibbaldia parviflora*				*80.2*						
26	*Taraxacum officinale*	*12.0*±1.9	*84.2*	*10.4*±2.9	*98.9*			*9.1*±1.4			
27	*Tenacetum dolichophyllum*				*86*				*56.7*		
28	*Trachydium roylei*	*197.5*±20.7	*99.8*	*106.1*±16.3	*96.2*	*6.3*±3.9		*21.3*±6.7		*7.6*±3.9	
29	*Veronica canna*					*4.1±2.1*					

Species similarity among communities, Habitat Preferences

The similarity of communities depends on number of species common to them. On average all communities were more than 70% like each other. Mixed *Danthonia* and *Danthonia* (80.4%) communities had highest similarity followed by Mixed *Danthonia* and Mixed Herbaceous (78.6%) communities and Mixed Herbaceous and *Trachydium* (76.7%) communities. The *Trachydium* and *Polygonum* community were least similar (63.9%) followed by *Trachydium* and *Danthonia* (65.9%) and Mixed Herbaceous and *Polygonum* (65.98%) communities respectively (Table 3.3).

Table 3.3. Similarity between different communities. (T: *Trachydium* community; MH: Mixed Herbaceous community; P: *Polygonum* community; MD: Mixed *Danthonia* community; D: *Danthonia* community)

	T	**MH**	**P**	**MD**	**D**
T	100.00	76.74	63.92	74.16	65.96
MH	76.74	100.00	65.98	78.65	74.47
P	63.92	65.98	100.00	72.00	72.38
MD	74.16	78.65	72.00	100.00	80.41
D	65.96	74.47	72.38	80.41	100.00

Out of total 80 species recorded, 24 species were present in all communities namely *Anaphalis nepalensis, Bistorta affinis, Bistorta amplexicaulis, Bupleurum candollei, Carex setosa, Euphorbia stracheyi, Fragaria nubicola, Gaultheria trichophylla, Gentiana argentea, Geum elatum, Goodyera repens, Kobresia duthiei, Oxygraphis polypetala, Parnessia nubicola, Pedicularis hoffmeisteri, Plantago ovata, Polygonum polyastachium, Potentilla ancerina, Potentilla liniata, Rannunculus hirtellus, Swertia ciliate, Taraxacum officinale, Trachydium roylei,* and *Viola biflora;* 11 species were common for 4 communities namely *Euphrasia himalayica, Gentiana tubiflora, Gerbera gossypiana, Poa annua, Potentilla astrosingiana, Primula dendiculata, Picrorhiza kurroa, Sassurea taraxifolia, Sibbaldia cuneata, Tanecetum dolichophyllum* and *Veronica canna*; 9 species common for 3 communities namely *Anaphalis royeli, Epilobium royeli, Juncus himalenses, Jurenia* *dolomiaea, Phlomis bractiosa, Pimpinella diversifolia, Polygonum vaccinifolium, Potentilla polyphyla* and *Selenium veginatum;* 10 species were present only in 2 communities namely *Arenaria neelgherrensis, Cerastrium ceratoides, Cynanthus lobatus, Danthonia cachemyrina, Geranium collium, Myriactis wallichii, Polygonum delicatula, Polygonum filicule, Prunella vulgaris* and *Senecio laetus* while remaining 26 species were unique to a single community.

3.3.5 SIMPER

SIMPER (Similarity Percentage) analysis suggested the primarily responsible taxa (species) for observed differences between groups of samples i.e. sites. The average dissimilarity between sites in different communities was 32 %, respectively with 20 species, namely *Anaphalis nepalensis, A. royeli, Bistorta affinis, Carex setosa, Fragaria nubicola, Gentiana argentea, Goodyera repens, Kobresia duthiei, Oxygraphis polypetala, Pimpinella diversifolia, Plantago ovata, Poa annua, Polygonum polyastachium, Potentilla astrosingiana, Picrorhiza kurroa, Rannunculus hirtellus, Sassurea taraxifolia, Trachydium roylei, Veronica canna,* and *Viola biflora* contributing about 70 % dissimilarity in all communities.

The maximum contribution to dissimilarity (up to 50%) within communities in decreasing order was contributed by following species: in the *Trachydium* community by *Trachydium roylei* (26.2 %) > *Oxygraphis polypetala* (18.4 %) > *Gentiana argentea* (10.7 %); in the Mixed Herbaceous community by *Trachydium roylei* (19.1 %) > *Carex setosa* (11.6 %) > *Oxygraphis polypetala* (8.7 %) > *Gentiana argentea* (7.8 %) > *Plantago ovata* (5.2 %); in *Polygonum* community *Rannunculus hirtellus* (10.3 %) > *Poa annua* (8.3 %) > *Polygonum delicatula* (7.6 %) > *Polygonum polyastachium* (6.8 %) > *Rumax nepalensis* (6.8 %) > *Potentilla polyphyla* (4.5 %) > *Polygonum filicule* (4.3 %) > *Carex setosa* (4.2 %); in Mixed *Danthonia* community *Danthonia cachemyriana* (14.3 %) > *Anaphalis nepalensis* (9.1 %) > *Gentiana argentea* (6.6 %) > *Goodyera repens* (6.1 %) > *Fragaria nubicola* (5.4 %) > *Anaphalis royeli* (4.5 %) > *Carex setosa* (4.4 %); in *Danthonia* community *Danthonia cachemyriana* (26.7 %) > *Rannunculus hirtellus* (7.9 %) > *Fragaria nubicola* (6.1 %) > *Carex setosa* (5.1 %) > *Geranium wallichianum* (4.9 %; Fig. 3.7 and 3.8).

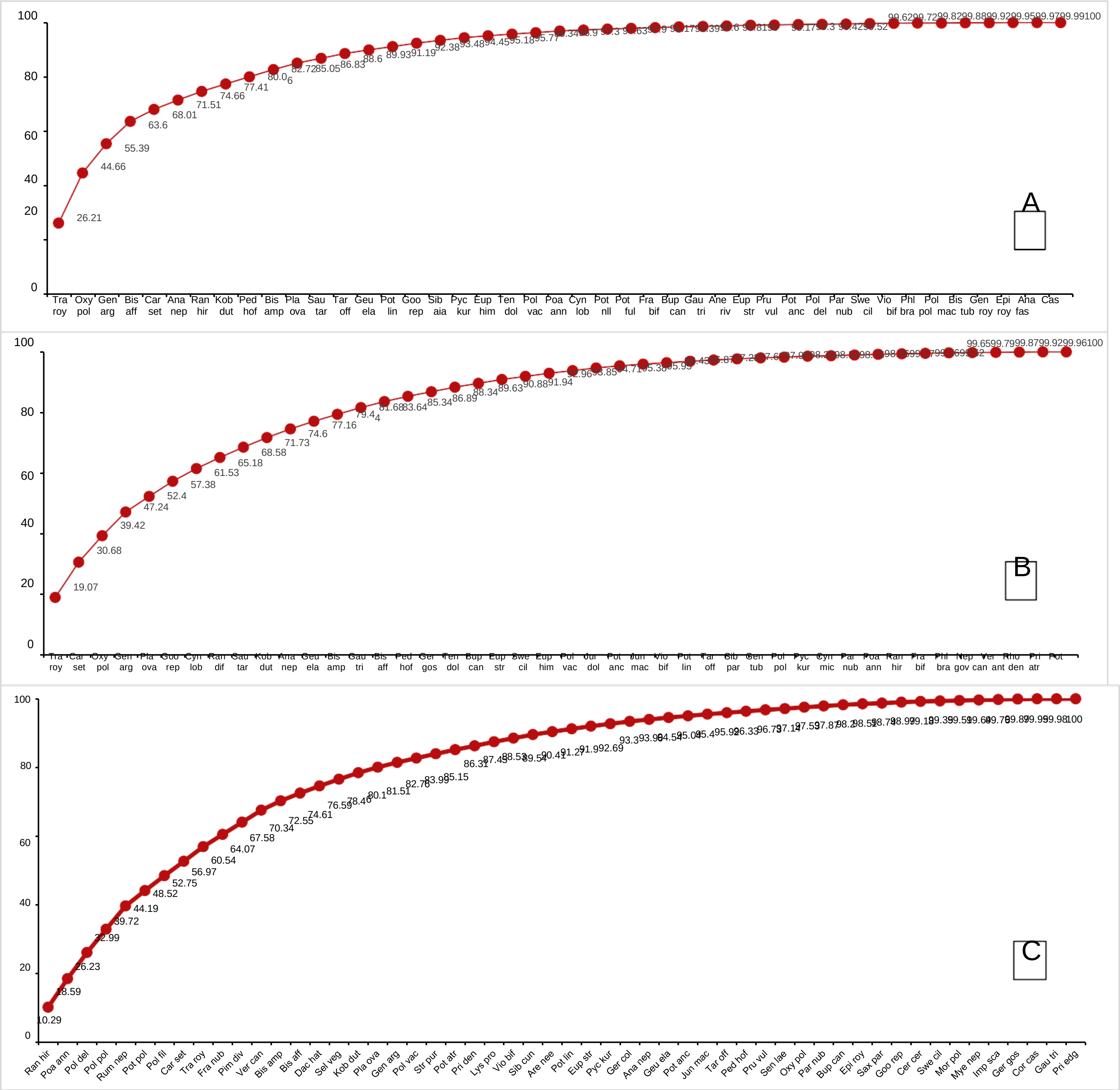


Figure 3.7. SIMPER Analysis showing per cent contribution of species towards dissimilarity within communities. A: *Trachydium* community; B: Mixed Herbaceous community; C: *Polygonum* community

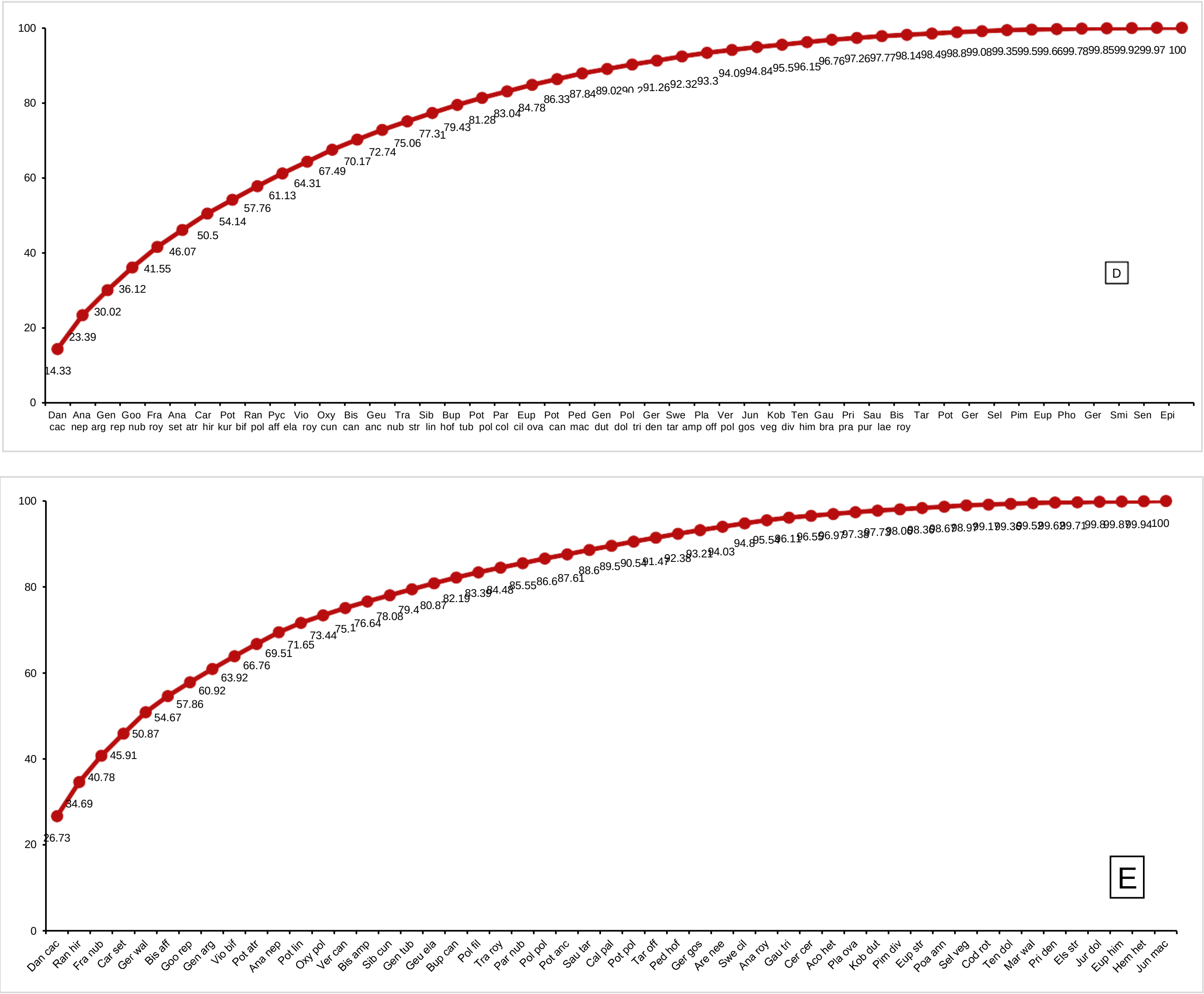


Figure 3.8 .SIMPER Analysis showing per cent contribution of species towards dissimilarity within communities. D: Mixed *Danthonia* community; E: *Danthonia* community

3.3.6 Relationship between Community distribution and Edaphic Factors

In present study, the dependent variable (species abundance) was computed against exploratory environmental variables (Soil OC%, NPK %, pH, moisture%, texture, and snowmelt) as these have strong influence on vegetation structure and composition. To understand which environmental factors, contribute significantly to define communities during early growing season (May and June) and peak growing season (August and September), Principal Component Analysis (PCA) was performed. Of the 10 selected environmental factors tested, the Principal Component 1 and 2 (PC1, PC2) explained more than 86% of variation inboth early and peak growing seasons. As shown in biplot (Fig. 3.9a and 3.9b), it is evident that soil texture and moisture content play a significant role in the distribution of communities,while snowmelt water, pH, and soil chemical properties do not as is evident from eigen values. Among the soil chemical properties Phosphorus % and Nitrogen % were most influential whilethe influence of Potassium %, OC % and pH was negligible.

A Canonical Correspondence analysis (CCA) was performed for species relationship with environmental variables. The permutation tests revealed non-significant (p = 0.059, significance level alpha = 0.001) linear relationship between species and different sampling sites. The Eigenvalues for first 3 CCA axis were 0.411, 0.396, 0.145 with p value of 0.29, 0.013, and 0.2 respectively. The cumulative total variance (65%) was explained by first 2 axis. The accuracy of correspondence between related pair of species was found to be good for first 2 axis. The CCA biplot for communities reveal that *Trachydium* community positively correlates with soil moisture content and available Nitrogen %; Mixed Herbaceous community positively corelated with clay and moisture content but negatively correlated with pH, Phosphorous % and Potassium %; *Polygonum* community positively correlated with silt pH and Nitrogen %; Mixed *Danthonia* and *Danthonia* negatively correlated with moisture content but positively related to pH, Potassium % and Phosphorous % (Fig. 3.10a).

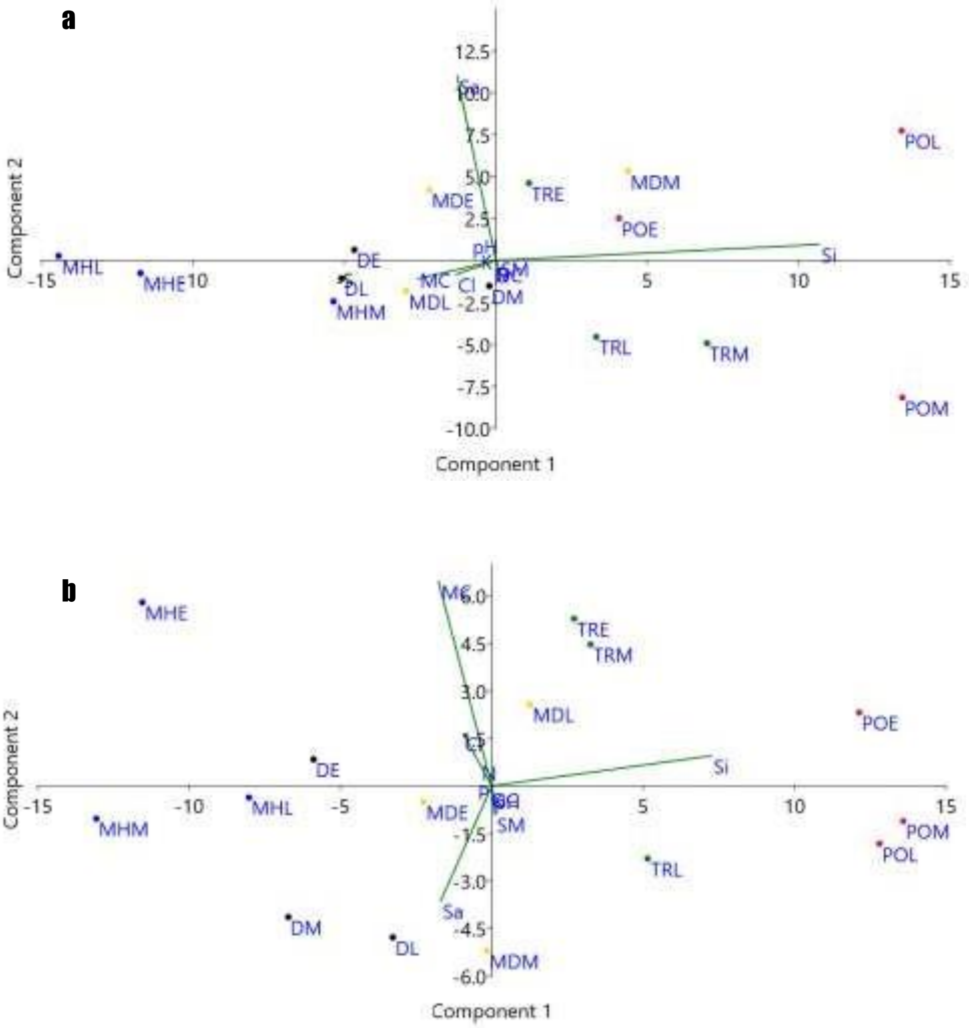


Fig.

9:

Figure 3.9. PCA graph showing relationship of edaphic factors and snowmelt with different communities during early growing period (a: May-June) and late growing period (b: August-September). Environmental factors: Sa: Sand; Si: Silt; Cl: Clay; MC: Moisture content; SM: Snowmelt; OC: Organic carbon %; N: Nitrogen %; P: Phosphorous %; K: Potassium %; Soil pH: pH. Communities: TR: *Trachydium*; MH: Mixed Herbaceous; PO: *Polygonum*; MD: Mixed *Danthonia*; D: *Danthonia*. E, M, L suffix after sites represent Early snowmelt site, Mid snowmelt site, and Late snowmelt site.

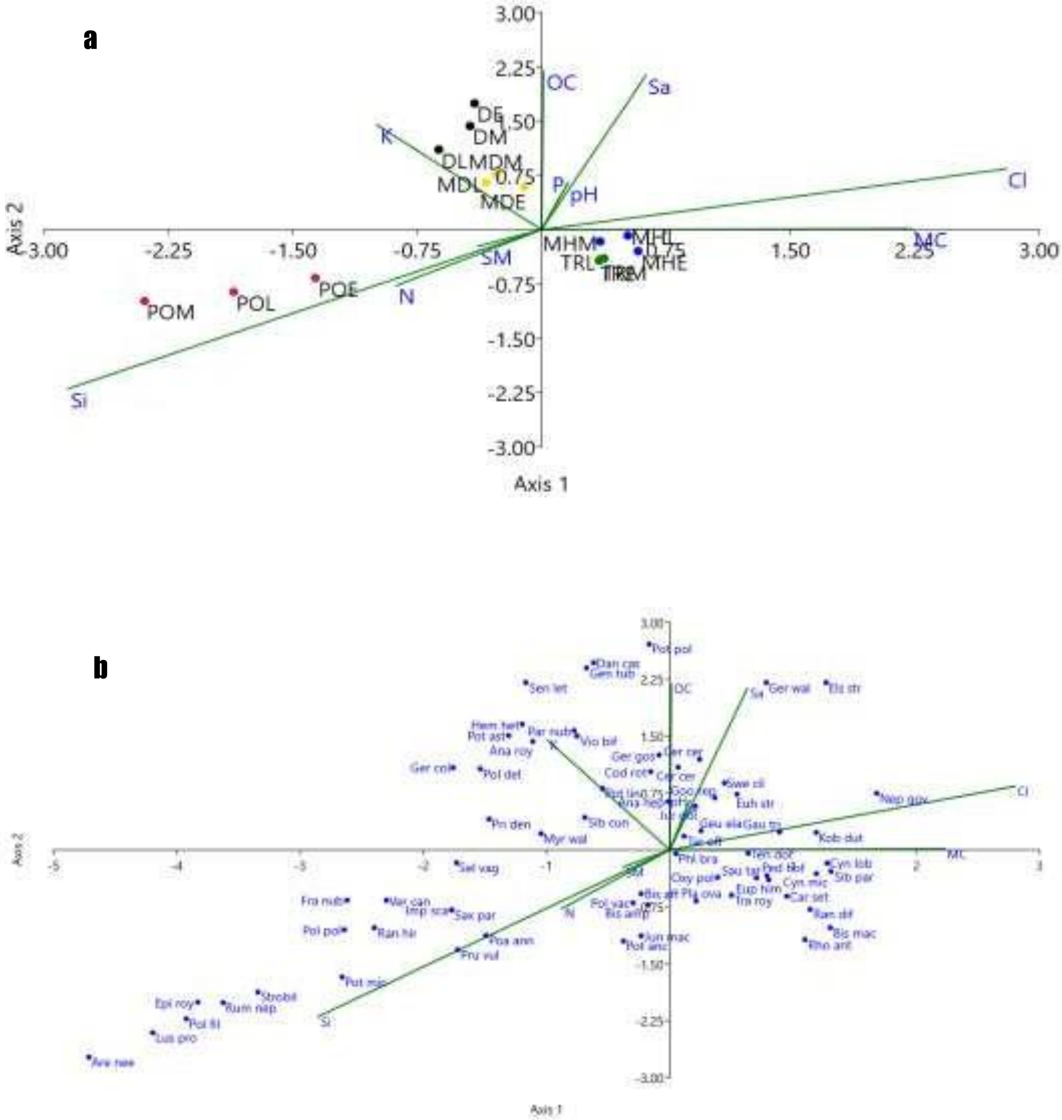


Figure 3.10. CCA graph showing relationship of edaphic factors and snowmelt with different communities (a) and species (b) during peak growing period (August-September). Environmental factors: Sa: Sand; Si: Silt; Cl: Clay; MC: Moisture content; SM: Snowmelt; OC: Organic carbon %; N: Nitrogen %; P: Phosphorous %; K: Potassium %; Soil pH: pH. Communities: TR: *Trachydium*; MH: Mixed Herbaceous; PO: *Polygonum*; MD: Mixed *Danthonia*; D: *Danthonia*. E, M, L suffix after sites represent Early snowmelt site, Mid snowmelt site, and Late snowmelt site.

Species: Ana nep - *Anaphalis nepalensis*, Ana roy - *Anaphalis royeli*, Are nee – *Arenaria neelgherensis*, Bis aff - *Bistorta affinis*, Bis amp - *Bistorta amplexicaulis*, Bis mac - *Bistorta macrophylla*, Bup can - *Bupleurum candollei*, Car set – *Carex setosa*, Cas fas - *Cassiope fastigata*, Cod rot - *Codonopsis rotundifolia*, Cyn lob - *Cynanthus lobatus*, Cyn mic - *Cynanthus microphyllus*, Dan cas – *Danthonia cachemeriyana*, Els str - *Elsoltzia strobilifera*, Epi roy - *Epilobium royeli*, Euh str - *Euphorbia stracheyi*, Eup him - *Euphrasia himalayica*, Fra nub -

Fragaria nubicolia, Gau tri - *Gaultheria trichophylla*, Gen tub - *Gentiana tubiflora*, Ger col - *Geranium colinum*, Ger wal - *Geranium wallichianum*, Ger gos - *Gerbera gossypina*, Geu ela - *Geum elatum*, Goo rep - *Goodyera repens*, Hem het - *Hemiphragma hetrophylum*, Imp sca - *Impatience scabarida*, Jun mac - *Juncus himalensis*, Jur dol - *Jurinea dolomein*, Kob dut - *Kobresia dutheii*, Lus pro - *Lusimachia prolifera*, Myr wal - *Myriactis wallichii*, Nep gov - *Nepta govanianna*, Oxy pol - *Oxygraphis polypetala*, Par nub - *Parnessia nubicola*, Ped hof - *Pedicularis hoffmeisteri*, Phl bra - *Phlomis bractiosa*, Pla ova - *Plantago ovata*, Poa ann - *Poa annova*, Pol del - *Polygonum deliculata*, Pol fil - *Polygonum filicule*, Pol pol - *Polygonum polystrachium*, Pol vac - *Polygonum vaccinifolium*, Pot anc - *Potentilla ancerina*, Pot ast - *Potentilla astrosingiana*, Pot lin - *Potentilla liniata*, Pot mic - *Potentilla microphylla*, Pot pol - *Potentilla polyphyla*, Pri den - *Primula dendiculata*, Pru vul - *Prunella vulgaris*, Ran dif - *Rannunculus diffuses*, Ran hir - *Ranunculus hirtellus*, Rho ant - *Rhododendron anthopogon*, Rum nep - *Rumex nepalensis*, Sau tar - *Saussurea taraxacifolia*, Sax par - *Saxifraga parnessifolia*, Sel vag - *Selenium veginatum*, Sen let - *Senacio letus*, Sib cun - *Sibbaldia cuneata*, Sib par - *Sibbaldia parviflora*, Strobil - *Strobilanthus atropurpurae*, Swe cil - *Swertia ciliate*, Tar off - *Taraxacum officinale*, Ten dol - *Tenacetum dolichophyllum*, Tra roy - *Trachydium roylei*, Ver can - *Veronica canna*, Vio bif – *Viola biflora*

3.3.7 Species-Environment relationship

CCA biplot (Fig. 3.10b) for species environment relationship showed that *Bupleurum candollei, Cerastrium ceratoides, Elsoltzia strobilifera, Euphorbia stracheyi, Gaultheria trichophylla, Geranium wallichianum, Geum elatum, Goodyera repens, Jurenia dolomiaea Kobrasia dutheii, Nepeta govaniana, Swertia ciliata,* and *Taraxacum officinale* have positive relationship with sand, clay, pH, Phosphorous %, organic carbon %, and moisture content which plays critical role in the distribution of these species. However, at the same time, these species showed negative relationship with snowmelt, Nitrogen %, and Silt %. Similarly, *Anaphalis nepalensis, Anaphalis roylei, Codonopsis rotundifolia, Danthonia cachemyriana, Gentiana tubiflora, Geranium collium, Gerbera gossypiana, Hemiphragma heterophyllum, Myriactis wallichii, Parnesia nubicola, Potentilla atrosanguinea, Potentilla liniata, Potentilla polyphylla, Polygonum delicatula, Primula denticulate, Senecio laetus, Sibbaldia cuneata,* and *Viola biflora* showed positive relationship with available Potassium. The species in F3 quadrant namely, *Arenaria neelgherrense, , Bistorta affinis, Bistorta amplexicaulis, Epilobium royeli, Fragaria nubicola, Selenium veginatum, Impatiens scabrida, Juncus himalensis, Lysimachia prolfera, Poa annua, Polygonum filicule, Polygonum polyastachium, Polygonum vaccinifolium, Potentilla ancerina, Potentilla microphylla, Prunella vulgaris, Rannunculus hirtellus, Rumax nepalensis, Strobilanthus atropurpurea, Saxifraga parnessifolia,* and *Veronica canna* showed positive relationship with snowmelt, Nitrogen %, and Silt, while negative relationship with sand, clay, pH, Phosphorous %, organic carbon %, and moisture content. *Trachydium roylei, Plantago ovata, Carex setosa, Bistorta macrophylla, Rannunculus diffuses, Cynanthus microphyllus, Euphrasia himalayica, Oxygraphis polypetalae, Sassuria taraxifolia, Pedicularis hoffmeisteri, Sibbaldia parviflora, Cynanhus lobatus, Tanecetum dolichophyllim,* and *Phlomis bractiosa* showed negative relationship with Potassium % only, and other factors not showing any major influence on population distribution among communities. The overall semi-basal growth form species showed positive interaction with all environmental factors considered in the study, while majority of short-basal growth forms showed their distribution dependence on available Potassium. Erect leafy growth forms however showed positive interaction to snowmelt, Nitrogen %, and Silt respectively.

3.4 Discussion

In present study, the species richness for different communities ranged between 9-36 species per community throughout growing season during study period (2017-2019). Compared to species richness (α diversity, species per site) for different alpine communities of Greater Himalaya, the different communities in present study had 23-36 species per community during peak which is on the lower side of the range reported by Rawat (2007) for mixed herbaceous communities (27-56), Kandara Bugyal in Uttarkashi (36-52), less than Sangla Valley (40-45) and higher than Amarnath in Kashmir (31-35; Rawat, 2007) and Valley of flowers National Park (35-42; Kala *et al*. 1998; Table 3.4). In *Danthonia* community, the species per site ranged between 26-35 species during peak, which is higher than that of reported for *Danthonia* grasslands by Rawat (2007) for Greater Himalaya. The average species richness (species m^{-2}) in present study ranged between 12-22 (highest 25 species m^{-2}) which is less than that of south and southeast facing slopes of Greater Himalaya (25-36 m^{-2}, Rawat, 2007). Two-way ANOVA showed that the variance of species richness between communities in Tungnath is significantly different ($p<0.05$) especially between Mixed Herbaceous and *Polygonum*, Mixed Herbaceous and Mixed *Danthonia* and Mixed Herbaceous and *Danthonia* communities. The above differences showed that although overall climate might be similar for alpine communities, the microhabitats play a significant role in the richness and diversity of herbaceous plants in alpine meadows. The Species density also showed significant differences between *Trachydium* and *Polygonum,* Mixed *Danthonia* and *Danthonia* ($p<0.05$) communities and between Mixed Herbaceous and *Polygonum*, Mixed Herbaceous and Mixed *Danthonia*, and Mixed Herbaceous and *Danthonia* ($p<0.005$) communities.

The diversity values (H') of present study are lower than that of those reported for herb layer of south and south-east facing slopes of the Greater Himalaya (3.01-3.30) by Rawat (2007) and treeline gap (3.23) by Kala *et al*. (1998; Table 3.4). However, the diversity values of present study are comparable with the values reported by Samant and Joshi (2004, 0.29-3.41) for Nanda Devi National Park as a whole, and higher than those reported by Rawat (2007, 2.1-2.4) for Greater Himalaya as a whole, and north facing slopes (1.73), Kala *et al*. (1998) for Valley of Flowers National Park as whole (2.47), Singh (1999) for Upper Tirthan Valley between 3200-3300m (2.39), Adhikari (2004) for Sarson Patal , core Nada Devi National Park (1.57-1.76), and Tambe (2007) (for alpine landscape of Khangchendzonga National Park 1.44-2.48; Table 3.4). The average diversity values for *Danthonia* community in present study during peak (2.59) was less than that of *Danthonia* community (2.81) for Valley of Flowers National Park (Kala *et al*. 1998) and higher than the values reported for Upper Tirthan Valley, Himachal Pradesh (2.10) by Singh (1999).

Table 3.4 Comparative account of Species Richness and Species Diversity (H') in various regions of Greater Himalaya

Study Region (Location)	Elevation Range (masl)	Species Richness	Diversity (H')	Reference
Greater Himalaya (Whole)	>3200	27 - 56	2.1 - 2.4	Rawat, 2007
Khangchendzonga National Park	4000 - 5000	15 - 21	1.44 - 2.48	Tambe, 2007
Manali Wildlife Sanctuary	>3400	20 - 36	2.98 - 3.64	Rana *et al*., 2011
Sarsonpatal, Nanda Devi National Park	4000 - 4500	9 - 14	1.57 - 1.75	Adhikari, 2004
Tungnath	3200 - 3500	12 - 24	1.09 - 2.8	Malik and Nautiyal, 2016
Tungnath Treeline	3200 - 3300	17 - 38	1.6 -3.9	Adhikari *et al*., 2018
Upper Tirthan Valley	3200 - 4000	-	1.61 - 2.62	Singh, 1999
Valley of Flowers National Park	3200 - 4400	35 - 42	1.48 - 3.23	Kala *et al*., 1998
Tungnath	3250 - 3500	9 - 36	1.48 - 2.84	Present Study

An analysis of Raunkaier's life form across Greater Himalaya shows that Hemicryptophytes dominate most alpine meadows (Sundriyal *et al*. 1987; Nautiyal, 2001; Rawat 2007; Dad and Khan, 2010; Vashistha *et al*. 2011; Kumar, 2016) with some exceptions as reported by Ram and Arya (1991) in Rudranath region, Pangtey *et al*. (1990) for Central Himalaya and Dhar and Kachroo (1983) in Yusmarg indicating the higher proportion of Chamaephytes (31, 47 and 46%, respectively). It is interesting to note that the percentage of hemicryptophytes (87.5%) have increased considerably in alpine region of the study area compared to the past study conducted by Sundriyal *et al*. (1987) while other life forms' contribution decreased drastically. The higher percentage of hemicryptophytes in the Greater Himalaya of Uttarakhand is probably because the majority of meadows are w*et al*pine meadows due to higher precipitation while the rest of meadows are drier leading to higher percentage of Chamaephytes (Table 3.5).

Table 3.5. Comparative account of life forms in various regions of Greater Himalaya (Ph: Phanerophyte; Ch: Chaemophyte; He: Hemicryptophyte; Hy: Hydrophyte; Ge: Geophyte; Th: Therophyte)

Study area **(#: Number of species)**	**Life form***						**Reference**
	Ph	**Ch**	**He**	**Hy**	**Ge**	**Th**	
Panwalikantha	8.3	6.8	44.7	-	35.0	5.3	Nautiyal (1996)
Central Himalaya (Snowline)	-	46.7	30.0	-	18.3	5.0	Pangtey *et al*. (1990)
Yusmarg	10.4	46.4	25.4	-	10.2	6.2	Dhar & Kachroo (1981)
Tungnath	-	27.0	43.0	-	18.0	12.0	Sundriyal *et al*. (1987)
Tungnath (#171)	6.4	10.5	48.0	-	29.2	12	Nautiyal *et al*. (2001)
Tungnath Grazed area (#68) and Ungrazed area (#65)	4.4 6.2	16.2 15.4	50.0 49.2	- -	26.5 26.2	2.9 3.1	Vashistha *et al*. (2011)
Rudranath (# 142)	2.8	31.0	24.6	-	28.9	12.7	Ram & Arya (1991)
Valley of Flowers (# 525)	7.5	6.1	68.4	0.4	11.8	5.0	Rawat (2007)
Kashmir	5.7	13.8	48.3	-	13.8	18.4	Dad & Khan (2010)
Upper Dhauli Valley (#495)	11.9	5.1	61.4	0.2	10.5	11.1	Kumar (2016)
Tungnath region (Treeline, # 86)	**2.4**	**3.5**	**83.5**	**-**	**2.4**	**8.2**	Adhikari *et al*. (2018)
Normal	46.6	9.0	26.0	2.0	4.0	13.0	Raunkaier (1934)
Tungnath (Alpine, # 80)	**-**	**2.5**	**87.5**	**-**	**3.7**	**6.25**	Present Study

In the present study, phanerophystes were absent while therophytes (6.3%), geophytes (3.7%) and chamaephytes (2.5%) had very less presence in the alpine communities. Most of the species (70%) are native to the Himalayan region, 11% Indian subcontinent and 8% Indian origin which indicates the high conservation value of Tungnath region. A major reason for the dominance of hemicryptophyte might be better adaptation to grazing, trampling and other environmental factors viz. wind, heavy rainfall/erosion, and heavy frost than that of other life forms (Sternberg *et al*. 2000; Hanninen*,* 2016).

The 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). Besides species richness, changes in community composition due to warming have also been observed over time and experimental treatments (Wahren *et al*. 2013). This influence seems to vary among local habitats globally leading to significant variability in observed responses, as some communities are more susceptible to shifts due to longer growing season (Elumeeva *et al*. 2013) while others may give way to shrub encroachment or changes in life form dominance depending on the changes in snowmelt timing (Kudo *et al*. 2010, Jagerbrand *et al*. 2009).

The warming and snowmelt are not the only factor leading to changes in community composition. The grazing and anthropogenic pressure is another leading component in alteration of species composition overtime. According to McIntyre and Lavorel (2001) annual grasses, low growing leafy perennials (grasses, sedges, and forbs) and mat forming herbs like *Trachydium* are associated with excessive grazing in alpine region. These are present in abundance and form dominant vegetation composition across different communities leading to higher grazing intensity in present study area. This encourages perineal species clonal growth (Nautiyal *et al*. 1997) however, unrestricted grazing affects balance between survival and vegetative spread of plants and establishment of its seedlings (Bullock *et al*. 1994). The grazing suppression increases the perennial grasses and long vegetative growth cycled plant resulting in rapid decline in species diversity (Hill *et al*. 1992).

In Tungnath, the 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 is resulting in early snowmelt in the alpine communities of Tungnath leading to moisture not be a limiting factor for germination in early growing period. The snowmelt timing and soil moisture influences plant growth in treeline and alpine areas (Winkler *et al*. 2018) and many studies demonstrates increase in site productivity with advancing snowmelt timing (Kudo, 1991; Stanton *et al*. 1994; Litaor *et al*. 2008). Nautiyal *et al*. (2004), showed increase in early growing species and long growth cycle species over a period of 10 years in Tungnath region. Furthermore, they showed heavy grazing may incite invasion of species in w*et al*pine meadows (Nautiyal *et al*. 2004) by creation of gaps by the suppression of dominant palatable growth forms (Watt and Gibson, 1988) leading to increase in diversity. Over the period there is an obvious increase in relative humidity, frost point, rainfall, the maximum and minimum temperature (Adhikari and Kumar, 2020) while decrease in diurnal range during peak growing season (12.2 ºC in June in 1984, Sundriyal *et al*. 1987; 6.27 ºC in August in 2018, present study) which may lead to opening of alpine meadows to lower elevation species by decreasing degree of environmental constraints, thus creating pressure for upward migration for alpine species, as establishment of the migrating species was recorded by Nautiyal *et al*. (2004) in Tungnath meadows with 2° C increase in the maximum temperature and early snowmelt. Similar trends of species encroachment from timberline/treeline into alpine meadows have been observed globally (Sturm *et al*. 2001, 2005; Kullman, 2002; Dullinger *et al*. 2003; Tape *et al*. 2006; Buras *et al*. 2012), in some cases leading to local extinction of purely alpine species (Parmesan, 2006).

The early snowmelt results in a longer period of growth, provided there are species to take this advantage. This might be a reason for high species richness and density in *Trachydium* and Mixed Herbaceous communities than that of other communities. Wide range species like *Taraxacum officinale, Potentilla atrosanguinea* and *Anaphalis* spp., take advantage and show presence in early growing season multiplying rapidly across different communities. Furthermore, these are non-palatable thus further increasing their survivability while specialized species like *Dactylorhiza*, *Picrorhiza* etc., are equipped to exploit only a narrow set of specific resources in particular habitat/communities which may put greater pressure on these species due to upward migration of low elevation species along with grazing and anthropogenic pressure. Besides macro-climate, soil water content variations and other variables related to topography also largely influence species richness at micro-climatic scale (Nabe-Nielsen *et al*. 2017), furthermore snow loss might lead to an increase in species richness.

Changes in climatic patterns may induce changes in vegetation composition during early growing season and long season by increase/decrease in abundance alone (Jagerbrand *et al*. 2009) or in combination with productivity (Zheng and Welker, 1996; Wahren *et al*. 2013) which may be consistent for shrubs and inconsistent for gramanoids and forbs. To understand long term changes in community structure and composition, it is imperative to understand different functional traits to predict changes in abundance (Spasojevic and Suding, 2012) as demonstrated by Soudzilovskaia *et al*. (2013) where high leaf mass index species increased in abundance with increasing temperature. Similarly, other studies suggest thermophilization of alpine species by decrease and increase in abundance of cold growing and warm adaptive species (Gottfried *et al*. 2012; Rosbakh *et al*. 2014; Elmendorf *et al*. 2015; Gigauri *et al*. 2016).

3.5 Conclusion

Numerous studies conducted worldwide have highlighted early snowmelt as a significant factor driving changes in communities, often resulting in increased species richness and density. However, the findings of the current study reveal a non-significant decrease or no change in species richness within the same community in a small microhabitat. Nevertheless, when compared to past studies, it is observed that the proportion of hemicryptophytes has increased in the study area. This suggests that the response of the community may differ at the microhabitat scale compared to the broader altitude scale. Further investigation is necessary, considering the lengthy growth period and diverse climatic conditions and orography across the alpine region of the Himalayas.

Therefore, it is crucial to minimize confounding factors, examine trends in undisturbed areas, and assess significant associations with climate change. Particularly in the Himalayas, where there is a lack of sufficient basic studies encompassing different climatic and topographic regimes, it is necessary to understand the patterns and associations of various environmental factors with changes in community structure and composition. The present study emphasizes the need for an increase in primary level studies and advocates for the establishment and long-term monitoring of permanent plots to comprehend the effects of climate change on vegetation composition and soil stability in alpine regions of the Himalayas. Consequently, it is essential to regularly record the structure and composition of different alpine regions to gain insights into the various drivers influencing community changes in the current warming environment before drawing definitive conclusions.

4. Temporal Changes in Species Phenology

4.1 Introduction

Over the past few decades seasonality changes as characterized by early seasonal above-average warming and changes in precipitation regimes leading to earlier snowmelt (Stocker *et al*. 2013; Ernakovich *et al*. 2014) may cause drastic change for alpine systems. The increase in isolated events of extreme precipitation (Wanner *et al*. 1997) as well as greater interannual variability due to increasing temperature (Beniston *et al*. 1997) in alpine systems has been recorded across the globe. Over past several decades warming across alpine has shown elevation dependence, i.e high elevation mountains are warming up faster than the low elevation mountains, and geographic dependent effects (Giorgi *et al*. 1997; Theurillat and Guisan, 2001; Rangwala and Miller, 2012; MRI, 2015) on snow regimes.

But this trend globally is unconfirmed (Oyler *et al*. 2015), especially in relation to regional trends of warming, which deviate from global trends (Zhang *et al*. 2007). This is because warming is expected to be asymmetrical i.e higher in winter and lower in summer (Stocker *et al*. 2013), emphasizing on local topographic influence on direction and magnitude of changes especially in relation to snow persistence, melt pattern, growing season, plant production etc.

This exposes alpine ecosystems to climate changes at a faster rate than the lowlands. The alpine plants, in general, flower and reproduce quickly after snowmelt to take advantage of relatively shorter snow-free growing season with various adaptations to cope with intense solar radiation (Kirshbaum, 1995). Due to these adaptation these plants show greater sensitivity to biological and chemical processes (Kirshbaum, 1995). Theoretically, this may elicit a larger response in alpine species to even small environmental changes, making alpine environments an indicator of environmental changes (Petralgia *et al*. 2014; Pervey *et al*. 2017). One such consequence of warming is alteration of plant phenology of alpine ecosystems (Kudo, 2020).

Phenological modifications are one of the most serious warming impacts on, be it up land or lowland, alpine systems (Parmesan, 2006,2007; Ovaskainen *et al*. 2013). This not only influence individual species fitness, but also the population dynamics, migration, facilitation, interspecific interactions, or local species extinctions lead to change in community structure (Elzinga *et al*. 2007). The long-term monitoring already suggests advance of plant phenophase initiation during early spring and lengthening of phenophases in mid or late growing season with multiple studies reporting species specific interannual variations of reproductive phenophase in response to warming (Myneni *et al*. 1997, Parmesan and Yohe 2003; Root *et al*. 2003; Molau *et al*. 2005; Studer *et al*. 2005; Hoffmann *et al*. 2010; Hülber *et al.* 2010; Wolkovich *et al.* 2012). This will lead to a long growing season with increased primary production (Edwards and Richardson, 2004) and may have cascading effects on reproductive synchrony, pollinator interactions (Memmott *et al*. 2007; Liu *et al*. 2011) and birds and mammals depending on vegetative matter or seeds (Moritz *et al*. 2008) further limiting suitable habitat for endemics and cryophilic species (Dirnbock *et al*. 2011; Walther er al. 2005).

Most studies in alpine and arctic ecosystems are manipulation experiments that either shows an advance in flowering phenology in response to warming (Abeli *et al*. 2012; Barrett and Hollister, 2016; Bjorkman *et al*. 2015) via change in temperature (Kopp and Cleland, 2015) or an advance in snowmelt (Wipf *et al*. 2009; Iler *et al*. 2013; Petralgia *et al*. 2014) while some shows delay in phenology due to increase in snow and additional warming (Cooper *et al*. 2011; Smith *et al*. 2012). Some experiments also show varied response to warming events, with some species neither advancing nor delaying the timing of spring events (Sherry *et al*. 2007; Reyes-Fox *et al*. 2014; Marchin *et al*. 2015) while other experiments show advance and delay in species phenology of species in same habitat under changes in snowmelt regime (Adhikari *et al*. 2018, 2020). Therefore, species under different snow regimes may give different responses depending on local topographic influence. Petralgia *et al*. (2014) documented that the early snowmelt without warming may not affect phenology significantly while another study by Wipf *et al*. (2009) showed that the early snowmelt causing frost damage due to cooler temperature. Some snow manipulation experiments in sub-alpine ecosystems have shown species advancing their phenology initiation but showing no effect on phenophase period

(Gezon *et al*. 2016; Dunne *et al*. 2004) even through years and greater overlap between co-flowering species.

Across the globe, much work has been conducted on phenology of alpine and subalpine species (Hegland *et al*. 2009; Inouye, 2008; Walck *et al*. 2011) focusing on temperature/growing degree days (Haggerty and Galloway, 2011; Shen *et al*. 2014), phenotypic plasticity and adaptation (Byars *et al*. 2007; Frei *et al*. 2014; Gonzalo-Turpin and Hazard, 2009), but there is a lack of even baseline studies in context to Western Himalaya. Although multiple studies have been conducted to understand floristic diversity and composition in Western Himalayan alpine landscape, only a few studies can be found on herbaceous phenology of alpine plants (Sundriyal *et al*. 1987; Ram *et al*. 1988; Negi *et al*. 1992; Kala, 1999; Nautiyal *et al*. 2001; Vashistha *et al*. 2009; Bijalwan *et al*. 2013; Bisht *et al*. 2014; Adhikari and Kumar, 2020) that too focusing on community phenology, with very few records for species phenology (life cycle).

Similarly, there is a severe lack of data for alpine species phenology (life cycle) as well as phenological response to warming climate in Western Himalaya. Therefore, there is a need to not only record present phenology of alpine species; there is also a need to study phenological sensitivity of different species. This is especially needed in relation to spatial and temporal variations within a given set of parameters, which may be different especially in IHR (elevation range of treeline ~2000m from West to East Himalaya), and might result in species showing wide range of behavior under similar conditions depending on orography. This is especially true for the studies on relationship between snowmelt and phenology in the Himalaya, due to remoteness and difficult terrain leading to inaccessibility to conduct long term ecological monitoring is a task.

With this background this study deals with temporal changes happening in five dominant alpine communities of wet alpine meadows in Tungnath. Furthermore, the temporal changes in growth form phenology for the study area is also presented in the chapter. The chapter also deals with phenology of all species recorded in the study area with respect to different communities/habitat types, as well as the phenology of specific species have changed over time by comparing phenograms of 13 species available from past studies.

4.2 Methods

4.2.1 Phenological observations

The phenological changes in the species were monitored visually at fortnight 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 (2017-2019) following "Biologische Bundesanstalt, Bundessortenamt and CHemischeIndustrie"(BBCH) scale by Hess *et al*. (1997) and modified by Adhikari *et al*. (2018; Table 4.1). The existence of a particular phenophase was considered if 5% of the individuals were in that phenophase. Based on the 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).

Table 4.1 Various stages, their names and description as per BBCH scale (Hess *et al*. 1997, modified Adhikari *et al*. 2018).

Code	Stage	Code Names	Code description
0	Vegetative phase	Germination/sprouting/bud development	From dry seed till leaf breaks the soil
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
4	Reproductive Phase	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 end of flowering till fruit set visible
7	Fruit/Seed development and Maturation	Development of fruit	Fruit begins to develop till maturity for species and location
8		Ripening and maturity of fruit or seed	Beginning of ripening o fruit colouration till fully ripe
9	Senescence	Senescence or beginning of dormancy	Plant dead or plant resting or dormant

4.3 Results

4.3.1 Temporal changes in communities

In *Trachydium* community during study period (2017-2019), the vegetative phase initiated in May and lasted till August with a peak in June. The reproductive phase initiated in May and lasted till October with a peak in August. The fruiting phase lasted from June to September in 2017 and 2019 and, July to September in 2018. In 2017, the species in fruiting phase gradually increased as growing season progressed till their peak in September while in 2018 and 2019, species increased sharply in July then declined in August and attained peak in September respectively. The senescence initiated in July and sharp increase was observed August onwards with a peak in October, during the study period except in 2018, the senescence was also recorded in May (Fig.4.1).

In Mixed Herbaceous community, the vegetative phase initiated in May and lasted till August in 2017 and October in 2018 and 2019 with a peak in June. The reproductive phase initiated in May and lasted till September and peaked from July to September in 2017, July-August in 2018 and July in 2019. The fruiting phase duration was July-October in 2017, in June-September in 2018 and June-October in 2019 with a peak in August for the study period. In 2017, few species showed senescence in July after which the phase was observed September onwards. Senescence phase initiated in June in 2018, and number of species in senescence increased sharply August onwards. Like 2017, in 2019 senescence phase was recorded during May-June and then August onwards (Fig. 4.1).

In *Polygonum* community, the vegetative phase initiated in May and lasted till September, with a peak in May in 2017 and 2018, and July in 2019. The reproductive phase initiated in May, with a peak in September and lasted till October in 2017, but in 2018 and 2019 the peak was observed in August and lasted till September. The fruiting phase initiated in July in 2017 and 2018 and June in 2019 and with a peak in August during the study period. The fruiting lasted till October in 2017 and September in 2018 and 2019. The senescence phase initiated in July in 2017 and 2018, while in June in 2018 with a peak in October and number of species in senescence increased sharply August onwards (Fig. 4.1).

In Mixed *Danthonia* community, the vegetative phases initiated in May and lasted till September peaking in July. The reproductive phase initiated in May, peaked in August and lasted till October. The fruiting phase initiated in July in 2017 and 2018 and in June in 2019 while peak was observed in September in 2017 and August in 2018 and 2019. The fruiting lasted till October in 2017 and September in 2018 and 2019. The senescence phase was recorded in June-July in 2017 after which it was recorded in September. The senescence was initiated in June and May in 2018 and 2019, respectively. The number of species in senescence increased sharply August onwards (Fig. 4.1).

In *Danthonia* community, the vegetative phase initiated in May and lasted till July in 2017 and 2018 and till September in 2019. The vegetative phase peaked in July in 2017 and May in 2018 and 2019. The reproductive phase initiated in May, with a peak in September in 2017 and August in 2018 and 2019. The fruiting phase was quite short in 2017 lasting only June-July, but initiated in May with a peak in August, and lasted till September in 2018 and 2019. The senescence phase was first recorded in July in 2017 and 2018 and in June-July in 2019, after which it was recorded in September (Fig. 4.1).

At a community level as indicated by species number, during the study period (2017-2019), in general, the vegetative phase peaked in June for *Trachydium* and Mixed Herbaceous community and July for remaining communities, Mixed *Danthonia, Polygonum* and *Danthonia*. The flowering peaked in all communities in August while the fruiting peaked during September in *Trachydium* and Mixed Herbaceous communities and in August in Mixed *Danthonia Polygonum*, and *Danthonia* communities. The senescence phase peaked in October in all the communities (Fig. 4.2).

The communities supported the vegetative as well as the reproductive growth of plants even after the end of rainy season and it especially lengthened in open communities (not surrounded by *krummholz* and dwarf shrubs) like *Trachydium,* Mixed Herbaceous and

Polygonum, but a certain number of species entered in the senescence phase at end of June and beginning of July. No major time difference was observed in fruiting and seeding phase between communities (Fig. 4.2). It is important to note that the species common to more than two communities, their phenological behaviour varied depending on the prevailing micro-climatic conditions in the communities. Sometimes they showed all phases in all communities or sometimes a phenophase was absent in one community but present in other community.

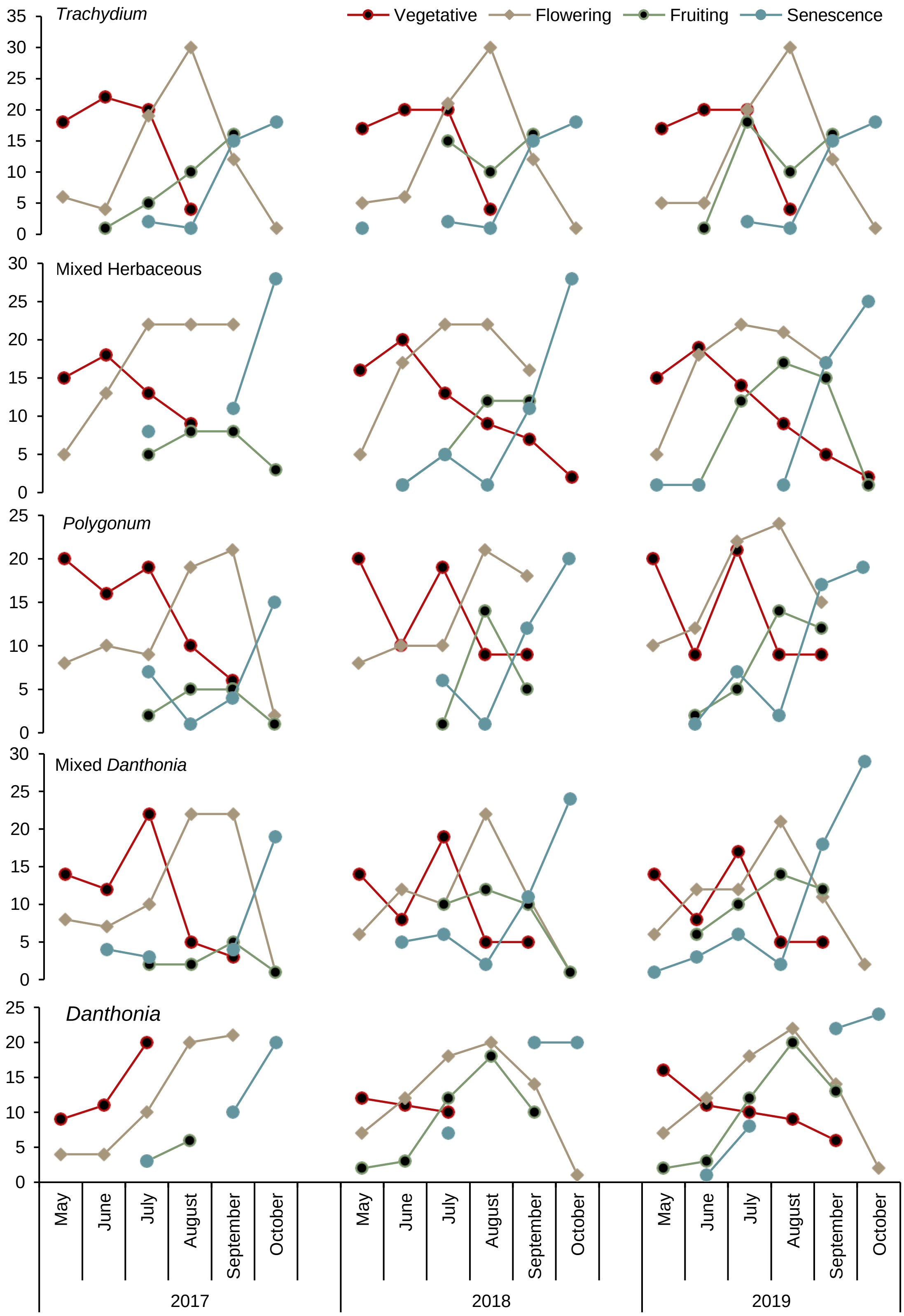


Figure 4.1. Temporal changes in number of species present in different phenophases

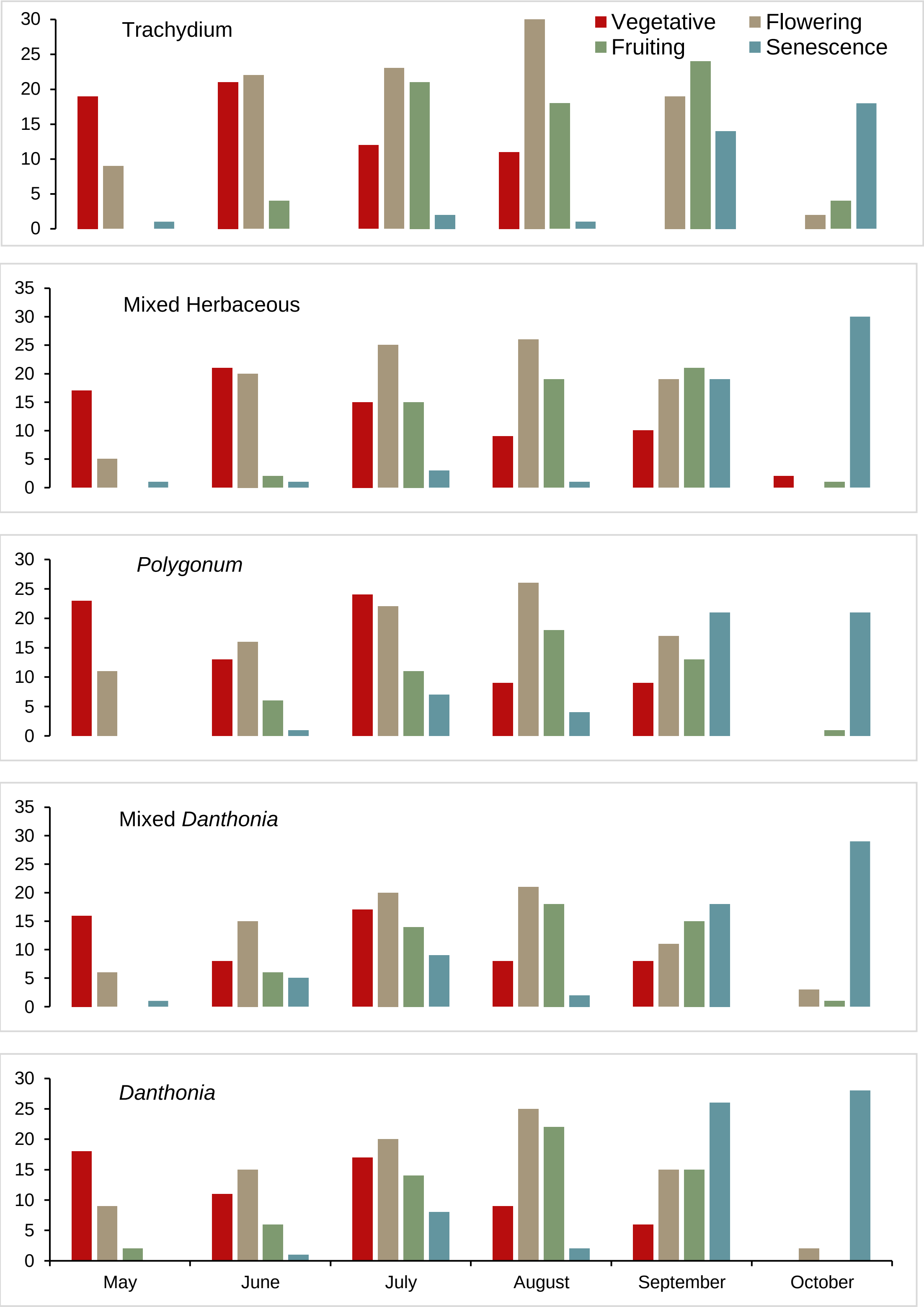


Figure 4.2. Species under different phenophases across growing season

4.3.2 Temporal changes in species present in a single community

Five species were unique to *Trachydium* community of which, *Anemone obtusiloba* only showed vegetative phase during the early growing period for a month period and then disappered. Similarly, *Bistorta macrophylla* initiated vegetative phase in early June, and showed two distinct reproductive phase (mid to late June and August) and fruiting phase (July and September), but the senescence phase was absent. *Cassiope fastigata* initiated vegetative and reproductive phase simultaneously in early May while reproductive phase dominated by mid-May. The vegetative phase reappered again in June while reproductive phase reappered in late June. The fruiting initiated in mid-July and declined gradually till mid-August and than increased till late September transition with reproductive phase and senescenced by late September. *Potentilla fulgens* initiated vegetaive phase in early May and disappeard than reappered early August. It flowered early September and senescenced in late September while fruiting phase was absent. *Potentilla microphylla* initiated vegetative phase in early July, reproductive phase in late July, fruiting in early September and senescence phase in early October (Fig. 4.3).

Four species were unique to mixed Herbaceous community. *Cynanthus microphyllus* was present in 2018 onwards and initiated vegetative phase in early June, reproductive phase in late June, fruiting and senescence phase by early and mid-August. In *Nepeta govaniana*, the vegetative phase initiated in early July, reproductive phase in early August, fruiting and senescence phase by early and late September respectively, and was absent in September 2018 onwards. In *Rannunculus diffusus* both vegetative phase and reproductive phase saw two distinctive period. The vegetative phase initiated in early May and later in early June where it gradually replaced by reproductive phase, while reproductive phase initiated mid-May till early July and mid-August to mid September. Fruitinig phase was absent and senescence started mid-September. In *Sibbaldia parviflora*, the vegetative phase started in late May, reproductive phase in late June, fruiting initaited mid-August, while senescence early September (Fig. 4.3).

Nine species were unique to *Polygonum* community. *Corydalis cornuta* initiated vegetative phase in early May, reproductive phase in mid-June, fruiting and senescence early and mid-August respectively. *Dactylorhiza hatagirea* initiated the vegetaive phase in early May and disappeard than reappered again in mid-July. The reproductive and fruiting phase initiated early and late August, respectively while the species entered senescence in early September. *Impatiens scabrida* initiated vegetative phase in early July, reproductive phase in early August and senescence in early September, while fruiting was absent. *Lysimachia prolifera* was present 2018 onwards and initiated growth in May and than disappered by mid-June and reappeared in early July, while reproductive and fruiting phase started in late July and August, respectively; after which it again entered in vegetative phase in early September and entered in senescecne at the end of September. *Morina longifolia* was present in vegetative form in May only. *Primula edgeworthii* initiated the vegetative and reproductive phases in early and mid-May, repectively after which it disappered and reappered in vegetative phase in early July and entered into the reproductive phase within a week. The fruiting initiated in late July. The reproductive and fruiting phases run simultaneously till late August after which fruiting phase dominated. The senescecne lasted mid to late September. *Rumex nepalensis* initiated the vegetaive phase in early May, reproductive phase in mid-June, fruiting in early August, and senescence in early September. *Saxifraga parnassifolia* initiated the vegetative and reproductive phases in early and late July and senescence phase in early September while the fruiting phase was absent. *Strobilanthus purpurea*, the vegetative phase initiated in early July while reproductive phase inititated in mid-July, but did not dominated till early August. The fruiting and senescence phases initiated in early and mid September, respectively (Fig. 4.3).

Only two species were unique to Mixed Danthonia community. *Geranium pratens* inititated the vegetative and reproductive phases in early and mid-July, fruiting phase in early August and senescenced in early September. *Smilacina purpura* initiated the vegetative phase in early June, reproductive phase in mid-July and senescenced in late September while the fruiting phase was absent (Fig. 4.3).

Six species were present only in Danthonia community. *Aconitum heterophyllum* was recorded only in 2017 and 2018 but was absent in 2019. It only showed the vegetative phase in 2017 and 2018, in early May and reproductive phase in early June and disappered by mid-June. *Caltha palustris* initiated the vegetative growth in early May and immidietly entered into reproductive phase. It senescenced and disappered by early and mid-June, respectively. *Codonopsis rotunifolia* initiated the vegetative and reproductive phases in early and mid-July, respectively while fruiting was observed in 2nd and 3rd week of August after which it senescenced. *Elsoltzia strobilifera* was recorded only in 2017 and entered the vegetative phse in early June after which it showed senescence phase early July onwards. It commneced the reproductive phase in early August and returned to the vegetative phase in late August and senescened again in late September. *Gerenium wallichianum* initiated the vegetative phase in early June, reproductive phase in mid-July and senescened in late September. The fruiting was absent during the study period while in 2019 it was only present in the month of August in reproductive phase. *Hemiphragma heterophyllum* initiated the vegetative phase in mid-July, reproductive and fruiting phases in early and mid-August, respectively and senescened in early September (Fig. 4.3).

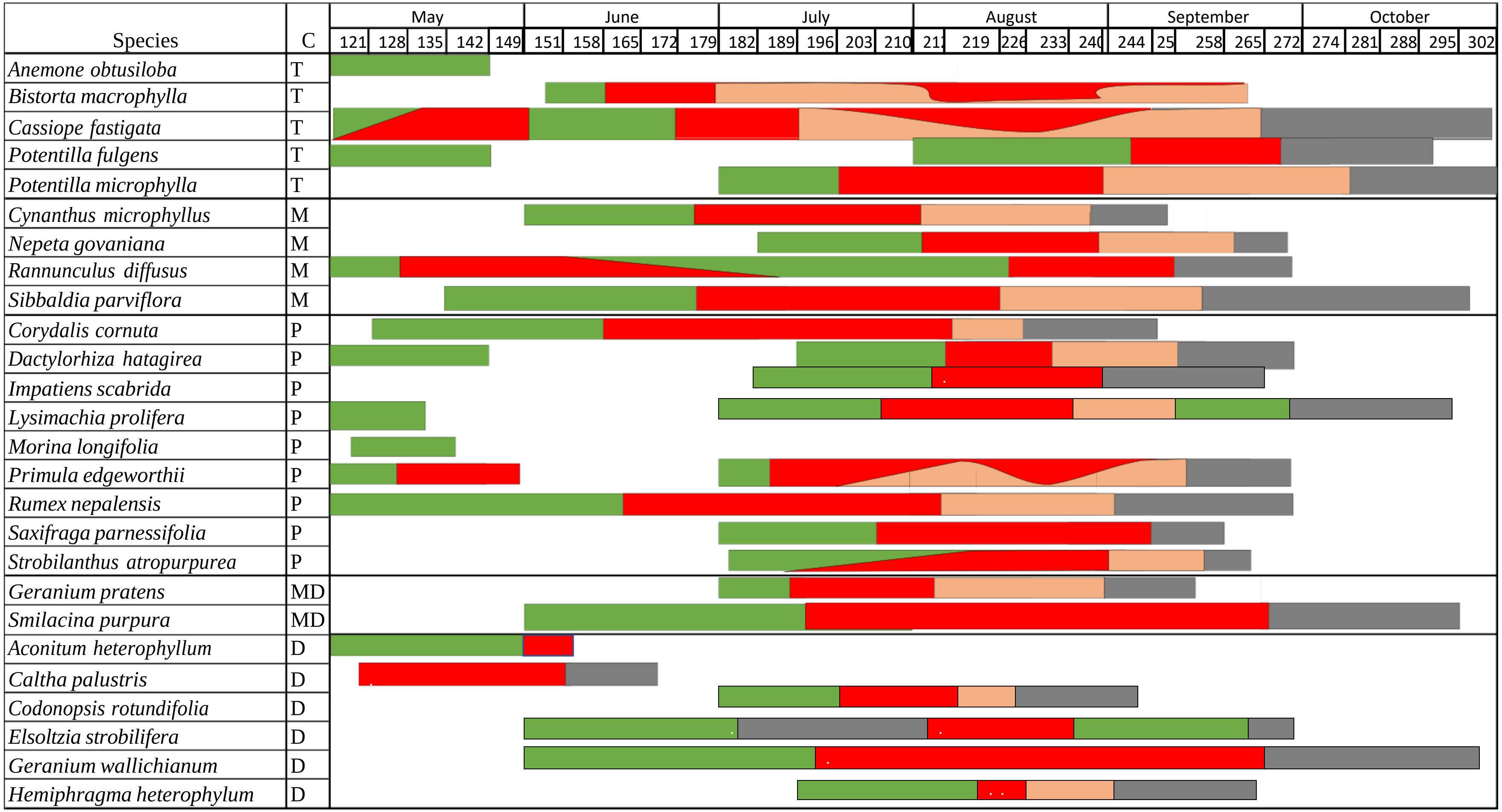


Figure 4.3. Phenogram of species unique to communities. (T: *Trachydium;* M: Mixed Herbaceouos ; P: *Polygonum*; MD: Mixed Danthonia; D: *Danthonia*; Green: Vegetative, Red: Reproductive, Pink: Fruiting and Seeding, Grey: Senescence)

4.3.3 Temporal changes in species present in two Communities

Cynanthus lobatus was common between *Trachydium* and Mixed Herbaceous community. It initiated the vegetative phase in early and mid-June. The reproductive phase started in mid-July while fruiting and senescence phases were recorded early and mid-September onwards, respectively in *Trachydium* community while in Mixed Herbaceous community the reproductive phase was observed twice, initiated in late June and attained peak by mid-July. The fruiting started in mid-August and declined gradually from late August till early September and gradually replaced by reproductive phase which lasted till mid September giving way to senescence (Fig. 4.4).

Polygonum delicatula and *Prunella vulgaris* were common to *Trachydium* and *Polygonum* communities. *Polygonum delicatula* initiated the vegetative phase in early June and mid-May, reproductive phase initiated in early July and late June while senescence in mid and early September. It showed two distinctive vegetative and reproductive phases in *Trachydium* community while fruiting was only present in *Trachydium* community. In Prunella vulgaris the vegitative phase was recorded in Polygonum community only in early July. The reproductive phase started in mid-July in both communities lasting briefly for 1 and 2 weeks respectively. In *Trachydium* community reproductive phase reappered in early August till late August. The fruiting started in mid and late July, in *Trachydium* and *Polygonum* communities and ended in early and mid-September, respectively. The reproductive phase showed two distinct periods in *Trachydium* community (Fig. 4.4).

Geranium collinum and *Senecio laetus* were common between *Polygonum* and mixed *Danthonia* communites. In both communitie, the vegetaive phase in *Geranium collium* initiated in early July, while the reproductive phase initiated in mid and early August in *Polygonum* and mixed *Danthonia* communities, repectively. The fruiting and senescence initiated in late August and early September, respectively. *Senecio laetus* started vegetative phase in early July, while the reproductive phase started in late July and August in *Polygonum* and Mixed *Danthonia* communities, respetively. The fruiting was absent and senescence phase started in late September in both communities, but lasted till September end in *Polygonum* community and till late October in mixed *Danthonia* community (Fig. 4.4).

Four species were common between *Polygonum* and *Danthonia* communities. *Arenaria neelgherrense* germinated and entered into the vegetative phase in early May in both communities. However, in *Polygonum* community it showed vegetative phase only, in *Danthonia* community it entered into reproductive phase and than disappered in early and late June. In *Polygonum* community, *Cerestrium ceratoides* entered the vegetative and reproductive phases in early and mid-May till June end after which it reentered into the vegetative phase, while in *Danthonia* community, the vegetative phase was initiated in early July, reproductive and fruiting phase in early and late August, respectively and senescence in late September. The fruiting and senescecnce phases were absent in *Polygonum* community. In *Myriactis wallichi*, in both communities, the vegetative and reproductive phase initiated in early and late July, respectively and senescence in early September, while the fruiting phase was absent in both communities. *Polygonum filicaule* entered the vegetative phase in mid-June and early July in *Polygonum* and *Danthonia* communities, respectively while it entered into reproductive phase a month after in mid-July and early August and ended mid-September give way to fruiting phase in *Polygonum* community and the vegetative phase in *Danthonia* community. The senescence started early in early October and late September (Fig. 4.4).

Danthonia cachemyriana was present only in Mixed *Danthonia* and *Danthonia* communities. It initiated the vegetative phase in early July and mid-June in mixed *Danthonia* and *Danthonia* communities, respectively, while the reproductive phase in early August and mid-July, respectively. The fruiting phase was recorded in *Danthonia* community only in late August, which start declining gradually with onset of senescence in mid and early September in mixed *Danthonia* and *Danthonia* communities, respectively (Fig. 4.4).

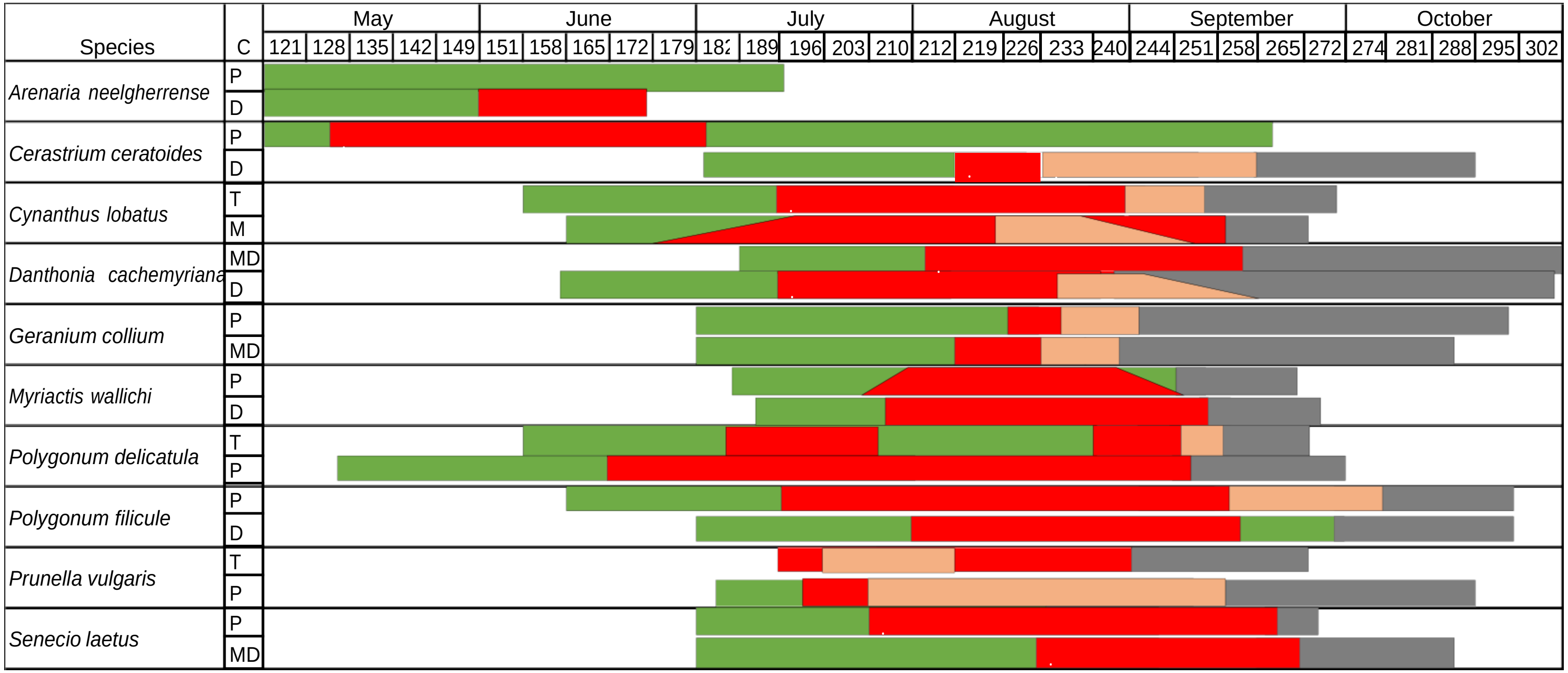


Figure 4.4. Phenogram of species common to two communities. (T: *Trachydium;* M: Mixed Herbaceouos ; P: *Polygonum*; MD: Mixed Danthonia; D: *Danthonia*; Green: Vegetative, Red: Reproductive, Pink: Fruiting and Seeding, Grey: Senescence)

4.3.4 Temporal changes in species present in three communities

A total of nine species were common to three communities. *Polygonum vaccinifolium* was present in *Trachydium,* Mixed Herbaceous and *Polygonum* communities. The vegetative phase was initiated in early July in *Trachydium* and *Polygonum* communties and mid-May in Mixed Herbaceous community. It showed two distinctive reproductive phases, from mid-June to early July and late July to early September, respectively in *Trachydium* community, while reproductive phase was initiated in early July in Mixed Herbaceous and *Polygonum* communities. The fruiting and senescence phases were present in *Trachydium* and Mixed Herbaceous communities only, and absent in *Polygonum* community. In *Trachydium* community, two distinctive fruiting phases (mid-July and early to mid-September) were recorded, while in Mixed Herbaceous community the fruiting phase initiated in early September. The senscence commenced by 3rd and 4th week of September in *Trachydium* and Mixed Herbaceous communities, respectively. *Phlomis bractiosa* was common to *Trachydium,* Mixed Herbaceous and Mixed *Danthonia* communities. In *Trachydium* and Mixed Herbaceous communites the vegetative phase initiated in early June while the reproductive phase initiated in early and mid-June, repectively and showed two distinct periods. Similarly, the fruiting phase showed two distinct periods in these two communities from mid-July to early August and late August to September, respectively and the sensescence phase initiated in mid and early September in both communities. In Mixed *Danthonia* community, the vegetative phase initiated in early July, the reproductive in mid-July, the fruiting phase in late August and senescence in mid-September. *Epilobium roylei* was common to *Trachydium, Polygonum* and Mixed *Danthonia* communities and germinated in early August, mid and early July, respectively. In *Trachydium* community it only showed the vegetative phases. The reproducctive phase initiated in late July in both *Polygonum* and Mixed *Danthonia* communities, but in *Polygonum* community it reentered the vegetative phase in early September. Its’ compleate lifecycle was only recorded in Mixed *Danthonia* community where it entered both fruiting and senescence phases in late August and mid-September, respectively. *Anaphalis royeli* germinated in early July in *Trachydium*, Mixed *Danthonia* and

Danthonia communities, and entered the reproductive phase in mid-July. The fruiting phase was initiated in only *Danthonia* community in late August, and senescence in mid Spetember in all three communities (Fig. 4.5).

Juncus himalensis was present in Mixed Herbaceous, *Polygonum* and *Danthonia* communites. In Mixed Herbaceous community, it entered the vegetative and reproductive phases in late June, fruiting phase in late August and senescence in mid September. In *Polygonum* community it germinated in late July and immediately entered reproductive phase, which lasted till early September when it disappered. In *Danthonia* community, it germinated and directly entered reproductive phase in mid-July, and entered fruiting and senescence phases in mid and late August, respectively. *Jurenia dolomiaea*, in Mixed Herbaceous community, germinated and entered the reproductive phase directly in early June and showed two distinct fruiting and senescence phases from late June to mid-September, respectively. In *Danthonia* community, it initiated vegetative phase in June and showed two distinct fruiting and senescence phases from late June to mid-September, respectively while in Mixed *Danthonia* community, it directly entered reproductive phase after germination in early July, and initiated reproductive and senescecne phases in early August and September, respectively (Fig. 4.5).

Three species were common in *Polygonum*, Mixed *Danthonia* and *Danthonia* communites. *Pimpinella diversifolia* initiated vegetative phase in early May in *Polygonum*, Mixed *Danthonia* and *Danthonia* communities. It entered the reproductive and fruiting phases in only *Polygonum* communtiy in mid-May and start of June, respectively while it disappered in other two communities by end of May. It was absent 2018 onwards in *Polygonum* community. In *Potentilla polyphyla*, in *Polygonum* and Mixed *Danthonia* communities, the vegetative phase initiated at the start of July, the reproductive and fruiting phases initiated simultaeously in early July and it reentered the vegetative phase in early September and the species disappered by mid-September and did not enter the senescence phase. It was absent 2018 onwards in *Polygonum* community. But in *Danthonia* community, the vegetative and reproductive phases initiated mid and late June,respectively while the fruiting phase started from mid-July and coexisted with the reproductive phase till early September, after which only the fruiting phase was present till the species disappered in September end. In *Selinum vaginatum*, the species germinated in all three communities in early July, but it directly entered the reproductive phase in *Danthonia* community. In the *Polygonum* community, the reproductive phase was recorded from mid to late July and reentered the vegetative phase in early August, but it was absent in Mixed Herbaceous community. The fruiting phase was absent in all three communities and the senescence phase started at end of September and early October in all three communities, respectively (Fig. 4.5).

Figure 4.5. Phenogram of species common to three communities. (T: *Trachydium;* M: Mixed Herbaceouos ; P: *Polygonum*; MD: Mixed *Danthonia*; D: *Danthonia*; Green: Vegetative, Red: Reproductive, Pink: Fruiting and Seeding, Grey: Senescence)

4.3.5 Temporal changes in species present in four communities

Four species were common to *Trachydium*, Mixed Herbaceous, Mixed *Danthonia* and *Danthonia* communities. *Eupharasia himalayica* initiated the vegetative phase in early June in *Trachydium*, Mixed Herbaceous and *Danthonia* communities and early July in Mixed *Danthonia* community. The reproductive phase was initiated in early July in Mixed Herbaceous and *Danthonia* communities and in mid-July in *Trachydium* and mixed *Danthonia* communities. The fruiting phase was absent while the senescence started mid to late September in all communities. In *Gentiana tubiflora,* the vegetative phase was initiated in early July in all four communities. Only the vegetative phase was recorded in *Trachydium*, Mixed Herbaceous and Mixed *Danthonia* communities till mid-September, after which species disappered in above three communities. In *Danthonia* community, the reproductive phase initiated in late August and lasted till late September after which the senescence phase initiated (Fig. 4.6).

In *Saussurea taraxacifolia,* the vegetative phase was initiated in early May and was only recorded in three communities namely, *Trachydium*, Mixed Herbaceous and Mixed *Danthonia* communities. Two distinctive reproductive phases were recorded in *Trachydium* (initiating mid-May and early August) and Mixed Herbaceous communities (initiating early June and late July) with two distinctive fruiting phases (initiating early July and mid-September), respectively. In Mixed *Danthonia* community, the reproductive and fruiting phase alternated three times in succession resulting in three distinctive reproductive and two distinctive fruiting phases. In *Danthonia* community, it germinated and immidietly entered fruiting phase in early July, reverting back to the reproductive phase in late July and the second fruiting phase in early September. Senescene initiated in early October in all four communities. In *Tanacetum dolichophyllum,* the vegetative and reproductive phases were initiated in early May and mid-June in *Trachydium*, Mixed Herbaceous, and Mixed *Danthonia* communities. The fruiting phase initiated in mid-July in Mixed Herbaceous and Mixed *Danthonia* communities and mid-August in *Trachydium* community. In *Danthonia* community, the reproductive phase was recorded immidietly after germination in mid-July while the vegetative and fruiting phases were not recorded. The senescence was recorded early October onwards in all four communities (Fig. 4.6).

Poa annua was common to *Trachydium*, Mixed Herbaceous, *Polygonum* and *Danthonia* communities. In *Trachydium* and Mixed Herbaceous communties, it entered the vegetative phase in early June and showed two distinct reproductive phases (late June and late August). The fruiting phase commnced in mid July for both communities while a second fruiting phase was recorded from mid September onwards in Mixed Herbaceous community only. In *Polygonum* community it entered the vegetative phase immideatly after snowmelt, the reproductive phase in late May, the fruiting phase in mid-June, after which it reentered the reproductive and vegetative phases in mid-July and early August, respectively. The second reproductive phase was recorded late August onwards. In *Danthonia* community, two distintive vegetative and reproductive phases were recorded from early July onwards while the fruiting phase was absent. The senescence started in early September in *Trachydium* community while in other communities it started in early October (Fig. 4.6).

Picrorhiza kurroa was recorded only in 2017 in *Trachydium*, Mixed Herbaceous, *Polygonum* and Mixed *Danthonia* communities. In *Trachydium* community, it germinated and immidiately entered reproductive phase, while in remaining communities it entered vegetative phase immideatly after snowmelt. It disappered by end of May in *Trachydium* and Mixed Herbaceous communities, while in *Polygonum* and mixed *Danthonia* communities it entered the senescence phase in start of June. *Sibbaldia cuneata* was recorded in *Trachydium*, *Polygonum*, Mixed *Danthonia* and *Danthonia* communities. It initiated the vegetative phase in early May, the reproductive phase between early and mid-June, the fruiting phase in early July and senescence in October in all communities. In *Trachydium* community two distinctive reproductive and fruiting phases were recorded (Fig. 4.6).

Four speceis were common to Mixed Herbaceous, *Polygonum*, Mixed *Danthonia* and *Danthonia* communities. *Gerbera gossypiana* showed only the vegetative phase from early July to late September in Mixed Herbaceous and *Polygonum* communities, while in *Danthonia* community it germinated and immidiatly entered the reproductive phase in late July and the senescence phase in early October. In Mixed *Danthonia* community, the vegetative phase started in early July, two distinctive reproductive phases were recorded in late July and early September and the senescence phase in early October. The fruiting phase was completely absent. *Potentilla atrosanguinea* germinated in early July in Mixed Herbaceous, *Polygonum* and Mixed *Danthonia* communities and in early June in *Danthonia* community. In Mixed Herbaceous and Mixed *Danthonia* communities, it showed reproductive phase from July end while two distinctive fruiting phases were recorded from mid-July and early September, respectively. In *Polygonum* community it entered the senescence phase immidieatly after germination in early July, the fruiting phase in August and senescence phase in September. No other phases beside the fruiting and senescence phases were recorded. In *Danthonia* community, the reproductive phase was recorded in early June, the fruiting phase in early July and the senescence phase in August end (Fig. 4.6).

Primula denticulata, in Mixed Herbaceous community, started the vegetative and reproductive phases in early and mid-July, respectively and the fruiting and senescence phases in last week of July and August respecively. In *Polygonum* community, it entered the reproductive phase immidiatly after snowmelt, the fruiting phase in early June and the senescence phase in early July. In July end it reentered in the fruiting, vegetative and senescence phases in late July, early August, and September, respectively. In Mixed *Danthonia* community, the vegetative phase initiated immidiatly after snowmelt, the reproductive in early May and the fruiting phase in early August. The senescence was recorded twice; from early to late July and early September onwards. It was absent 2018 onwards in mixed *Danthonia* community fro the study duration (2017-2019). In *Danthonia* community, it was present briefly in month of July and September in senescence phase only. *Veronica canna* started the vegetative phase mid-July, the fruiting phase in early August and the senescence in early September in Mixed Herbaceous community while the reproductive phase was absent. In *Polygonum* community, the vegetative phase was present in two distinctive phases between early July and mid-September, two reproductive phases between mid July and mid August, the fruiting phase in late July and senescence phase mid-September onwards, respectively. In Mixed *Danthonia* community it was present between late July and mid-September in only fruiting phase during study period. In *Danthonia* community, the vegetative phase was recorded in early July, the fruiting phase was recorded in late July and senescecne phase in October while reproductive phase was not recorded in *Danthonia* community during study period (Fig. 4.6).

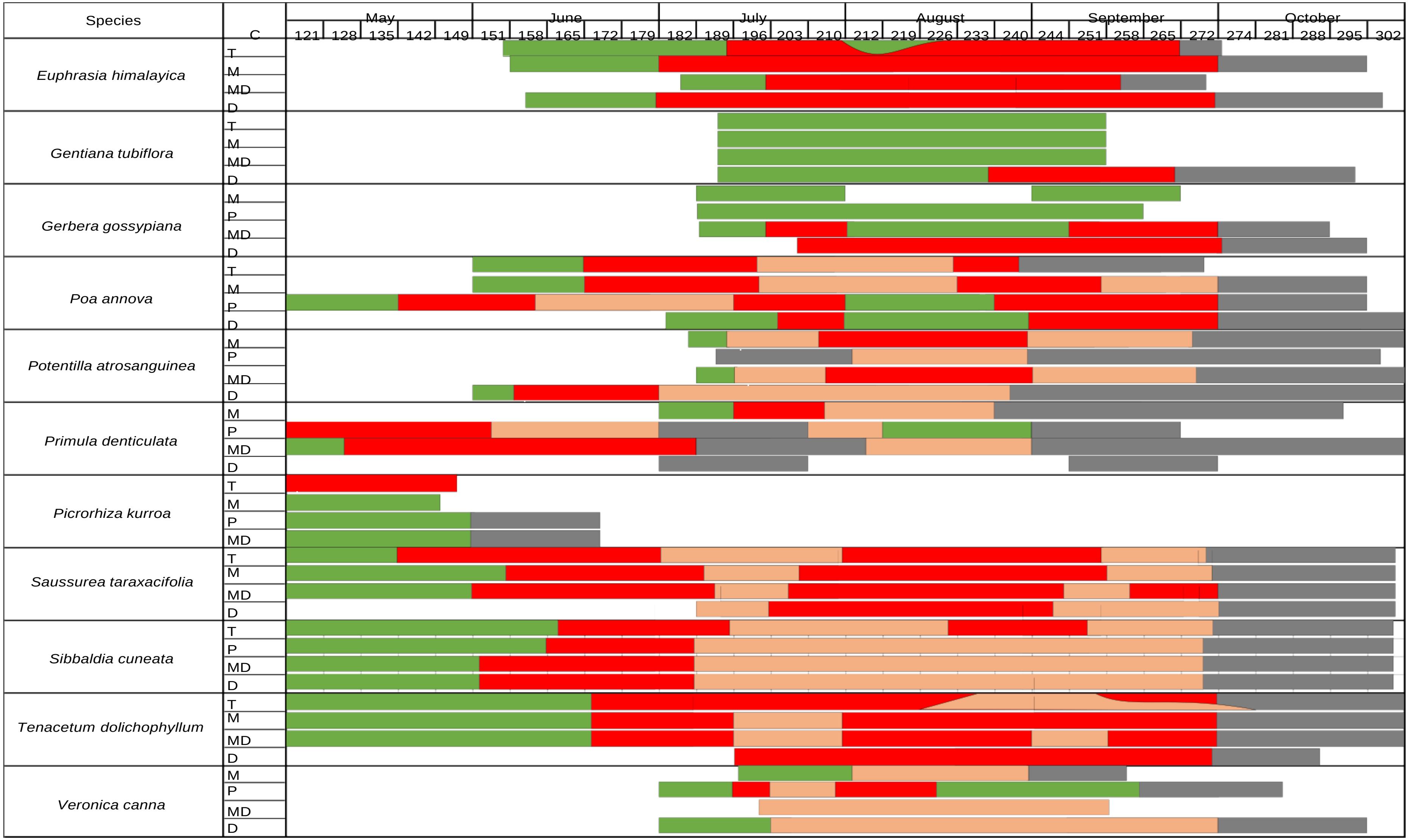


Figure 4.6. Phenogram of species common to four communities. (T: *Trachydium;* M: Mixed Herbaceouos ; P: *Polygonum*; MD: Mixed Danthonia; D: *Danthonia*; Green: Vegetative, Red: Reproductive, Pink: Fruiting and Seeding, Grey: Senescence)

4.3.6 Temporal changes in species present in all communities

A total of 24 species were common in all five communities. In *Anaphalis nepalensis*, vegetative phase initiated between early and mid-May and lasted between early and late June, the reproductive phase initiated between early and late June lasting till September end, the fruiting phase was recorded between mid July and mid September and senescence phase initiated between late September and ealy October. The fruiting phase was not recorded in *Polygonum* and Mixed *Danthonia* communities during the study period. *Bistorta affinis* initiated the vegetative phase immidiatly after snowmelt, the reproductive phase between late May and mid-June, the fruiting phase between late June and late July and the senescence phase from September onwards. In *Trachydium* community two distinctive reproductive and fruiting phases were recorded 2018 onwards while in *Polygonum* and *Danthonia* communities two distinctive fruiting and senescecne phases were recorded. In Mixed Herbaceous and Mixed *Danthonia* communities the reproductive and fruiting phases coexisted together. In *Bistorta amplexicaulis,* the vegetative phase initiated immidiatly after snowmelt, the reproductive phase initiated between late May and mid-June and the fruiting phase in late June. In Mixed *Danthonia* community only the vegetative phase was recorded till late May after which it disappered, while the vegetative and reproductive phases were present simultaneously in*Trachydium* community. No fruiting and senescence phases was recorded in *Trachydium* and Mixed Herbaceous communities. In *Polygonum* and *Danthonia* communities two distinctive fruiting and senescence phases were recorded. For *Bupleurum candollei*, the vegetative phase initiated in mid-June, the reproductive phase between late June and early July, the fruiting phase in late July and senescence was recorded in October. In *Trachydium,* Mixed *Danthonia* and *Danthonia* communities two distinctive reproductive and fruiting phases were recorded respectively, and in Mixed Herbaceous community three distinctive reproductive and fruiting phases were recorded, while no vegetative phase was recorded for Mixed Herbaceous and *Polygonum* communities as individuals immideatly entered reproductive phase after germinating in early July. No other phenophase except reproductive phase was recorded in *Bupleurum* in *Polygonum* community during study period

(2017-2019). The senescecne phase was not recorded in *Trachydium* and *Polygonum* communities for entire study duration. *Carex setosa* initiated the vegetative phase immediately after snowmelt. In *Polygonum*, Mixed *Danthonia* and *Danthonia* communities it was recorded only in month of May in vegetative phase during entire study period. In Mixed Herbaceous and *Trachydium* communities, two distinct reproductive phases was recorded early June onwards while the fruiting phase was recorded in late June and late July, respectively. The senescecne was initiated between early and late September (Fig. 4.7).

Euphorbia stracheyi completed its lifecycle only in Mixed Herbaceous and *Danthonia* communities while in rest it disappered by late May. It initiated growth immediately after snowmelt in all communities except Mixed Herbaceous where it germinated in mid-May. In *Trachydium* and *Danthonia* communities it entered reproductive phase immediately after germination. In Mixed Herbaceous community it showed two distinctive reproductive phases in June and August while in *Danthonia* community it entered the vegetative phase after reproductive phase in late May. The senescence was recorded mid-September onwards in both *Trachydium* and *Danthonia* communities. The fruiting phase was completely absent in all communities. *Fragaria nubicola* germinated and entered vegetative phase by late May in all communities. The repoductive phase was initiated in early June in *Trachydium*, Mixed *Danthonia*, and *Polygonum* communities, while in Mixed Herbaceous community, it initiated in early July and was absent in *Danthonia* community. Two distinctive reproductive periods were recorded for Mixed Herbaceous and Mixed *Danthonia* communities. The fruiting phase was recorded in late June in *Trachydium* and late September in Mixed Herbaceous communities. It showed two distinct period in mid-June and August end in Mixed *Danthonia* community but was absent in *Danthonia* and *Polygonum* communities. The senescence was recorded early October onwards. *Gaultheria trichophylla* initiated the vegetative phase in early May in *Trachydium*, Mixed Herbaceous and *Danthonia* communities, and early June in *Polygonum* community. The reproductive phase was recorded in mid-May in *Trachydium* and *Danthonia* communities, late June in Mixed Herbaceous community and early July in *Polygonum* community and in Mixed *Danthonia* community where it directly initiated flowering after germination. The fruiting phase initiated between early and mid-July in all communities, while the senescecne initiated between early September and mid-October. In *Trachydium* community two distinct reproductive, fruiting and senescence phases were recorded. *Gentiana argentea* initiated growth as soon as snowmelt started and entered reproductive phase in all communities. No other phenophase other than reproductive phase was recorded. *Geum elatum* initiated growth after snowmelt in all communities and entered the reproductive phase in late May in *Trachydium* community and early June in others. The fruiting phase was initiated in late June in *Trachydium* and Mixed Herbaceous communities, early July in *Polygonum* community and early August in Mixed *Danthonia* and *Danthonia* communities. The senescence initiated from early to mid-September in all communities. Two distinct periods were recorded for reproductive and fruiting phases in *Trachydium* and Mixed Herbaceous communities, and senescence phase in Mixed *Danthonia* and *Danthonia* communities (Fig. 4.7).

Goodyera repens only showed the vegetative phase in *Trachydium* and Mixed Herbaceous communities, and the vegetative and senescecne phases in remaing *Polygonum*, Mixed *Danthonia* and *Danthonia* communities. *Kobresia duthiei* germinated immediately after snowmelt in all communities but entered senescence in *Trachydium,* Mixed Herbaceous and Mixed *Danthonia* directly. The reproductive phase was initiated in early June in *Trachydium* and Mixed Herbaceous and mid-June in *Danthonia* communities. In *Trachydium* and Mixed Herbaceous communities it showed multiple reproductive phases from June till September, and two distinct fruiting phases in late July and August-September. The fruiting phase initiated in early August in *Danthonia* community while in rest it was absent. *Kobresia* was absent 2018 onwards in Mixed *Danthonia* community. In *Oxygraphis polypetalae*, the germination was recorded alongside snowmelt and it entered reproductive phase immediately in all communites. In *Trachydium* and Mixed Herbaceous communities it entered into the vegetative phase in mid and early June, respectively and reentered reproductive phase in mid-July and early August, respectively while it reentered reproductive phase in late July in Mixed *Danthonia* and *Danthonia* communities. The fruiting phase was recorded in late July in

Trachydium communtiy, and in early June in Mixed *Danthonia* and *Danthonia* communities, but was absent in others. It is important to note that two distinct reproductive phases were recorded in all communities except *Polygonum* where it disappered by May end. In *Parnessia nubicola* the vegetative phase was present only in *Trachydium* community. The reproductive phase was initiated in early July in *Trachydium* community, and immediately after germination in Mixed Herbaceous and *Danthonia* communities. In *Polygonum* and mixed *Danthonia* communities fruiting phase was recorded immediately after germination in early July after which the species entered reproductive phase in late July in *Polygonum* and mixed *Danthonia* communities. The fruiting phase was recorded in mid-July in Mixed Herbaceous and *Danthonia* communities. Two distinct reproductive phases were recorded in Mixed Herbaceous and Mixed *Danthonia* communities while two distinct fruiting phases were recorded in Mixed Herbaceous, *Polygonum* and Mixed *Danthonia* communities. In *Pedicularis hoffmeisteri*, the germination was initiated immediately after snowmelt in *Trachydium,* Mixed Herbaceous and Mixed *Danthonia* communites and in late May in *Danthonia* community. In *Trachydium* and Mixed Herbaceous communties, two distinct reproductive period were recorded in June and early August and two fruiting periods in early July and mid August, respectively while the senescence was recorded only in Mixed Herbaceous community. In mixed *Danthonia* community the reproductive phase was recorded in early June, two fruiting periods were recorded in mid-June and August and two senescecne phases in July and Sepember. In *Polygonum* community, it germinated in early July and immediatley entered senescence, while only fruiting phase was recorded in August after which it reentered senescence phase (Fig. 4.7).

In *Plantago ovata*, the germination initiated immediately after snowmelt in all communities, but in *Polygonum* community it immediately entered reproductive phase. For *Trachydum* and Mixed Herbaceous communities two different reproductive phases were recorded in late May and early August, two fruiting periods were recorded in late June and mid-August and senescecned in early October. In Mixed *Danthonia* community, the reproductive phase initiated in mid-May but no reproductive phase was recorded in *Danthonia* community during study period. In *Polygonum*, Mixed *Danthonia* and *Danthonia* communities two distinct fruiting and senescence phases were recorded. *Polygonum polystachium* germinated between late May and early June in all communities. In *Trachydium*, Mixed Herbaceous and *Polygonum* communities it entered the reproductive phase by end of May and senescence phase in September while no fruiting phase was recorded. In Mixed *Danthonia* and *Danthonia* communities, it entered reproductive phase immediately after germination in early June, the fruiting phase began in early July and the vegetative phase were recorded between mid-July and mid-August. In mixed *Danthonia* and *Danthonia* communities, a second reproductive period was recorded in late and early August, respectively and senescence in late September (Fig. 4.7).

Potentilla ancerina germinated and entered the vegetative phase in early May in all communities after which it disappeared in all except Mixed *Danthonia*, where it entered into the reproductive phase in June and the senescence phase in early July. In *Trachydium* community, it germinated again in early July, entered the reproductive phase in August and senescence in late August. No fruiting phase was recorded. It was absent 2018 onwards in the *Polygonum* community. *Potentilla liniata* initiated the vegetative phase between early May and early July, showed two distinct reproductive phases in all communities except *Danthonia* where it entered reproductive phase only once throughout the study period. The first reproductive phase initiated between mid-June and early July and second between mid-July and early August. Similarly, two fruiting phases were recorded in all communities while senescence initiated between mid-September and early October. *Rannunculus hirtellus* entered the vegetative phase between late April to early May in all communities, except in *Danthonia* where it entered reproductive phase immediately after germination. It showed two distinct flowering periods in the communities, except Mixed *Danthonia* and *Trachydium* communities where it flowered only once from early May. In Mixed Herbaceous and *Polygonum* communities first reproductive phase initiated in May and second in mid-August, while in *Danthonia* community it reentered reproductive phase in late July. The fruiting phase was recorded in early October in *Trachydium*, mid-September in Mixed Herbaceous, early

July in *Polygonum* and mid-June in *Danthonia* communities while it was absent in Mixed *Danthonia* community. The senescence initiated between mid-September and October except in Mixed *Danthonia* community where two senescence periods were recorded, first in June and second in mid-September. *Swertia ciliate* germinated mid-June in Mixed Herbaceous community and early July in remaining communities. It entered the vegetative phase after germination only in *Trachydium* and Mixed Herbaceous communities, while in others it directly entered reproductive phase. Two distinct reproductive periods were recorded for all communities in July and late August. Two distinctive fruiting phases were recorded in *Danthonia* community and one in Mixed Herbaceous community while in others it was absent. The senescence initiated from early September to mid-October (Fig. 4.7).

Taraxacum officinale initiated the vegetative phase immediately after snowmelt, the reproductive phase in early June, the fruiting phase between early and mid-July and senescence in late September and October. Two vegetative periods were recorded in *Trachydium* community, two reproductive periods were recorded in Mixed Herbaceous, Mixed *Danthonia* and *Danthonia* communities, and two fruiting periods were recorded in *Trachydium*, Mixed Herbaceous and *Danthonia* communities. the fruiting phase was absent in *Polygonum* community. In *Trachydium roylei*, the vegetative phase initiated in early May, two reproductive periods recorded in June and August, two fruiting period recorded in July and September and senescence phase in October in *Trachydium* and Mixed Herbaceous communities. In remaining communities, it entered flowering immediately after germination. Two distinct reproductive periods were recorded in *Danthonia* community while two fruiting period were observed in Mixed *Danthonia* and *Danthonia* communities. In *Polygonum* community fruiting phase was recorded in late September. In Mixed *Danthonia* and *Danthonia* two senescence phase were present in July and September. In *Trachydium* community, *Viola biflora* initiated the vegetative phase mid-June, showed two reproductive phases in mid-July and mid-September, the fruiting phase in early August, and entered senescence in late September. But in remaining communities it germinated and directly entered the senescence phase in August, showed fruiting phase in September and reentered senescence in October (Fig. 4.7).

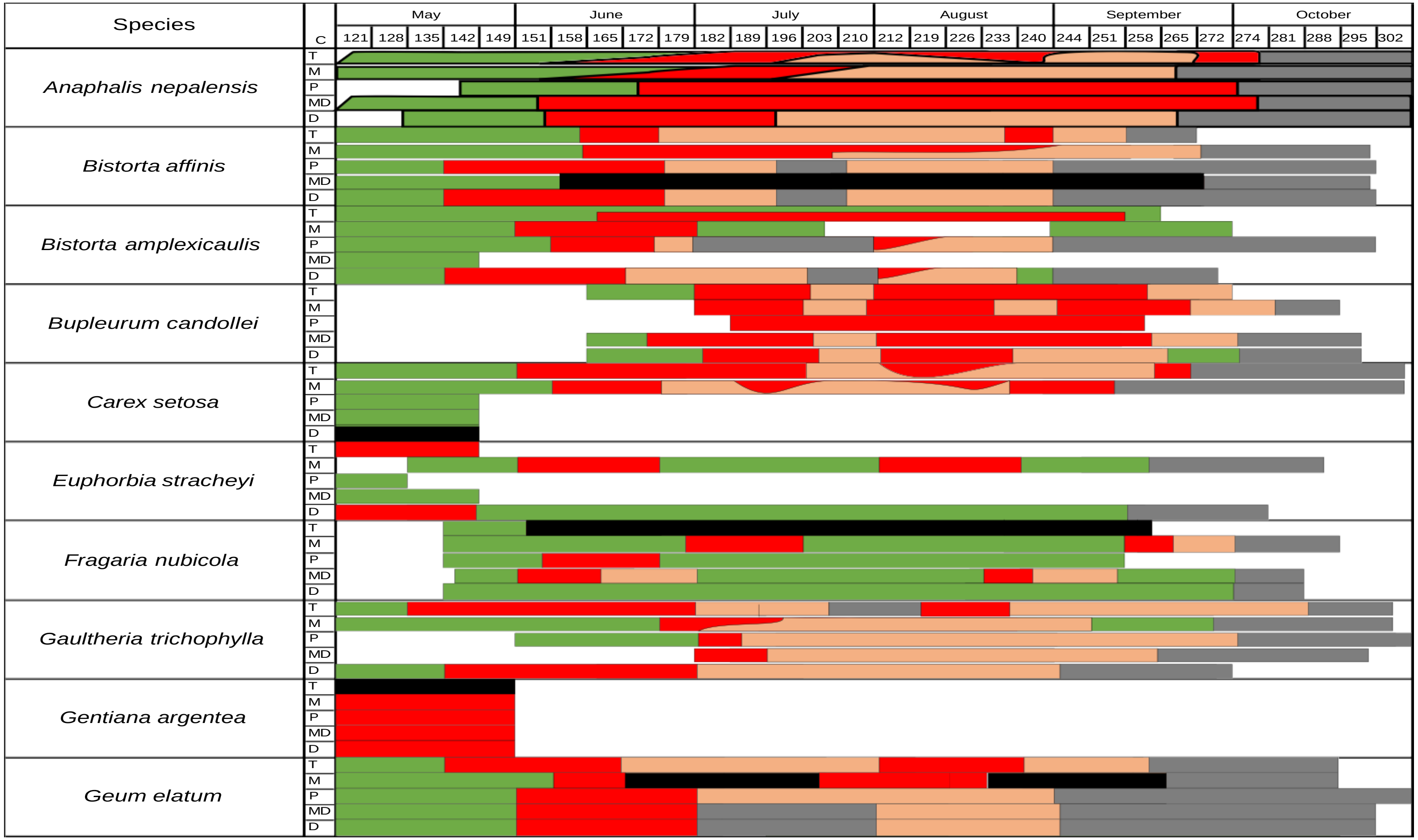
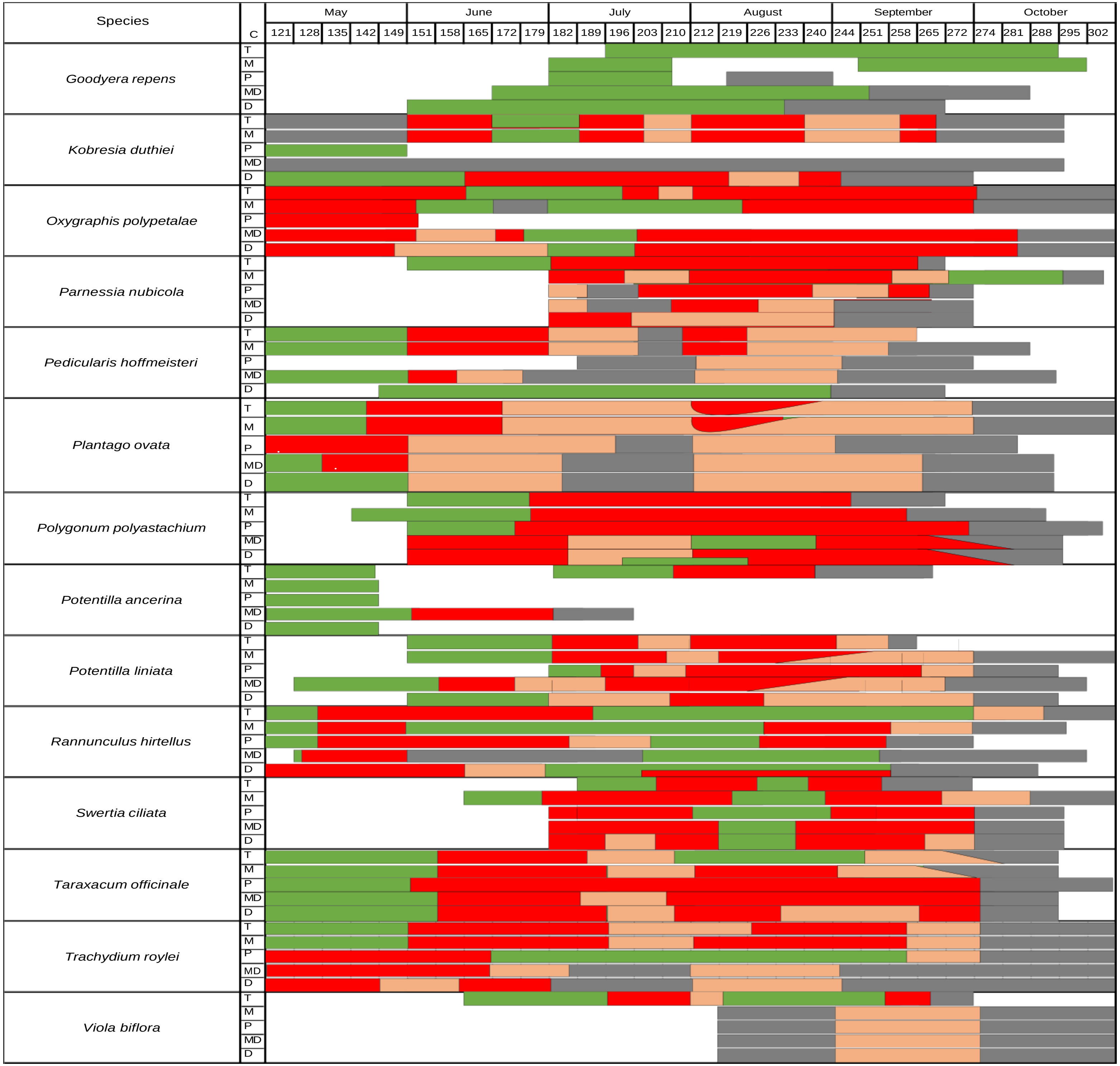


Figure 4.7. Phenogram of species common to all communities. (T: *Trachydium;* M: Mixed Herbaceouos ; P: *Polygonum*; MD: Mixed Danthonia; D: *Danthonia*; Green: Vegetative, Red: Reproductive, Pink: Fruiting and Seeding, Grey: Senescence; cntd.)


Species
C
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
Goodyera repens
Kobresia duthiei
Oxygraphis polypetalae
Parnessia nubicola
Pedicularis hoffmeisteri
Plantago ovata
Polygonum polyastachium
Potentilla ancerina
Potentilla liniata
Rannunculus hirtellus
Swertia ciliata
Taraxacum officinale
Trachydium roylei
Viola biflora
T
M
P
MD
D

4.4 Discussion

The growth of plants in communities initiated immediately after snow melt and soil thawing in May. However, some species like *Aconitum, Arenaria, Caltha, Lysemichia, Primula edgeworthii, Picrorhiza kurroa*, *Pimpinella, Potentilla fulgens, Anemone, Dactylorhiza hatagirea* and *Gentiana argentea* initiated germination immediately after aboveground snowmelt between late March and mid-April as the soil temperature increased considerably mid-March onwards and was constantly above freezing point by 10th April. These species were early growing and disappeared by July. *Fragaria nubicola, Gentiana argentia, Oxygraphis polypetala, Plantago ovata, Rannunculus hirtalus, Selinum vaginatum, Trachydium roylei* and *Gaultheria trichophylla* initiated germination in late April, when soil thawed completely, in different communities and observed flowering in early to mid-May. Some species like *Geranium, Lysemichia, Nepeta, Oxygraphis, Plantago major, Poa, Polygonum filicaule, Potentilla polyphylla* and *Primula denticulate* showed early flowering in Mixed Herbaceous and *Trachydium* communities. This may be due to warmer temperature in these two communities (due to orography) which may be encouraging these few species to postpone the reproductive phenophase for better opportunities. *Aconitum* and *Swertia chirayata* were present only in *Danthonia* community which is north-west facing sites during early growing period (May and June) and only showed vegetative phenophase. However, these two species were present on the south facing slopes from June to October and showed all the phenophases. Overall, 38% species in the study area germinated before May of which 8 species were in flowering in early May.

The average vegetative phase duration for erect leafy and semi basal growth form species was longer than short basal growth form species. Similarly, the reproductive phase duration was much longer in erect leafy growth form species followed by semi-basal growth form species and short basal growth form species, while the fruiting phase and senescence phase duration was longer for short basal growth form species followed by semi-basal sand erect leafy growth form species (Table 4.2).

Among sites, there was no significant differences between individual stages of vegetative, flowering and fruiting and seeding phases. Similarly, between growth forms, there was no significant differences observed for phenophase duration between individual stages of vegetative, fruiting and senescence stages but significant difference was observed for reproductive stage ($p < 0.04$). Dun post-hoc test showed that the reproductive phase duration differed significantly between erect leafy species and short basal species, while no such differences were present between other growth forms.

Table 4.2. Mean Phenophase duration of different species growth forms (EL: Erect leafy species; SeB: Semi basal species; SrB: Short basal species)

Growth Form	Vegetative	Reproductive	Fruiting	Senescence
EL	48.93±23.99	47.77±17.63	8.83±8.05	20.60±9.92
SeB	42.88±23.33	36.62±19.77	10.33±8.94	21.64±12.39
SrB	39.04±21.75	33.90±21.5	15.27±22.7	22.83±12.28

Changes in phenology based on comparison with past studies

In comparison with previous studies, the flowering advanced for *Anaphalis roylei* (3 weeks), *Pedicularis hoffmetiari* (2 weeks) and *Potentilla atrosangnia* (2 weeks) as compared with the study by Nautiyal *et al*. (2001) for the same study area and in *Bupleurum candolli* and *Geum elatum* (4 weeks each), *Anemone* (1.5 weeks) and *Taraxacum* (2 weeks) as compared to the study by Bijalwan *et al*. (2013). The flowering phase in the present study was longer by one and half month in *Trachydium* and delayed in *Selinum* by 2 months as compared to the study by Sundriyal *et al*. (1987) at Tungnath. The flowering phase extended in *Parnassia* and *Geum* by 4 weeks' period and in *Danthonia* and *Potentilla* by 2 weeks as compared to to the study by Sundriyal *et al*. (1987). *Oxygraphis* flowered twice in all communities and the length of overall flowering duration increased by ca. 3 weeks. In the present study, the duration of flowering shortened by a week for *Potentilla* as compared with those reported by Bijalwan *et al*. (2013; Table 4.3).

The fruiting has delayed in *Anaphalis* by a month and in *Parnassia* by 2.5 weeks and advanced in *Pedicularis* by a month. The length of fruiting duration has 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 4.3). The fruiting in *Danthonia* confined to a week and it was not observed in *Selinum* and *Anemone*. The flowering phase advanced in *Bupleurum* (3 weeks) and *Taraxacum* (2 months) and the length of duration increased in *Geranium* (2 weeks) as compared to the study by Bijalwan *et al*. (2013). The senescence delayed by a month in *Anaphalis*, 2 weeks in *Oxygraphis* and 1 week in *Parnassia* as compared with Sundriyal *et al*. (1987) and by 2 weeks in *Parnassia* as compared with Bijalwan *et al*. (2013). The senescence was advanced in *Danthonia*, *Trachydium* (2 weeks) and *Pedicularis* (1 week) as compared with Sundriyal *et al*. (1987) and *Geum* and *Potentilla* (1 month) as compared with Bijalwan *et al*. (2013). However, no change was observed in *Selinum* as compared with Nautiyal *et al*. (2001) and *Geum* as compared with Sundriyal *et al*. (1987) from the past studies (Table 4.3).

Table 4.3. A comparison of timing and length of plant phenophase of the present study (PS*) with past studies conducted at Tungnath (a: Sundriyal *et al*. 1987; c: Nautiyal *et al*. 2001) and Dyara (b: Bijalwan *et al*. 2013)

Plant species	**Vegetative**	**Flowering**	**Fruiting**	**Senescence**	**Reference**
Anaphalis roylei	May 1w	June 3w	Aug 1w	Sep 1w	1984 [a]
	May-mid July	July-late Sep	Sep	Oct	PS*
Anemone obtusiloba	May 1 w	June 1 w	July 5 w	Sep 1 w	2009 [b]
	May -Sep	May-Jul		Jun-Sep	PS*
Bupleurum longicaule	June late	Aug 4w	Sep. 3 week	Oct 1w	2009 [b]
	June late	Jun-Aug	Sep	Oct	PS*
Danthonia cachemyriana	May 1w	June 4w	Aug 2w	Sep 3w	1984 [a]
	May	Aug 4w		Sep-oct	PS*
Geranium walliichianum	May 1 w	July 3 w	Aug 4 w	Oct 1 w	2009 [b]
	May	Jun-Sep		Sep	PS*
Geum elatum	May 1w	June 2w	July 2w	Sep 1w	1984 [a]
	May 1 w	June 3 w	July 4 w	Aug 3 w	2009 [b]
	May	May-Sep	Jul-Sep	Sep-oct	PS*
Oxygraphis polypetala	May 1w	May 3w	June 1w	Aug 3 w	1984 [a]
	May	May-Jun/Aug-Sep		Oct	PS*
Parnassia nubicola	May 3w	July 2w	Aug 3w	Sep 4w	1984 [a]
	May 3 w	Aug 4w	Sep 1w	Oct 1w	2009 [b]
	June -July	Aug-Sept	Sept	Sept-Oct	PS*
Pedicularis pectinata	May 1w	June 3w	Aug 1w	Sep 2w	1984 [a]
	May	May-Jul	Jul	Sep-oct	PS*
Potentilla atrosanguinea	May 1w	July 3 w	Aug 4 w	Sep 4w	1984 [a]
	May 1 w	July 3 w	Sep 1 w	Oct 2 w	2009 [b]
	May	Jul-Aug	Aug-Sep	Sep-Oct	PS*
Selinum vaginatum	May	Late July-Aug	Sep	Oct	1988-1998[c]
	May	May/Aug-Sep		Oct	PS*
Taraxacum officinale	May 1 w	July 3 w	Sep 2 w	Oct 1 w	2009 [b]
	May	Sep		Oct	PS*
Trachydium roylei	May 1w	June 4w	Aug 2w	Sep 5w	1984 [a]
	May	May-jul	Jun-Jul	Oct	PS*

A comprehensive study on phenophases of alpine plants in Tungnath was carried out by Sundriyal et al. (1987) reported the growth initiation from early May to mid-June, but with

considerable differences in phenological phases of different species, while stability in phase duration for a single species was remarkable despite different locations. Of the total species (#171) reported by Nautiyal et al. (2001) 16 species showed the flowering phase in May immediately after snowmelt in Tungnath which is more than what was observed in present study (8) in alpine communities of Tungnath. Bijalwan *et al*. (2013) in Dayara meadows, Garhwal Himalayas reported 70% plants initiating growth in early May which is much more than present study (57%), while May and June saw rapid vegetative growth as temperature increased. The flowering happened mostly between mid-June to early September, while fruiting started in early July, and attained peak in late August which is similar to present study. Similarly, Negi *et al*. (1992) reported species entering flowering in May and rapidly increasing from June with peak in in July in Bedni-Ali alpine meadows. The fruiting started in June and peak fruiting was observed in mid-July and mid-August (70%), respectively. Most of the species bore fruits within a month of fruit formation, senescence gradually started from June showed abrupt increase in August and peaked between late August and early September. The flowering buds of the species flowering in May or immediately after snowmelt remain dormant throughout the months of snow cover, with flowering commence immediately after snowmelt illustrating adaptation for survival under harsh climatic conditions as topographical features and environmental conditions directly influence the phenology of alpine plant species (Germino, 2014). A similar trend was observed overall with vegetative phase peak recorded during May and June (68%), while majority species flowered between June and September peaking in August (75 %). It is imperative to note that less than 75 % species were recorded in fruiting and seeding phase in the entire study period duration. Among the species entering fruiting and seeding phase, a majority of species which were present in more than one community showed fruiting and seeding phase (>5% individuals showing fruiting concurrently) in less communities than what they were recorded in. That is, in certain communities, although the species population showed fruiting and seeding at particular time, not enough individuals fruited concurrently (≤ 5%) to be specified/denominated as species fruiting and seeding phase in that time period (Fig. 4.4-4.7).

Comparison of community phenophase progression of the present study with Nautiyal *et al*. (2001) for Tungnath showed similarity in phenophase progression. The vegetative phase duration has extended compared to past while fruiting and senescence has delayed and advanced respectively compared to past (Fig. 4.8). In Tungnath, over a period (from 1984 to 2019) the duration of vegetative phenophase has increased from 2 months (Sundriyal *et al*. 1987) to 4 months (Nautiyal *et al*. 2001) and 5 months (the present study). The phenophase stability and duration was prominent in Sundriyal *et al*. (1987) and Nautiyal *et al*. (2001), but in present study (2017-2019) phenophases overlapped resulting in no clear-cut dominance (stability) of phenophase at a particular time. This difference i.e overlapping of phenophases in present study is because in present study a much larger area was covered and the frequency of sampling done was higher than studies conducted by Sundriyal *et al*. (1987) and Nautiyal *et al*. (2001). Sundriyal *et al*. (1987) selected four stations and laid 10 quadrats of 25x25 cm to carry out phenological study, while Nautiyal *et al*. (2001) made phenological observations at places where species population was most extensive. A population showed vegetative in one community while in other it was either in flowering or fruiting phase. As such flowering period extended by a week till first half of October, but fruiting and seed maturation started early July in present study, while in June in Nautiyal *et al*. (2001). The senescence in present study started from June, which is a month prior than that reported by Nautiyal *et al*. (2001). The longer vegetative phenophase for present study could be due to higher precipitation in recent years (Adhikari *et al*. 2012 and GBPIHED 2017) and decrease in diurnal temperature in recent years (6.3°C in August) as compared to Sundriyal *et al*. (1987; Fig. 4.8).

Tungnath region in general has higher maximum and minimum temperature and precipitation as compared to other meadows which might be influencing extension and delayed termination of vegetative and flowering phases. Considering early snow melt (by March) in past few years certain species (*Primula edgeworthii, Anemone rivularis, Gentiana spp., Picrorhiza kurroa, Kobressia*) have stared their growth in early April compared to past, may be due to high absorbing ability if their roots at low soil temperature and resulted in early senescence. The species percent in senescence increased sharply from August to September in both studies while September to October in present study. The less variation in temperature (minima and maxima) during the peak growth period i.e., July-August might be helping species to remain in different phenophases for a longer period leading to overlapping of phenophase in general in Tungnath (Adhikari *et al*. 2018). A shift of phenophase timing and period for majority of species was observed in general as compared to similar studies conducted in the study area (Nautiyal *et al*. 2001; Sundriyal *et al*. 1987).

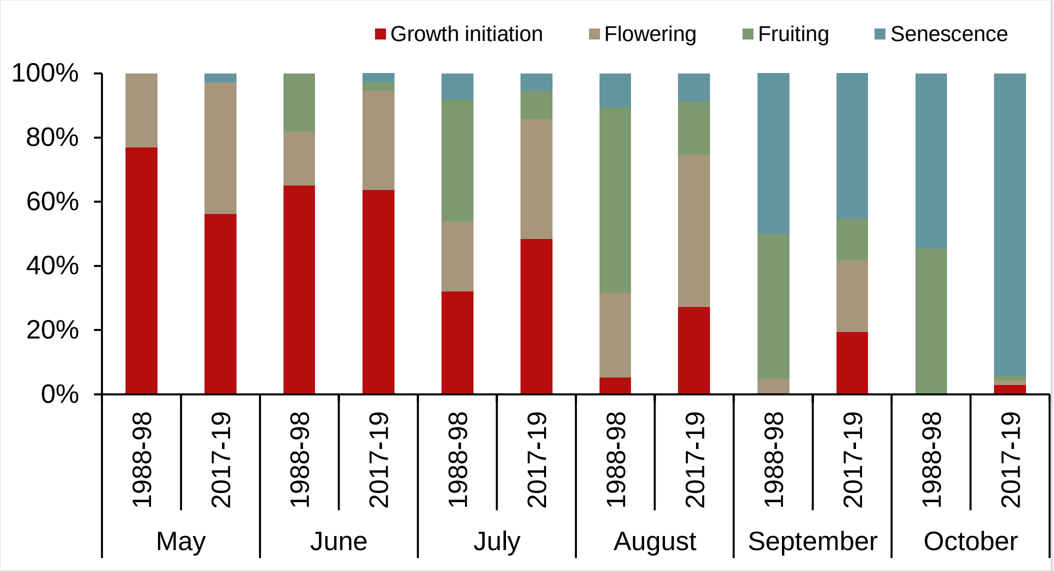


Figure 4.8. Percent changes in species across months in different phenophases in alpine communities (Tungnath, Nautiyal *et al*. 2001; 2017-2019: Tungnath, Present Study)

Snowmelt water is precursor for initial plant growth in alpine regions during early growing season, which was received by the area in the form of snow fall (39 days; 4 days in December 2016 and 35 days during January to April in 2017 and 43 days; 14 days in November and Decemner 2017, 29 days during January to April 2018), before onset of the monsoon. Furthermore, increase in precipitation during recent years (Adhikari *et al*. 2012; GBPIHED, 2017) and apparent increase in temperature with shortening of diurnal range during peak growing season (7.7 ºC in October to 12.2 ºC in June in 1984; Sundriyal *et al*. 1987, as compared to 6.27 ºC in August to 13.16 ºC in October in 2018; Present Study) in study area might be one of the reasons responsible for advancement and extension of vegetative and flowering phases as species might look for homeostasis under lack of stress which was present in past and delay in senescence of early growing species.

The early onset of observed growth initiation and extended vegetative phenophase could be due to early snowmelt/soil water thawing led to early soil moisture availability and ambient temperature which favored early growth as suggested by several workers (Ram *et al*. 1988; Holway and Ward, 1965; Kudo, 1991; Kudo and Suzuki, 1999; Kudo and Hirao, 2006). The flowering and fruiting phenophases have also seen a shift (both advance and lag) in phenophase initiation and duration of period have extended in general as compared to other studies (Nautiyal *et al*. 2001; Sundriyal *et al*. 1987). The patterns of phenological events vary at spatio-temporal scale from species to species due to micro-environmental variables as well as orography of the region, which was also observed by Nautiyal *et al*. (2001).

The plant phenology is an indicator of ecosystem response to climate change including abiotic (gas exchange and energy balance) and biotic (species interactions and reproductive synchrony) interactions (Memmott *et al*. 2007; Sherry *et al*. 2007; Moritz *et al*. 2008; Bonan, 2008; Liu *et al*. 2011). The initiation of spring growth is, heavily influenced by photoperiod and temperature (Chuine, 2010), and after photoperiod and cumulative temperature sums reaches a certain threshold, snowmelt timing becomes primary driver for growth initiation and flowering of alpine and subalpine species (Molau *et al*. 2005; Hulber *et al*. 2010; Iler *et al*. 2013; Oberbauer *et al*. 2013; Petraglia *et al*. 2014). It is important to note that the growth initiation in alpine species depends on seasonal accumulation of heat sums for species present in exposed habitats with little snow cover, while it depends on snowmelt timing for snowy habitats (Kudo and Hirao, 2006; Carbognani *et al*. 2016). For short growth cycle species (life cycle less than 3 months) it is important to take advantage of these conditions by early flowering with snowmelt, which may increase reproductive success, thereafter building reserve for next growing season (Kimball *et al*. 2014). This decreases their competition with long growth cycle (life cycle more than 4 months) perennial species, as they avoid early spring initiation to avoid risk of damage from early growing season freeze events which can retard root and plant growth, thus negatively influencing reproductive success (Gezon *et al*. 2016).

4.5 Conclusion

There are various factors governing phenology, of which timing of snowmelt is a crucial factor. However, the literature regarding various phenological events in alpine is severely lacking on part of the IHR. This study addresses this gap and reveals that early snowmelt significantly advances the initiation of phenological events in early growth species found between the timberline and alpine regions of the IHR. However, the timing of snowmelt has less influence on phenology in late growth species that germinate after June, as their phenophase events are likely triggered by temperature sums. The study also finds that phenophase duration is relatively consistent, particularly in late growth species, indicating a limited reliance on warmer seasons. These findings align with manipulation experiments conducted in temperate or boreal forests, although there are inconsistencies in experimental settings, primarily due to the predominance of in-situ experiments. The growing season duration in alpine IHR is much longer (~6 months) than in other regions across the globe (3-4 months) therefore, species responses may not comply with the findings of studies conducted in temperate or boreal alpines.

The species modification of their phenophase across alpine communities already suggest 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 varying responses across different life forms, particularly in the anthesis (flowering) of herb species belonging to different functional groups, which could lead to competition and adjustment among species for resources such as pollinators. Additionally, considering the wide elevation range of treelines in the IHR (approximately 2000m) and the increasing global temperatures, it is necessary to study the phenological sensitivity of species in different alpine regions within the IHR, as species populations may exhibit variable responses under similar conditions due to orographic influences. While several studies have been conducted on phenology and warming, further research is needed in the IHR, specifically focusing on the influence of snowmelt on community phenology and introducing spatial variation across the region. As the temporal relationships between plants, such as the overlapping of anthesis events, evolve, a better understanding of these dynamics is crucial.

5. Temporal Changes in Community Biomass and Soil Nutrients

5.1 Introduction

Plants respond to seasonality of environmental conditions, showing vigorous growth in early growing season, reaching peak in mid growing season and then decline towards fall/ end of growing season. This pattern is often temporally compressed in high altitude meadows on account of short growing season. The alpine ecosystems are some of the most sensitive and vulnerable to warming terrestrial ecosystems (Pauli *et al*. 1994) probably due to slow growing plants and presence of high organic matter content (Bowman *et al*. 1993). It is important to note that plant growth pattern influences plant communities' ability to provide habitats and food resources to animals (Jobba´gy and Sala, 2000; Yahdjian and Sala, 2006; Gonsamo *et al*. 2018) thus determining and regulating carrying capacity, in which, compared to other ecosystems, biomass productivity of alpine ecosystems lags (Bowman and Fisk, 2001) compared to other terrestrial ecosystems.

Alpine ecosystems play a vital role as carbon sinks and are crucial for preserving mountain biodiversity and watershed integrity (Bowman and Fisk, 2001; Gret-Regamey *et al*. 2008), plus they are sensitive to nutrient deposition influencing nutrient deposition and plant community structure and carbon cycle (Smith *et al*. 2012). The current warming patterns already bring forward multitudes of existential issue for dominant alpine plant communities which may alter local abiotic conditions inducing community response by bringing ecological consequences manifested in various ecological processes including shifts in primary production (Bowen *et al*. 1993; Walker *et al*. 1994), soil carbon (Kikvidze *et al*. 2005), plant and soil mineral nutrition (Shaver and Chapin, 1991), community alteration (Elumeeva *et al*. 2013; Wahren *et al*. 2013), and phenology (Kudo 1992; Iler *et al*. 2016) among others. Long term monitoring already suggests an advance in phenology due to warming (Myneni *et al*. 1997, Parmesan and Yohe 2003; Root *et al*. 2003; Wolkovich *et al*. 2012), creating a longer growing season causing increase in primary production (Edwards and Richardson, 2004) and causing changes in seasonal CO_2 flux (Ernakovich *et al*. 2014).

The alpine vegetation biomass and productivity are of vital importance in global carbon cycle with both above ground biomass (hereafter referred as AGB) and below ground biomass (hereafter referred as BGB) contributing significantly to organic matter (Scurlock *et al*. 2002). Precipitation is a key factor influencing AGB in grasslands and is commonly used to explain spatial variations in production (Lauenroth, 1979; Sala *et al*. 1988; Burke *et al*. 1997; Jobba´gy *et al*. 2002; Ni, 2004; Fang *et al*. 2005). The soil moisture availability and soil texture also affects vegetative growth in alpine ecosystems thus affecting biomass accumulation (Yang *et al*. 2009). Although a notable relationship between AGB and temperature in grasslands is not observed, AGB tends to decrease with increasing temperature when annual precipitation is held constant at 50 mm intervals (Epstein et al., 1996, 1997; Burke et al., 1997). Additionally, soil texture interacts with precipitation to influence AGB in grasslands (Sala et al., 1988; Epstein et al., 1997)..

Some studies suggest that the warming may increase litter decomposition in alpine and tundra regions, which will effectively accelerate the carbon turnover within alpine systems albeit mediated by soil moisture availability (Aerts *et al*. 2006). There are chances that even with increase in litter production due to longer growing season, if microbial decomposition does not increase proportionately, it may increase the overall carbon stock due to slow decomposition of recalcitrant litter or due to changes in community composition (Cornelissen *et al*. 2007) by shifting from grass/forbs dominated systems to dwarf shrubs/shrubs dominated systems.

The productivity of alpine ecosystems is influenced by various factors, including the composition of the ecosystem and environmental drivers such as snowmelt timing, soil moisture availability, and temperature (Gasarch and Seasted, 2015), community response to the warming will likely alter overall productivity (Kikvidze *et al*. 2005). These changes may manifest as an extension of the peak period of community biomass (Zhang and Welker, 1996), and fluctuations in community primary productivity with presence/absence of supplementary watering (Winkler *et al*. 2016), different life forms responding differently to warming thus muting overall community productivity (Kudo and Suzuki, 2003; Wang *et al*. 2012), nullifying productivity boost due to early snowmelt by decreasing summer precipitation (Winkler *et al*. 2019).

Due to colder climate alpine systems have slower decomposition rate and biochemical transformations, resulting in more liable soil organic matter and more soil carbon than lower elevations (Sjogersten *et al*. 2003). The warming may alter soil organic matter (carbon pool fluxes) differently depending on the type of alpine systems as warmer temperatures generally promote increased soil respiration, but this process is limited by the availability of sufficient soil moisture (Shen *et al*. 2015). Additionally, the warming is expected to stimulate microbial activity, thereby accelerating the pace of nutrient cycling in alpine environments (Brooks *et al*. 2011).

Experimental warming shows increase in decomposition rates of organic matter and carbon leading to carbon loss in dry alpine meadow but increase in w*et al*pine meadow (Na *et al*. 2011). Some experiments done in Tibetan meadows show positive response of soil respiration to warming (Wang *et al*. 2014; Zhou *et al*. 2016), while another study done by Chen *et al*., (2016) showed differential response of autotrophic and heterotrophic soil respiration to warming thus cancelling each other's overall response. The snow cover and depth are an important factor for microbial function and distribution in alpine (King *et al*. 2010) as it acts as insulator thus preserving soil nutrients. Early snowmelt may cause disturbances in these microbial communities causing intensification by causing changes in freeze thaw cycle (Gavazov, 2010), soil pH or moisture (Lauber *et al*. 2009; Zinger *et al*. 2010) and changes in precipitation that affect edaphic conditions in alpine communities. Thus, warming influence may shift alpine systems into carbon source or may cause changes in mineralization and nutrient pools remains to be studied as the underlying changes will likely vary with changing moisture regimes and changes in summer precipitation.

The soil organic carbon (SOC) stock in high altitude and latitude ecosystems are an important component of global terrestrial carbon reservoir (Hobbie *et al*. 2000, Ping *et al*. 2008) and is one of the most important indicators of soil fertility, productivity, and quality (Choudhury *et al*. 2013) of alpine ecosystem. The vertical patterns of SOC can contribute as an input or as an independent validation for biogeochemical models and thus provide valuable information for examining the responses of terrestrial ecosystems to global change (Jobbagy and Jackson 2000). Small changes in the SOC pool can have large implications for atmospheric CO2 concentrations. The grassland soils occupy quarter of world’s land surface, storing 10 % global carbon stock thus playing a critical role in stabilizing or reducing atmospheric carbon (Scurlock *et al*. 2002). It has been documented that these extensive areas of grassland have suffered some degradation (Kemp *et al*. 2013) especially in last years from livestock populations (Harris 2010) and about one third of alpine grasslands were in a degraded state in 1990s (Duan *et al*. 2013).

Presently the high mountain ecosystems are seeing a decline in biodiversity, habitat destruction and landscape modification (e.g. Korner 2003; Bruun *et al*. 2006) as they are sensitive to climate variables, species pool and biogeographical region all of which are further exacerbated by the threat of climate change (Beniston 2003; Pauli *et al*. 2012). These processes have garnered significant attention from ecologists, and a substantial body of scientific literature explores their impacts on biodiversity at various spatial and temporal scales (Parmesan 2006; Bellard *et al*. 2012). One notable example is the observed increase in soluble nitrogen (N) deposition in high-mountain habitats, which has been found to limit plant growth and reduce diversity in terrestrial ecosystems (Hattenschwiler and Korner 1997; Tørseth and Semb 1997; Vitousek and Howarth 1991; Gong *et al*. 2015), nd may also constrain plant growth in alpine species (Hiltbrunner *et al*. 2005). Additionally, studies have demonstrated that early snowmelt leads to increased soil moisture during the vegetative period, impacting community composition, species richness, and the occurrence patterns of individual species (Korner 2003; le Roux *et al*. 2013). However, in the context of Western Himalaya there is a lack of baseline studies, as only a few studies are present on patterns of temporal changes in biomass accumulation and productivity (Bisht and Gupta 1985; Sundriyal *et al*. 1992; Ram *et al*. 1989; Dhaulakhandi *et al*. 2010; Negi *et al*. 1992; Namgil *et al*. 2012; Kala and Rawat 1999; Seth 1996); productivity and energy transfer (Dhaulakhandi *et al*.2000; Sundriyal and Joshi, 1990; Sundriyal 1989), biomass and grazing intensity (Singh 1991; Ram 1992; Kala and Rawat, 1999; Joshi and Srivastav, 1988), biomass and soil organic carbon (SOC) accumulation (Aziz *et al*. 2019) grazing intensity and SOC stock (Khan *et al*. 2004) and, species richness and biomass (Bhattarai *et al*. 2004). It is important to note that the most of these studies were conducted in alpine meadows of the state of Uttarakhand, which is a very small part of entire Western Himalayan landscape.

There is severe lack of data for temporal changes in biomass and productivity as well as their response to warming climate in alpine Western Himalaya. Multiple studies are required in different parts of Himalaya in relation to spatial and temporal variations which may be different especially in IHR, to understand influence of warming and snowmelt on biomass accumulation, energy flow as well as on soil mineral cycle. This is especially required for the studies on relationship between snowmelt and macronutrient cycles (NPK) in Himalaya as these studies are negligible. With this background this chapter deals with temporal changes happening in biomass, productivity, soil carbon and soil macronutrient in five dominant alpine communities of w*et al*pine meadows in Tungnath.

5.2 Methods

5.2.1 Biomass

Aboveground biomass (AGB): Following the harvest method (Shaver and Chapin, 1991) the AGB data was collected. In each site of selected communities three random quadrats of differing sizes (*Trachydium*: 25x25 cm, Mixed Herbaceous: 25x25 cm, Mixed *Danthonia*: 50x50 cm, *Polygonum*: 50x50 cm and *Danthonia*: 1x1 m) for biomass harvesting were laid. The shoot biomass was harvested as close to the ground as possible at 30 days intervals during growing period (May-October, 2017-2018 and 2018-2019). No plot was harvested more than once. Fresh weight of harvested samples was taken in the field and, samples from each harvested quadrat were collected, weighed, and kept in the perforated paper bags. The samples were brought to the laboratory and oven dried at 60ºC for 48 hours till constant weight was acquired and then per meter square biomass was calculated.

Below ground biomass (BGB): BGB collected from harvesting monolith (soil cake 25x25x30 cm) from harvested plot, brought to the lab and washed with fine jet of water using 2 mm and 0.5 mm mesh screens. The samples were oven dried at 60ºC to constant weight and weighed.

Aboveground: Belowground biomass ratio: It was calculated for each month based on total standing crop (live + dead shoots) and belowground biomass, but ignoring the litter values.

Productivity: Aboveground net primary production (ANP) was determined as sum of positive changes in biomass before senescence setting in the community (Ram *et al*. 1989). The belowground net primary production (BNP) was calculated as difference between peak below ground biomass and preceding minimum biomass (Kuramoto and Bliss, 1970) however, difficulties and inaccuracies of this method has been discussed by several workers (Sims and Singh, 1978; Singh *et al*. 1984), therefore the estimated BNP should be taken as minimum and viewed with constraints imposed by available procedure.

Biomass carbon stock: The aboveground and belowground carbon stock (CS) was calculated by multiplying the respective mass of AGB and BGB with carbon conversion factors of 0.43 and 0.42 for AGB and BGB for herbaceous vegetation, respectively as per Ma *et al*. (2018). The accumulated aboveground and belowground carbon was calculated by multiplying the respective ANP and BNP with carbon conversion factors of 0.43 and 0.42.

5.2.2 Soil parameters

To characterize physico-chemical parameters of soils, a composite of 5 subsamples (0-30 cm each) from randomly selected points within each plot were taken. The samples were air dried for 24-48 hrs and transported to lab for physico-chemical analysis. Similarly, bulk density was taken from 5 points in each plot using core method (Grossman and Reinsch, 2002). The physico-chemical data measured were pH, moisture content, soil organic carbon content (SOC), Nitrogen (N), Phosphorus (P) and Potassium (K). Soil organic carbon was calculated using Walkley and Black method (1934). Potassium was measured following Reiner (2012) and the Nitrogen and Phosphorous were measured using modified micro-Kjeldahl process and spectrophotometer following Jackson (1958) respectively.

Soil organic carbon density (SOCD) was calculated using method of stratified cumulative sum (Liu *et al*. 2016):

$$\text{SOCDi} = \sum SOCi * Pi * Di * (1 - Ci)/100$$

Where SOCD is the SOC density (kg C m^{-2}) of the profile, SOCi is the SOC concentration (g kg-1), Pi is the bulk density (kg m^{-3}), Di is the soil depth (m), and Ci is the volume percent of gravel (particle sizes > 2 mm) in layer i, respectively. In present study SOCD was converted from kg C m^{-2} to g C m^{-2}.

5.3 Results

During the three years of study, the conditions were similar and seasonal periodicity for growth and biomass accumulation did not vary significantly. For study duration aboveground and below ground biomass were harvested for two consecutive seasons (2017-2018) respectively.

5.3.1 Aboveground Biomass (AGB)

The AGB for the year 2017 ranged between 102 to 504 g m^{-2} in *Trachydium* community, 208 to 511 g m^{-2} for Mixed Herbaceous community, 92 to 425 g m^{-2} for *Polygonum* community, 68 to 431 g m^{-2} for Mixed *Danthonia* community, and 160 to 579 g m^{-2} in *Danthonia* community. However, for year 2018 it ranged between 78 to 1247 g m^{-2} in *Trachydium* community, 208 to 687 g m^{-2} for Mixed Herbaceous community, 88 to 385 g m^{-2} for *Polygonum* community, 118 to 388 g m^{-2} for mixed *Danthonia* community, and 162 to 579 g m^{-2} in *Danthonia* community. In general, the aboveground biomass increased from May to September in all communities, after which it declined sharply. A sharp increase in biomass production was recorded in *Trachydium* and Danthonia communities from August to September (Fig. 5.1).

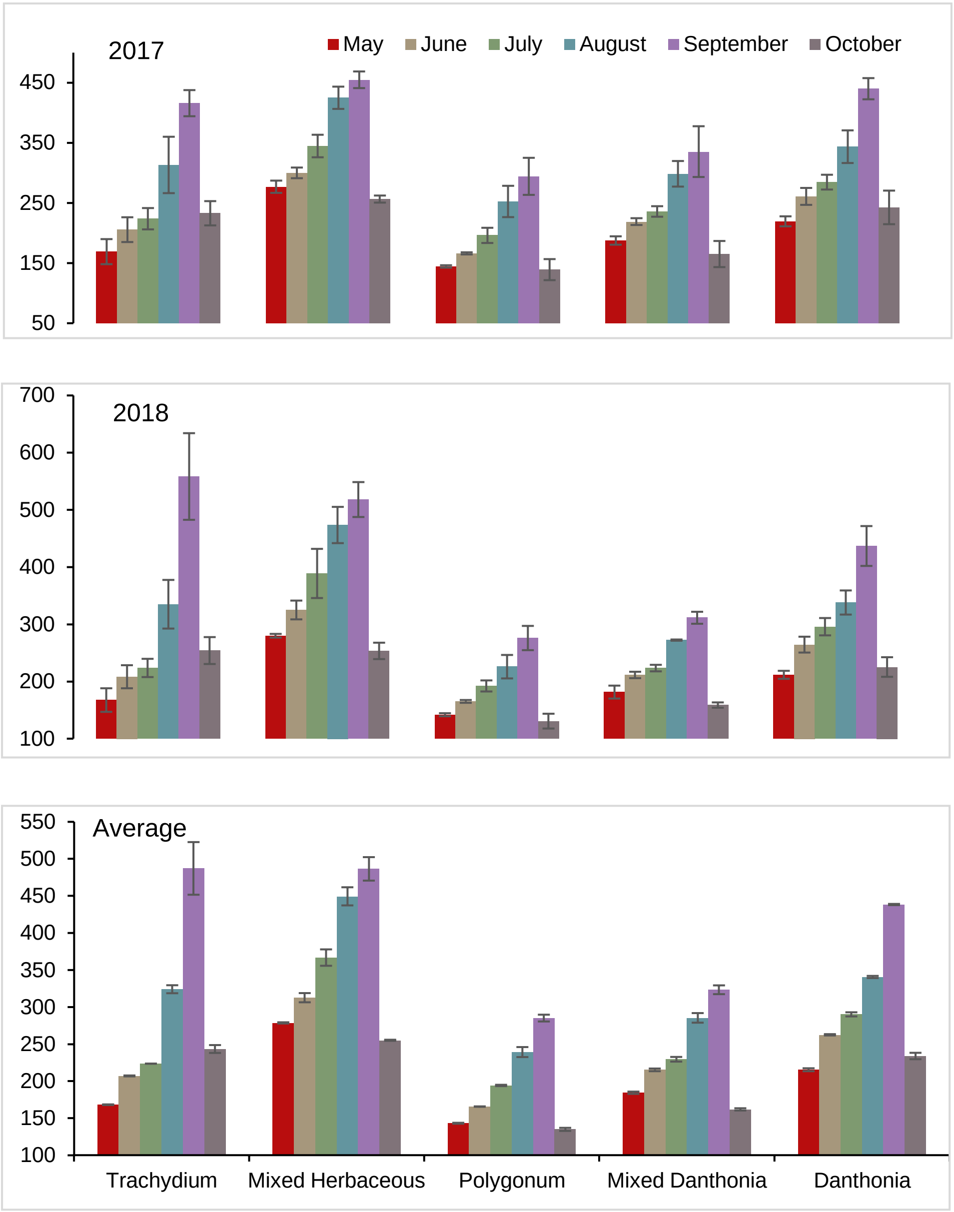


Figure 5.1 Temporal changes in above ground biomass of various communities

5.3.1.1 Shoot Biomass

Live Shoot mass

The live shoot biomass in 2017 ranged between 75 to 437 g m^{-2} in *Trachydium* community, 99 to 481 g m^{-2} for Mixed Herbaceous community, 46 to 340 g m^{-2} for *Polygonum* community, 30 to 347 g m^{-2} for Mixed *Danthonia* community, and 77 to 463 g m^{2} in *Danthonia* community. Similarly, for the year 2018 it ranged between 74 to 998 g m^{-2} in *Trachydium* community, 96 to 587 g m^{-2} for Mixed Herbaceous community, 46 to 308 g m^{-2} for *Polygonum* community, 54 to 310 g m^{-2} for Mixed *Danthonia* community, and 73 to 463 g m^{-2} in *Danthonia* community. The live shoot biomass increased from May to September in *Trachydium*, Mixed *Danthonia* and *Danthonia* communities, but in Mixed Herbaceous and *Polygonum* communities the live shoot biomass increased from May to August, after which it decreased till October end in the year 2017. Similarly, in the year 2018 the increase in live shoot biomass from May till September was recorded for Mixed Herbaceous and *Danthonia* communities only, while in *Trachydium*, *Polygonum* and Mixed *Danthonia* communities an increase till August was recorded, after which live shoot biomass started declining. Overall, the live shoot biomass increased till August in *Trachydium* and *Polygonum* communities while in remaining communities it increased till September after which declined sharply (Fig. 5.2).

Dead Shoot mass

In the year 2017, the standing dead shoot biomass ranged between 5 and 136 g m^{-2} for *Trachydium* community, for Mixed Herbaceous community it ranged between 6 and 124 g m^{-2}, 4 to 83 g m^{-2} for *Polygonum* community, 5 to 105 g m^{-2} for Mixed *Danthonia* community, and 6 to 134 g m^{-2} for *Danthonia* community. Similarly, in the year 2018, it ranged between 3 to 217 g m^{-2} in *Trachydium* community, 6 to 132 g m^{-2} for Mixed Herbaceous community, 4 to 76 g m^{-2} for *Polygonum* community, 5 to 78 g m^{-2} for Mixed *Danthonia* community, and 6 to 121 g m^{-2} for *Danthonia* community. The standing dead biomass declined from May to June in all communities, after which it started rising gradually till September, whereafter it increased sharply in September in 2017 and 2018. In *Trachydium* and Mixed Herbaceous communities, almost no dead shoot from previous years was recorded dead attached in May, so only shoots produced in sampled years (2017 and 2018) contributed to dead shoot standing crop. However, in *Polygonum*, Mixed *Danthonia* and *Danthonia* communities, although there was mortality of live shoots for the sampled years was recorded in form of plant senescence, however, most of the dead shoot biomass recorded till July was from shoots produced in previous years, especially as the shoots from previous year remained buried under snow. As it was difficult to segregate biomass of dead shoot produced in previous year and sampled year in the three communities, addition of dead shoots of previous season marked additions in this component by current year death. Only from August onwards did the total standing dead biomass increased because of large scale increase in shoot senescence of current year shoots (Fig. 5.3).

5.3.1.2 Litter mass

In the year 2017 the litter mass ranged between 1.8 to 30 g m^{-2} in *Trachydium* community, for Mixed Herbaceous community it ranged between 2 and 39 g m^{-2}, 1.5 to 34 g m^{-2} for *Polygonum* community, 1.9 to 30 g m^{-2} for Mixed *Danthonia* community, and 2 to 38 g m^{-2} for *Danthonia* community. Similarly, in the year 2018, it ranged between 1.8 to 61 g m^{-2} in *Trachydium* community, 3 to 37 g m^{-2} in Mixed Herbaceous community, 1.5 to 22 g m^{-2} for *Polygonum* community, 1.9 to 22 g m^{-2} for Mixed *Danthonia* community, and 2.5 to 33 g m^{-2} for *Danthonia* community. The litter biomass was absent at start of growing season (May) during study period (2017-2018). The dead shoots and litter were not visible overtly throughout the growing season in *Trachydium* and Mixed Herbaceous communities. The litter mass started generating May onwards, as previous year standing dead shoots/leaves detached from plant ramets due to new growth initiation. The litter mass declined continuously from June to July in all communities after which it started increasing subsequently and a sharp increase was recorded in October for all communities. Contrary to other studies, the absence of litter mass in early May shows dead attached shoots of previous growing season did not transfer to litter component in winter due to snow fall during the study period (Fig.5.4).

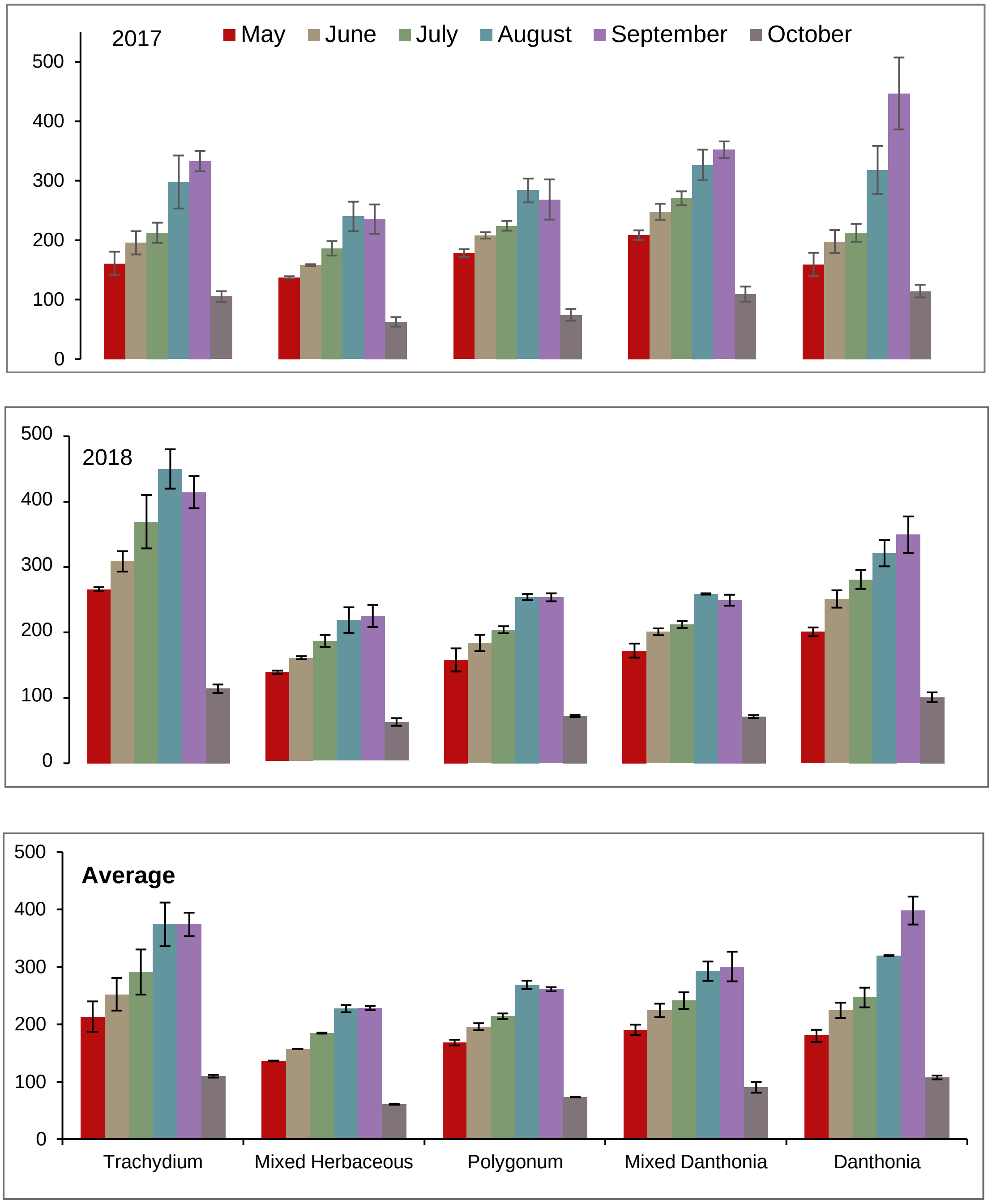


Figure 5.2 Temporal changes in above ground living biomass (g m^{-2}) of various communities

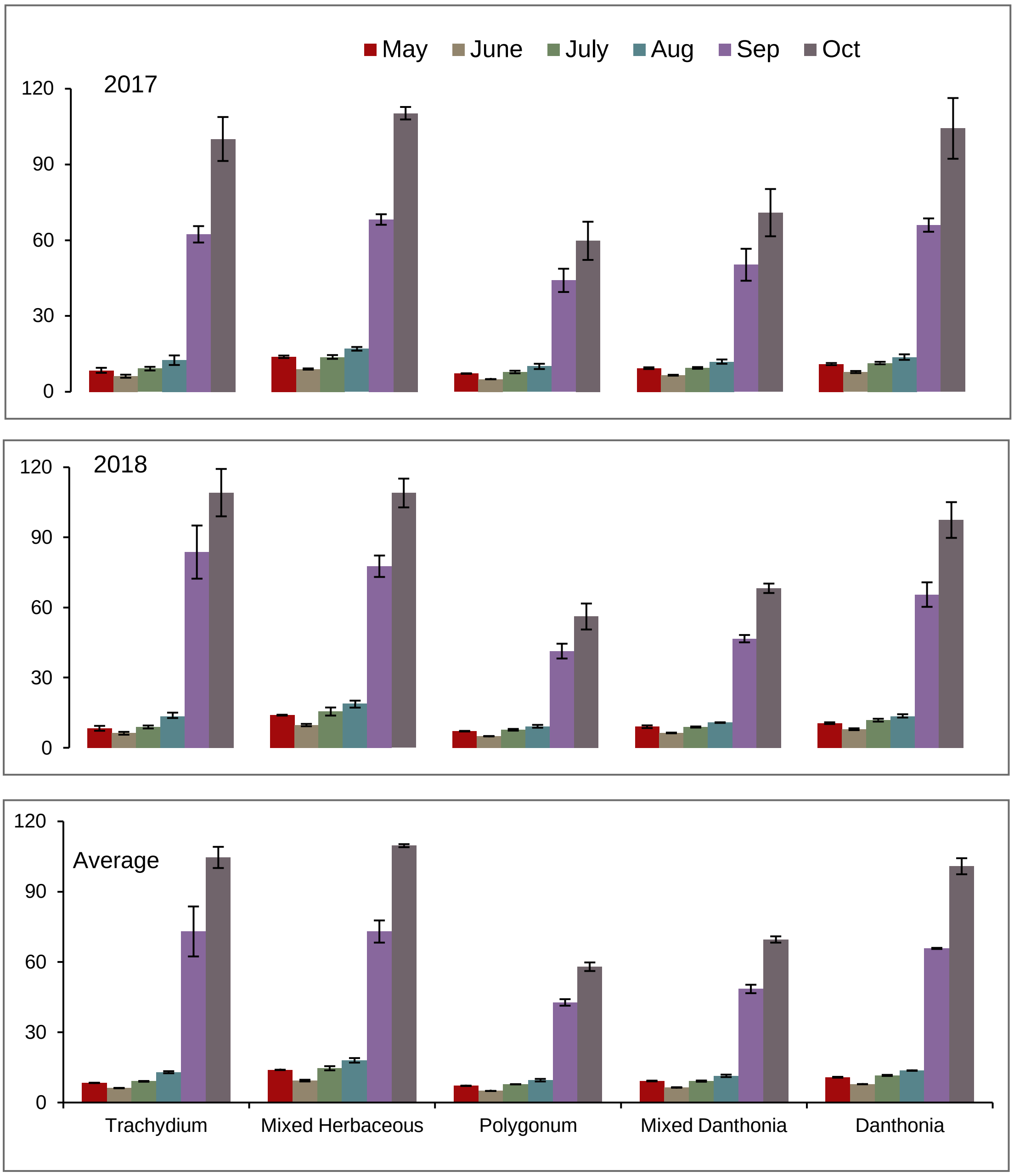


Figure 5.3 Temporal changes in above ground standing dead biomass (g m^{-2}) of various communities

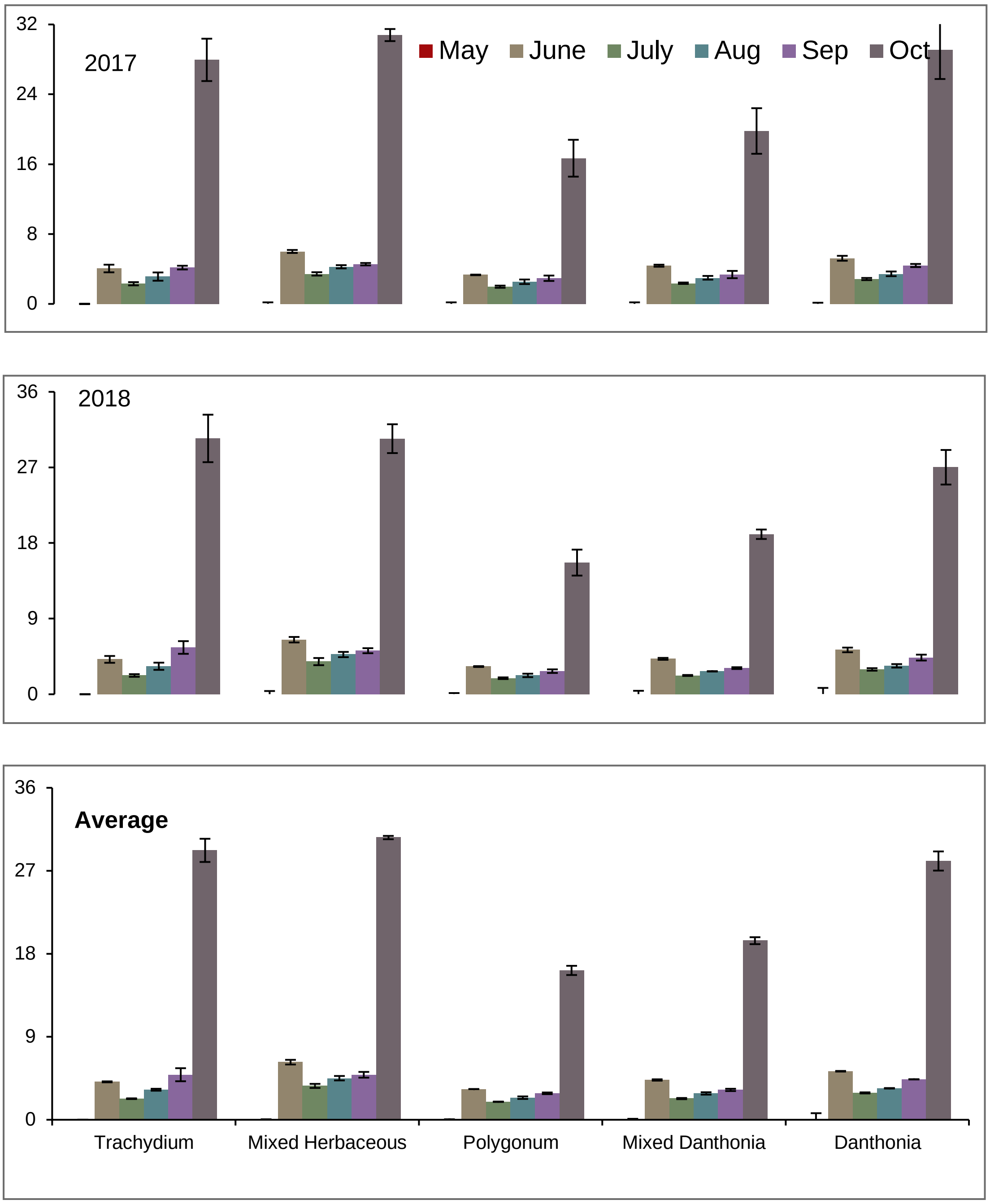


Figure 5.4 Temporal changes in Litter biomass (g m^{-2}) of various communities

5.3.2 Belowground Biomass (BGB)

The seasonal pattern of BGB during the study period (2017-2018) was similar in all communities. For the year 2017, the below ground biomass ranged between 193.6 to 352.0 g m^{-2} in *Trachydium* community, 150.4 to 387.0 g m^{-2} for Mixed Herbaceous community, 295.7 to 653.0 g m^{-2} for *Polygonum* community, 198.4 to 891.5 g m^{-2} for Mixed *Danthonia* community, and 340.8 to 1108.5 g m^{-2} in *Danthonia* community (Fig.5.5). For the year 2018 it ranged between 209.6 to 968.2 g m^{-2} in *Trachydium* community, 217.6 to 646.4 g m^{-2} for Mixed Herbaceous community, 305.5 to 564.8 g m^{-2} for *Polygonum* community, 416.0 to 560.0 g m^{-2} for Mixed *Danthonia* community, and 369.6 to 536.2 g m^{-2} in *Danthonia* community (Fig. 5.5). In general, the BGB decreased from May to July in all communities, after which it increased. A sharp increase in biomass production at end of growing season (September to October) was recorded in all communities. Analysis of variance indicated significant differences (in all cases $p < 0.05$) between communities as well as between months (in all cases $p < 0.02$) but not between years. Dunn Post hoc test was applied to see the significance between communities which showed that *Trachydium* and Mixed Herbaceous communities showed significant difference with *Polygonum*, Mixed *Danthonia* and *Danthonia* communities but no significant difference was observed between *Trachydium* and Mixed Herbaceous, and between *Polygonum*, Mixed *Danthonia* and *Danthonia* communities.

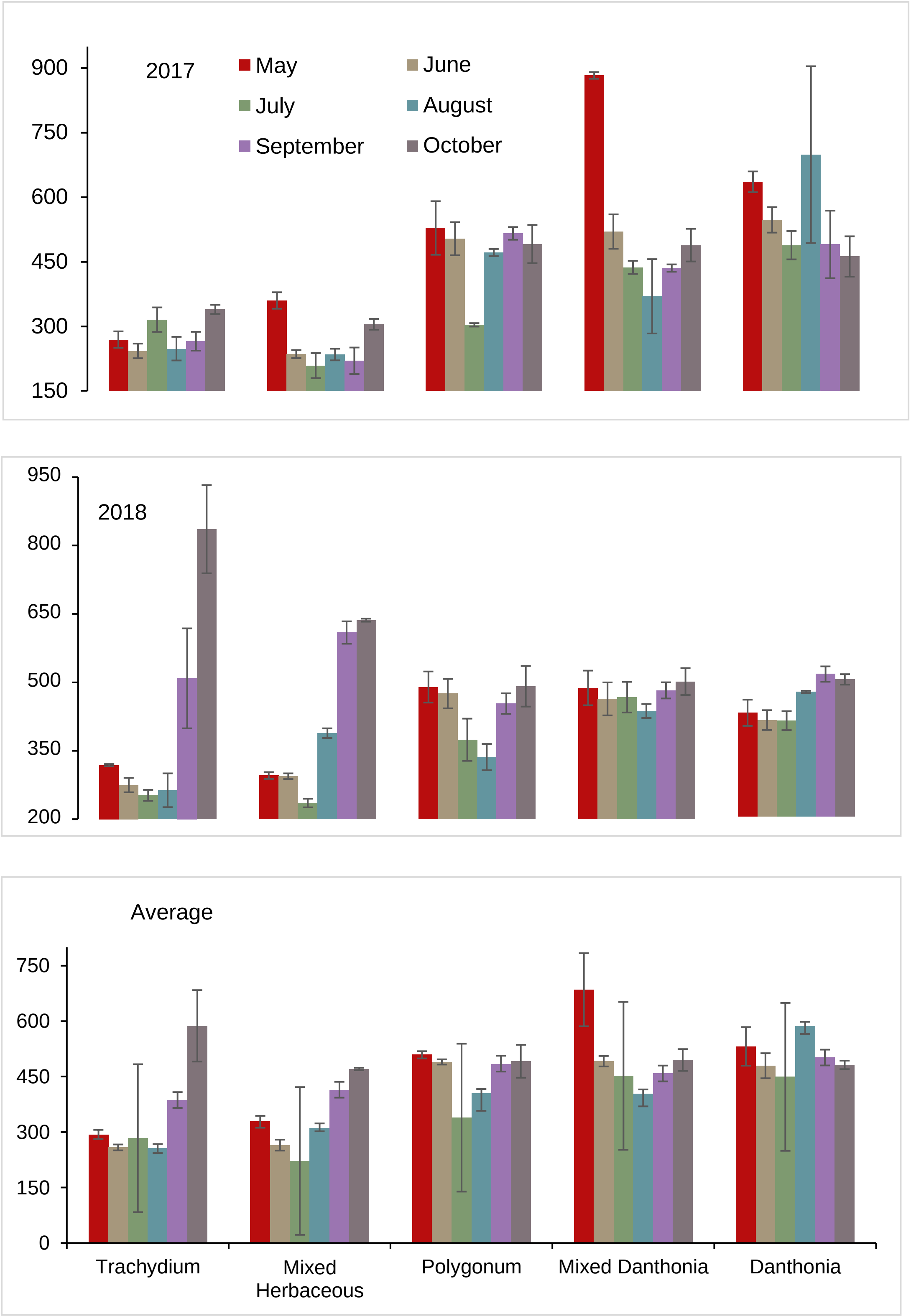


Figure 5.5 Temporal changes in belowground biomass of various communities

5.3.3 Belowground: Aboveground Biomass Ratio

In general, the BGB to AGB ratio decreased as growing season progressed, after which it increased sharply (Table 5.1). For the year 2017, the ratio was lowest for Mixed Herbaceous community (minimum 0.37 in September and maximum 1.32 in May) and highest for *Polygonum* community (minimum 1.44 in July and maximum 4.77 in October). For the year 2018, the ratio was lowest for Mixed Herbaceous community (minimum 0.50 in July and maximum 2.67 in October) and highest for *Polygonum* community (minimum 1.31 in September and maximum 4.56 in October). The overall biomass ratio decreased till September in *Trachydium* and *Danthonia* communities, July in Mixed Herbaceous community, and August in *Polygonum* and Mixed *Danthonia* communities (Table 5.1). The lowest ratio was recorded in the month of September 2017 for Mixed Herbaceous community (0.37) and highest ratio was recorded for the month of May 2017 in Mixed *Danthonia* community (5.1).

Table 5.1 Mean monthly variation in Belowground: Aboveground Biomass in the alpine communities of Tungnath during study period (2017-2019)

Months	***Trachydium***	**Mixed Herbaceous**	**Mixed *Danthonia***	***Polygonum***	***Danthonia***
May	1.79±0.2	1.18±0.1	3.55±0.1	3.73±0.9	2.46±0.4
June	1.26±0.1	0.85±0.1	2.95±0.1	2.29±0.1	1.83±0.3
July	1.27±0.1	0.61±0.0	1.76±0.2	1.98±0.1	1.56±0.2
August	0.80±0.0	0.69±0.1	1.70±0.2	1.41±0.2	1.73±0.3
September	0.79±0.1	0.83±0.4	1.73±0.1	1.44±0.1	1.16±0.0
October	2.45±0.9	1.86±0.7	3.79±0.1	3.08±0.1	2.09±0.2

5.3.4 Aboveground Net Primary Production (ANP)

The total aboveground biomass production was determined by summation of peak live biomass monthly increment. The initial aboveground biomass was assumed zero as no green material was present in beginning of growing season after snowmelt. The aboveground net primary production (ANP) for 2017 was 416.0±35.5 g m^{-2} for *Trachydium* community (maximum 458.1 g m^{-2}, minimum 386.1 g m^{-2}), 454.8±22.7 g m^{-2} for Mixed Herbaceous (maximum 480.5 g m^{-2}, minimum 433.1 g m^{-2}), 294.3±50.5 g m^{-2} for *Polygonum* (maximum

348.5 g m^{-2}, minimum 241.9 g m^{-2}), 335.2±69.2 g m^{-2} for Mixed *Danthonia* (maximum 419.7 g m^{-2}, minimum 292.4 g m^{-2}), and 439.9±28.9 g m^{-2} for *Danthonia* (maximum 475.1 g m^{-2}, minimum 420.3 g m^{-2}) communities. For the year 2018, the ANP was 558.2±124.1 g m^{-2} for *Trachydium* community (maximum 696.5 g m^{-2}, minimum 435.7 g m^{-2}), 518.0±50.0 g m^{-2} for Mixed Herbaceous (maximum 577.1 g m^{-2}, minimum 475.2 g m^{-2}), 275.9±34.7 g m^{-2} for *Polygonum* (maximum 314.0 g m^{-2}, minimum 240.9 g m^{-2}), 311.4±17.2 g m^{-2} for Mixed *Danthonia* (maximum 331.7 g m^{-2}, minimum 296.7 g m^{-2}), and 436.7±57.1 g m^{-2} for *Danthonia* (maximum 473.8 g m^{-2}, minimum 367.1 g m^{-2}) communities (Table 5.2).

5.3.5 Belowground Net Primary production (BNP)

The total belowground net production (BNP) was calculated by difference of maximum and minimum biomass during the study period. The BNP for the year 2017 was 127.5±33.1 g m^{-2} for *Trachydium*, 102.4±29.9 g m^{-2} for Mixed Herbaceous, 242.7±43.1 g m^{-2} for *Polygonum*, 174.4±91.7 g m^{-2} for Mixed *Danthonia*, and 346.3±263.7 g m^{-2} for *Danthonia* communities. The BNP for the year 2018 was 596.2±163.9 g m^{-2} for *Trachydium*, 406.2±20.4 g m^{-2} for Mixed Herbaceous, 186.9±77.1 g m^{-2} for *Polygonum*, 75.3±14.9 g m^{-2} for mixed *Danthonia*, and 103.1±16.3 g m^{-2} for *Danthonia* communities (Table 5.2).

5.3.6 Biomass Carbon Density

The monthly aboveground and belowground dry biomass of communities was converted into gram carbon m^{-2} by multiplying the mass with carbon conversion factors of 0.43 and 0.42 for AGB and BGB, respectively for the biomass carbon density (Carbon Stock) in the communities (Table 5.2). The aboveground carbon density (ACD) for the year 2017 ranged between 43.9 to 216.7 g m^{-2} in *Trachydium* community, 89.4 to 219.7 g m^{-2} for Mixed Herbaceous community, 39.6 to 182.6 g m^{-2} for *Polygonum* community, 29.2 to 185.3 g m^{-2} for Mixed *Danthonia* community, and 68.8 to 249 g m^{-2} in *Danthonia* community. However, for year 2018 it ranged between 33.5 to 536.2 g m^{-2} in *Trachydium* community, 88.4 to 295.4 g m^{-2} for Mixed Herbaceous community, 37.8 to 165.5 g m^{-2} for *Polygonum* community, 50.7 to 166.8 g m^{-2} for mixed *Danthonia* community, and 69.7 to 249.0 g m^{-2} in *Danthonia* community. The belowground carbon density (BCD) during the study period (2017-2018) was similar in all communities. For the year 2017, the BCD ranged between 81.3 to 147.8 g m^{-2} in *Trachydium* community, 63.2 to 162.4 g m^{-2} for Mixed Herbaceous community, 124.2 to 274.2 g m^{-2} for *Polygonum* community, 83.3 to 374.4 g m^{-2} for Mixed *Danthonia* community, and 143.1 to 465.6 g m^{-2} in *Danthonia* community. For the year 2018 it ranged between 88.0 to 406.6 g m^{-2} in *Trachydium* community, 91.4 to 271.5 g m^{-2} for Mixed Herbaceous community, 128.3 to 237.2 g m^{-2} for *Polygonum* community, 174.7 to 235.2 g m^{-2} for Mixed *Danthonia* community, and 155.2 to 225.2 g m^{-2} in *Danthonia* community.

To calculate the carbon sequestered by the communities the monthly aboveground and belowground net primary productivity (NPP) of communities was first converted into gram carbon m^{-2} and total carbon sequestered by the community was determined by summation of monthly sequestered carbon stock (CS) at the end of growing season (Table 5.2). The sequestered aboveground carbon stock (ACS) for 2017 was 178.9±15.3 g m^{-2} for *Trachydium* community (maximum 197.0 g m^{-2}, minimum 166.0 g m^{-2}), 195.5±9.8 g m^{-2} for Mixed Herbaceous (maximum 206.6 g m^{-2}, minimum 186.2 g m^{-2}), 126.5±21.7 g m^{-2} for *Polygonum* (maximum 149.9g m^{-2}, minimum 104.0 g m^{-2}), 144.2±29.8 g m^{-2} for Mixed *Danthonia* (maximum 180.5 g m^{-2}, minimum 125.7 g m^{-2}), and 189.2±12.4 g m^{-2} for *Danthonia* (maximum 204.3 g m^{-2}, minimum 180.7 g m^{-2}) communities. For the year 2018, the ACS was 240.0±53.4 g m^{-2} for *Trachydium* community (maximum 299.5 g m^{-2}, minimum 187.4 g m^{-2}), 222.8±21.5 g m^{-2} for Mixed Herbaceous (maximum 248.1 g m^{-2}, minimum 204.3 g m^{-2}), 118.7±14.9 g m^{-2} for *Polygonum* (maximum 135.0 g m^{-2}, minimum 103.6 g m^{-2}), 133.9±7.4 g m^{-2} for Mixed *Danthonia* (maximum 142.6 g m^{-2}, minimum 127.6 g m^{-2}), and 187.8±24.6 g m^{-2} for *Danthonia* (maximum 203.8 g m^{-2}, minimum 157.8 g m^{-2}) communities. For the year 2017 the sequestered belowground carbon stock (BCS) was not calculated as the previous year (2016) community biomass was not available to calculate carbon stock in May 2017. The BCS for 2018 was 208.5±69.8 g m^{-2} for *Trachydium*, 139.3±9.4 g m^{-2} for Mixed Herbaceous, 0.0±0.0 g m^{-2} for *Polygonum*, 5.4±9.8 g m^{-2} for mixed *Danthonia*, and 16.2±24.5 g m^{-2} for *Danthonia* communities.

Table 5.2 Mean values of carbon density, productivity, and accumulated carbon (g m^{-2}) during study period (2017 - 2019). ACD: Aboveground Carbon Density; ANP: Aboveground Annual Net Productivity; ACS: Aboveground Carbon Sequestered; BCD: Belowground Carbon Density; BNP: Belowground Annual Net Productivity; BCS: Belowground Carbon Sequestered

Year	**Compartment**	**Month**	***Trachydium***	**Mixed Herbaceous**	***Polygonum***	**Mixed *Danthonia***	***Danthonia***
2017	ACD	May	72.70	119.02	62.13	80.59	94.29
		June	88.45	128.96	71.44	94.06	112.11
		July	96.24	148.15	84.30	101.37	122.31
		August	134.70	182.70	108.61	128.27	147.67
		September	178.88	195.54	126.53	144.16	189.18
		October	100.14	110.31	59.80	70.92	104.27
	ANP	May	169.07	276.80	144.49	187.42	219.29
		June	36.62	23.11	21.64	31.33	41.42
		July	18.13	44.62	29.91	16.98	23.73
		August	89.42	80.36	56.53	62.58	58.98
		September	102.76	29.87	41.69	36.93	96.53
	ACS	May	72.70	119.02	62.13	80.59	94.29
		June	15.75	9.94	9.31	13.47	17.81
		July	7.80	19.19	12.86	7.30	10.21
		August	38.45	34.55	24.31	26.91	25.36
		September	44.18	12.84	17.93	15.88	41.51
	BCD	May	112.94	151.16	222.00	370.83	267.09
		June	101.90	98.78	211.55	218.40	229.95
		July	132.38	87.58	127.44	183.46	205.18
		August	104.16	98.34	198.02	155.21	293.62
		September	111.33	92.29	216.70	182.78	205.99

		October	142.42	127.90	206.30	205.16	194.23
2018	ACD	May	71.93	120.40	60.98	77.97	90.91
		June	89.44	139.74	71.02	90.91	113.62
		July	96.09	167.18	82.67	96.00	127.11
		August	143.94	203.65	97.14	117.11	145.28
		September	240.04	222.76	118.66	133.89	187.79
		October	109.16	109.01	56.19	68.25	96.82
	ANP	May	167.29	280.00	141.82	181.33	211.42
		June	40.71	44.98	23.33	30.09	52.80
		July	15.47	63.82	27.11	11.82	31.38
		August	111.29	84.80	33.64	49.11	42.27
		September	223.47	44.44	50.04	39.02	98.84
	ACS	May	71.93	120.40	60.98	77.97	90.91
		June	17.51	19.34	10.03	12.94	22.70
		July	6.65	27.44	11.66	5.08	13.49
		August	47.85	36.46	14.47	21.12	18.17
		September	96.09	19.11	21.52	16.78	42.50
	BCD	May	133.71	124.14	205.63	204.76	179.54
		June	115.23	123.51	199.56	194.66	172.84
		July	105.80	98.78	157.11	196.22	172.26
		August	110.50	163.16	141.15	183.46	198.91
		September	213.54	255.88	190.40	202.45	215.29
		October	350.94	267.23	206.30	210.58	210.38
	BNP	May	-20.75	-8.96	-1.60	-0.96	-34.99
		June	-44.00	-1.49	-14.47	-24.05	-15.95
		July	-22.45	-58.88	-101.05	3.73	-1.39

		August	11.20	153.28	-38.01	-30.40	63.47
		September	245.33	220.75	117.27	45.23	38.99
		October	327.15	27.04	37.87	19.36	-11.68
	BCS	May	-8.7136	-3.7632	-0.672	-0.4032	-14.6944
		June	-18.48	-0.6272	-6.076	-10.1024	-6.6976
		July	-9.4304	-24.7296	-42.4424	1.568	-0.5824
		August	4.704	64.3776	-15.9656	-12.768	26.656
		September	103.04	92.7136	49.252	18.9952	16.3744
		October	137.4016	11.3568	15.904	8.1312	-4.9056

5.3.7 Soil Physical Properties

The soil physico-chemical properties play a significant role to provide conducive environment for plant growth. The nutrient budget plays a vital role in overcoming stress in harsh conditions in high altitude regions. The physical makeup of soil regulates chemical and biological properties (biophysical soil functions) including nutrient cycling, carbon storage and turnover, water maintenance, soil structure attunement, physical stability and plant system support, water dynamics, buffering and filtering etc.

Soil Texture

The percentage of sand, silt and clay ranged between 41 to 53%, 35 to 41% and 17 to 21% respectively for *Trachydium* community. For Mixed Herbaceous community the percentage of sand, silt and clay ranged between 46 to 53%, 23 to 30% and 15 to 20% respectively. In *Polygonum* community the percentage of sand, silt and clay ranged between 38 to 51%, 39 to 48% and 14 to 18% respectively. For Mixed *Danthonia* community the percentage of sand, silt and clay ranged between 45 to 55%, 29 to 34% and 15 to 20% respectively. For *Danthonia* community the percentage of sand, silt and clay ranged between 45 to 54%, 28 to 35% and 14 to 20% respectively. In all communities the overall soil texture was Loam (Table 5.3).

Table 5.3. Soil texture of different communities

Communities	Samples (n)	Sand (%±SE)	Silt (%±SE)	Clay (%±SE)	Texture
Trachydium	36	46.9±2.0	38.0±0.7	18.9±0.5	Loam
Mixed Herbaceous	36	49.3±0.8	26.6±0.8	17.8±0.7	Loam
Polygonum	36	45.5±1.8	43.3±1.0	15.9±0.4	Loam
Mixed *Danthonia*	36	50.1±1.3	33.9±1.0	17.1±1	Loam
Danthonia	36	49.7±1.1	3.9±1.0	16.6±0.8	Loam

Soil pH

Soil pH has an influence on soil biogeochemical processes and therefore, can be described as primary soil variable. A general pattern of increase in soil pH as the growing season progressed was observed in *Trachydium,* Mixed Herbaceous and Mixed *Danthonia* communities, while a decrease was recorded for *Polygonum* and *Danthonia* communities (Fig.

5.6). In both the years 2017 and 2018, the pH ranged between 4.9 and 5.3 in *Trachydium* community, 4.9 and 6.4 for Mixed Herbaceous community, 4.9 to 6.5 for *Polygonum* dominated community, 5.0 to 6.0 for Mixed *Danthonia* community, and 5.0 to 5.22 for *Danthonia* community. Kruskal-Wallis test showed there was no significant difference between years and communities overall while Mann-Whitney test showed significant differences between *Trachydium* and Mixed Herbaceous, and between *Polygonum* and Mixed *Danthonia* communities (p<0.05).

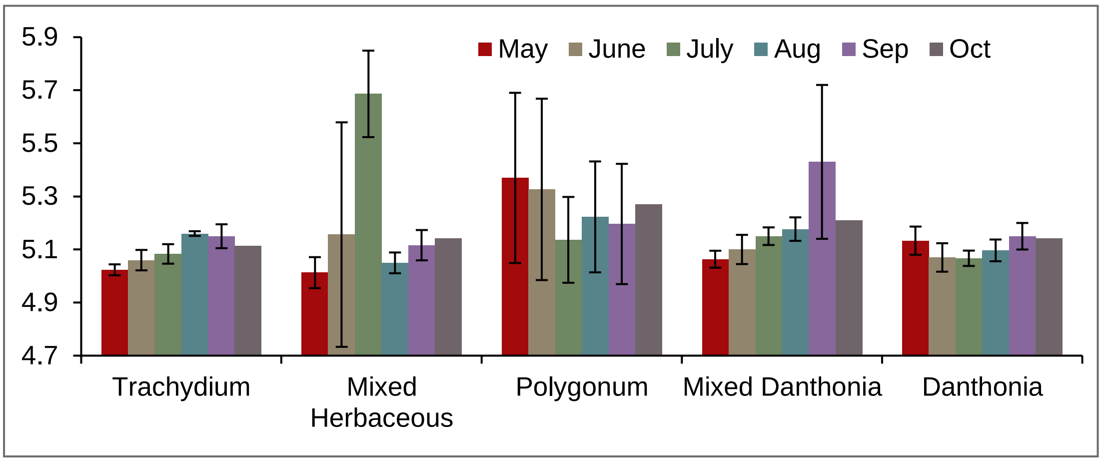


Figure 5.6. Temporal changes in soil pH of various communities

Soil Moisture Content

Soil moisture content is the water held in spaces between soil particles. It is a key variable in controlling the water exchange and heat energy between land surface and the atmosphere through evaporation and plant transpiration. Soil moisture in all communities was high in early growing season due to snowmelt. The soil moisture first decreased as growing season progressed, then increased sharply due to onset of monsoon, and declined towards the end of growing season in all communities (Fig. 5.7). In both the years 2017 and 2018, the soil moisture content ranged between 40 and 62% in *Trachydium* community, 41 and 65 for Mixed Herbaceous community, 41 to 62% for *Polygonum* dominated community, 34 to 54% for Mixed *Danthonia* community, and 39 to 59% for *Danthonia* community. The maximum soil moisture was recorded high for all communities in August and no significant difference was observed for communities (Fig. 5.7).

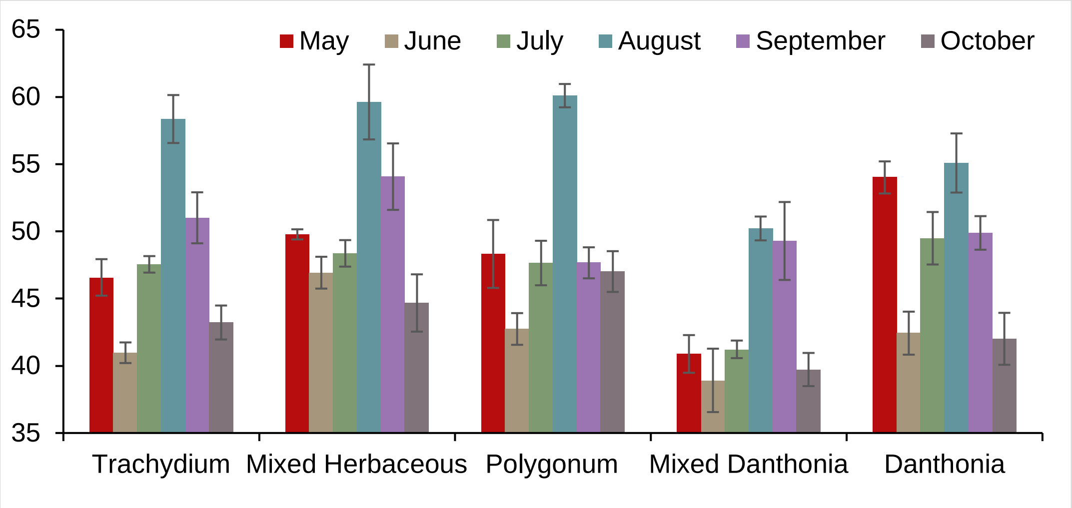


Figure 5.7. Temporal changes in soil moisture content of various communities

5.3.8 Soil Chemical properties

Soil Organic Carbon

The soil organic carbon (SOC) percent ranged between 3.5 to 8.9% throughout the study period (2017-2018; Fig. 5.8). In the year 2017, the SOC ranged between 3.98 to 4.54% in *Trachydium* community, 3.55 to 8.35% for Mixed Herbaceous community, 3.9 to 6.55% for *Polygonum* community, 7.33 to 8.78% for Mixed *Danthonia* community, and 5.66 to 8.62% for *Danthonia* community. In the year 2018, the SOC ranged between 3.55 to 6.44% in *Trachydium* community, 5.89 to 8.54% for Mixed Herbaceous community, 4.41 to 7.96% for *Polygonum* community, 7.37 to 8.81% for Mixed *Danthonia* community, and 5.85 to 8.81% for *Danthonia* community. A general trend of increase in SOC was observed in *Trachydium* community while a constant decrease was recorded for Mixed *Danthonia* community. In *Polygonum* and *Danthonia* communities an increase in SOC % till early and mid-growing season was recorded and declined afterwards, while an opposite trend was recorded for

Mixed Herbaceous community where SOC first decreased than increased with the progression of growing season.

Soil Carbon Stock

In the year 2017, the soil organic carbon stock (SOCS) ranged between ranged between 116.7 to 263.0 g m^{-2} in *Trachydium* community, 119.1 to 362.5 g m^{-2} in Mixed Herbaceous community, 103.8 to 203.4 g m^{-2} for *Polygonum* community, 375.8 to 534.0 g m^{-2} for Mixed *Danthonia* community, and 150.9 to 328.5 g m^{-2} for *Danthonia* community. The peak SOCS was recorded in the month of September for *Trachydium*, Mixed Herbaceous and *Danthonia* communities, May for Mixed *Danthonia* community, and July for *Polygonum* community. In the year 2018, the SOCS ranged between 99.5 to 233.8 g m^{-2} in *Trachydium* community, 117.6 to 267.5 g m^{-2} for Mixed Herbaceous community, 80.2 to 167.1 g m^{-2} for *Polygonum* community, 251.9 to 357.6 g m^{-2} for Mixed *Danthonia* community, and 104.1 to 224.1 g m^{-2} for *Danthonia* community. During the study, the peak SOCS for *Trachydium*, Mixed Herbaceous and *Danthonia* communities was recorded in the month of September, and in May for Mixed *Danthonia* community. However, for *Polygonum* community the SOCS peaked in July and June in 2017 and 2018, respectively. A general trend of increase in SOCS stock as the growing season progressed was observed in *Trachydium* community while a constant decrease was recorded for mixed *Danthonia* community. In *Polygonum* and *Danthonia* communities an increase in SOCS stock was recorded till early and mid-growing season, and then declined, while an opposite trend was recorded for Mixed Herbaceous community where SOCS stock decreased initially than increased with the progression of growing season.

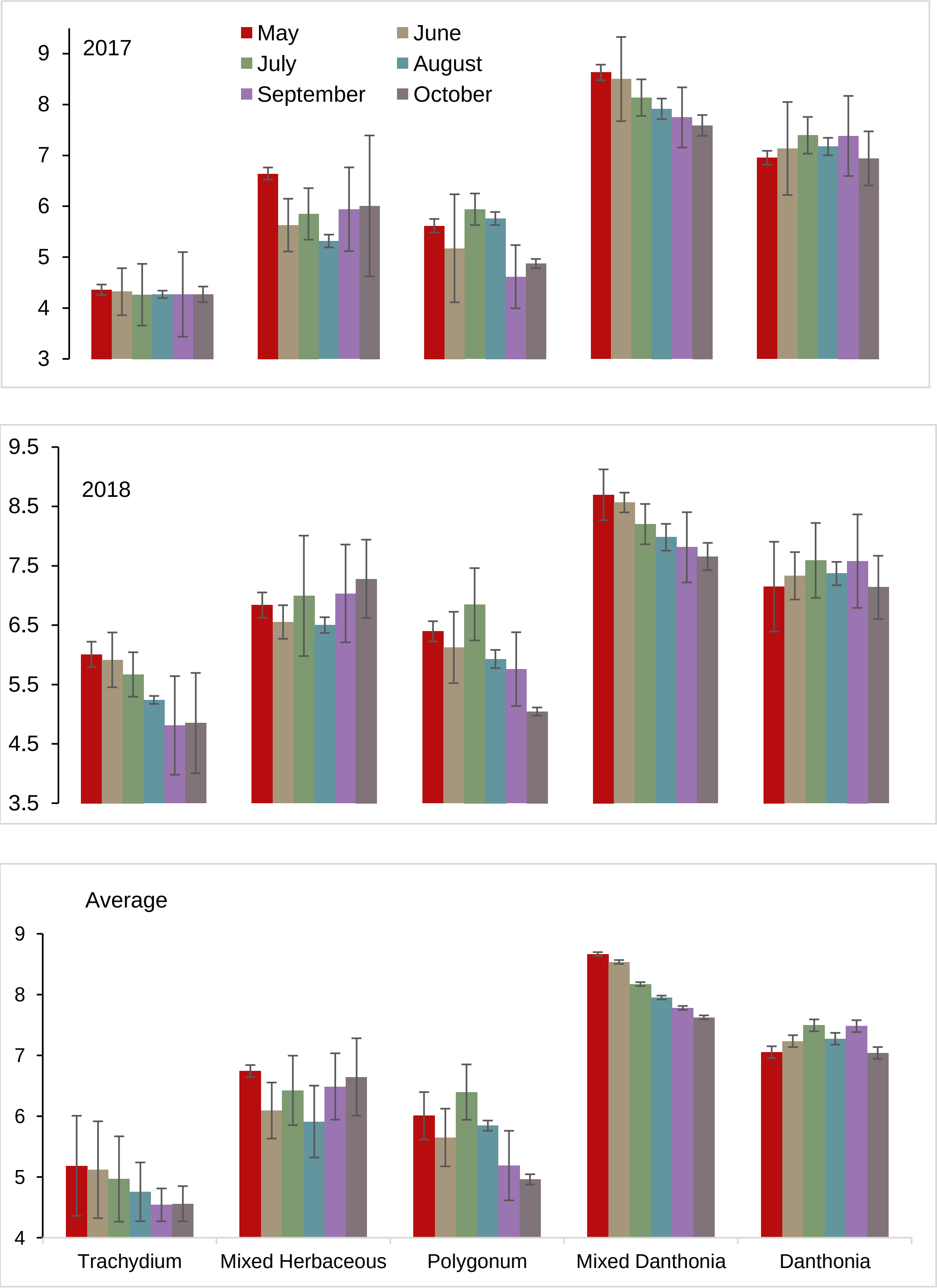


Figure 5.8. Temporal changes in soil organic carbon (SOC%) content of various communities

Soil Nitrogen

During the study period (2017 and 2018), the total nitrogen (N%) ranged between 0.02 to 0.99% throughout the growing season (Fig. 5.9). The N percentage ranged between 0.32 and 0.502% in *Trachydium* community, 0.23 to 0.703% for Mixed Herbaceous community, 0.33 to 0.99% for *Polygonum* community, 0.02 to 0.78% for Mixed *Danthonia* community, and 0.04 to 0.80% for *Danthonia* community for the study period (2017-2018; Fig. 5.9). The peak N percent was recorded in May for *Danthonia* and Mixed *Danthonia* communities, August for *Polygonum* and October for *Trachydium* and Mixed Herbaceous communities. A general trend of increase in N% as the growing season progressed was observed in *Trachydium,* Mixed Herbaceous and *Polygonum* community till early and mid-growing season, and then declined, while an opposite trend was recorded for Mixed *Danthonia* and *Danthonia* communities where N% declined till late growing period after which it increased with progression of growing season.

Soil available Phosphorus

In the year 2017, the available Phosphorus (P) percent ranged between 0.13 and 1.6% in *Trachydium* community, 0.07 to 0.83 % in Mixed Herbaceous community, 0.12 to 0.77% in *Polygonum* community, 0.20 to 0.98% for Mixed *Danthonia* community, and 0.17 to 0.98% for *Danthonia* community. Similarly, in the year 2018, the P percent ranged between 0.11 and 0.72% in *Trachydium* community, 0.04 to 0.85% in Mixed Herbaceous community, 0.09 to 0.77% for *Polygonum* community, 0.22 to 0.98% for Mixed *Danthonia* community, and 0.15 to 0.85% for *Danthonia* community (Fig. 5.10). In general, an increase in the P percent in the early growing season (May-June) was recorded in all communities, and decline afterwards except in *Trachydium* community in the year 2017 where the P% increased till July (Fig. 5.10). The P percent decline till late mid-growing season (August) after which an increase in P percent was recorded September onwards in all communities, except in Mixed *Danthonia* community where P percent kept declining till end of growing season. The peak P% was recorded in month of June for *Danthonia*, *Polygonum* and Mixed *Danthonia* communities, October for Mixed Herbaceous community throughout the study period, and July and October in 2017 and 2018, respectively for *Trachydium* community.

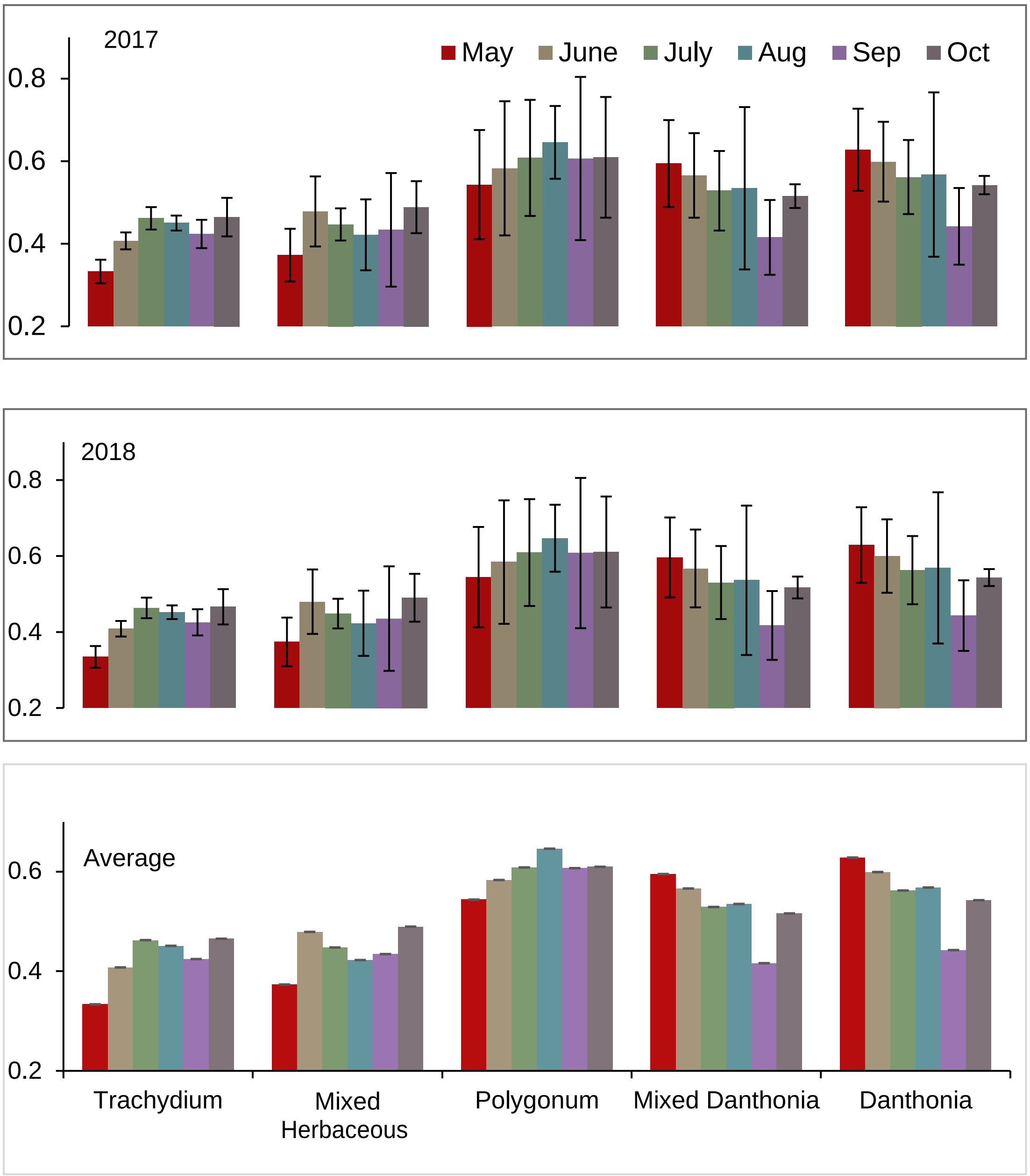


Figure 5.9. Temporal changes in total Nitrogen (%) content of various communities

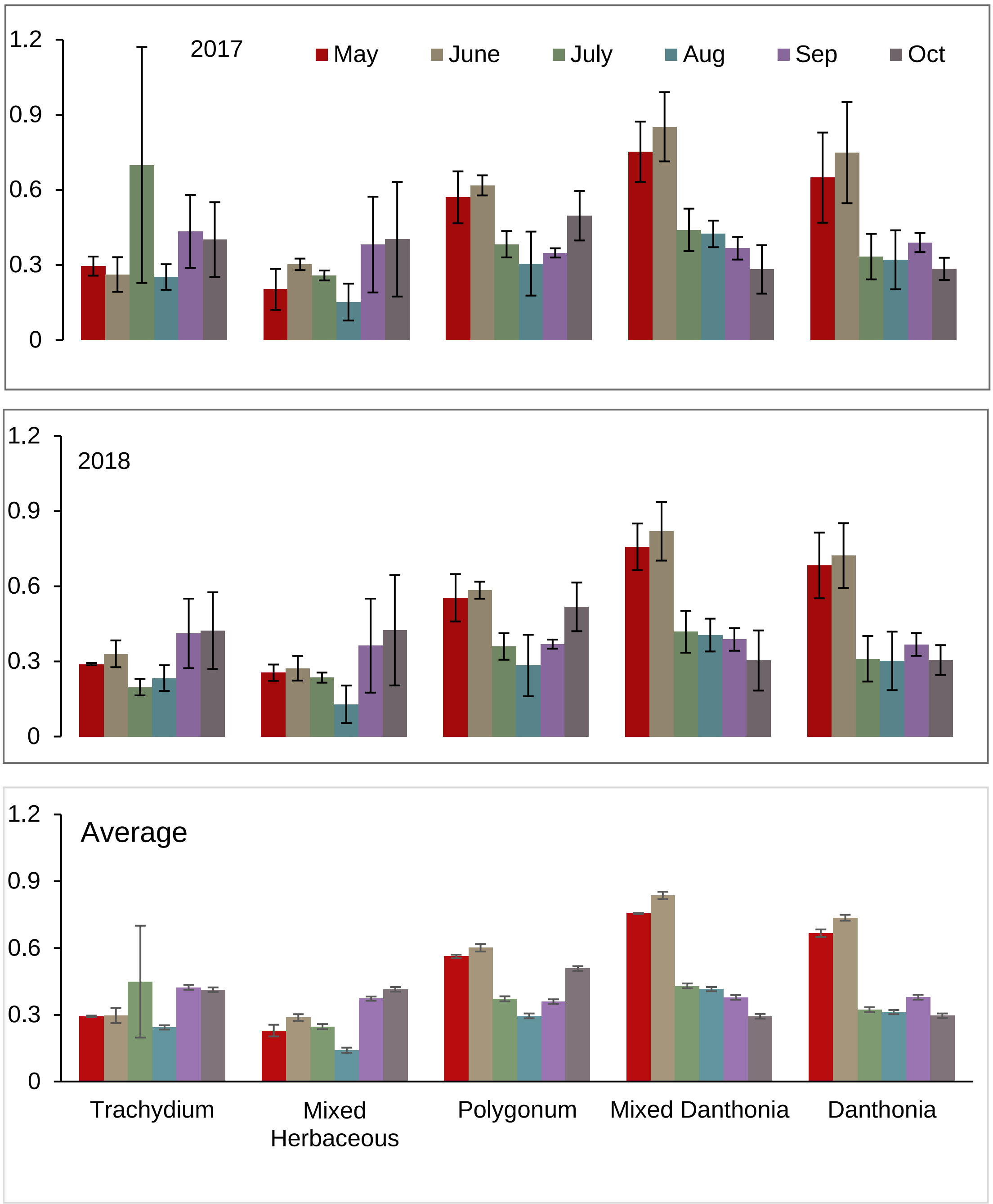


Figure 5.10. Temporal changes in available Phosphorous (%) content of various communities

Soil Potassium

The Potassium (K) percent ranged between 0.08 to 0.20% and 0.09 to 0.21% in 2017 and 2018, respectively in *Trachydium* community. It ranged between 0.08 to 0.154% and 0.09 to 0.164% for Mixed Herbaceous community; 0.08 to 0.22% and 0.09 to 0.23% for *Polygonum* community; 0.13 to 0.27% and 0.14 to 0.28% for Mixed *Danthonia* and *Danthonia* communities in 2017 and 2018 respectively (Fig. 5.11). In general, the K percent increased as growing season progressed in all communities till June in *Trachydium,* Mixed Herbaceous and *Polygonum* communities and July for Mixed *Danthonia* and *Danthonia* communities, and then declined. The K percent started increasing August onwards in all communities till the end of growing season. The peak K percent was recorded in the month of October for *Trachydium,* Mixed Herbaceous and *Polygonum* communities and in July for Mixed *Danthonia* and *Danthonia* communities.

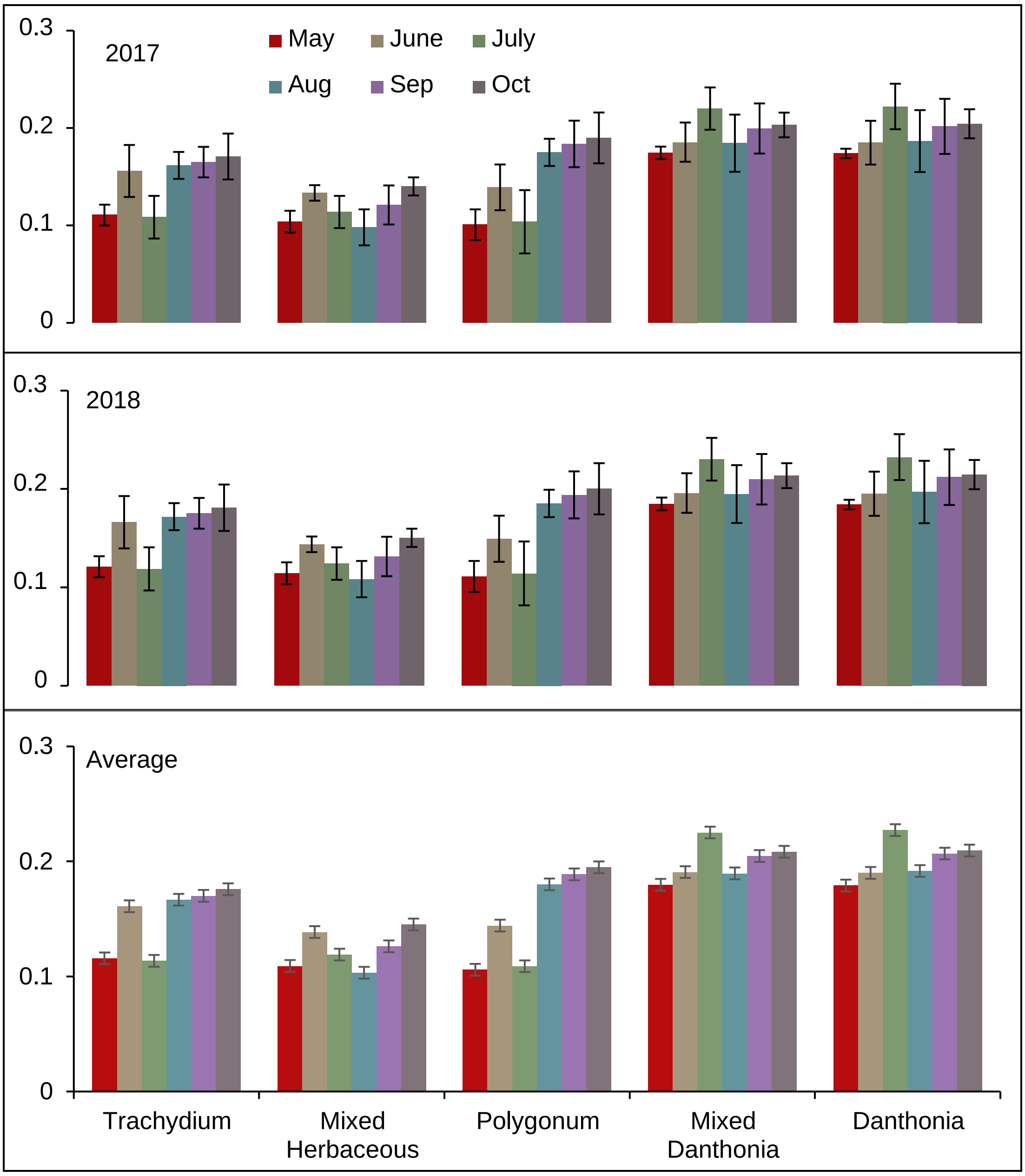


Figure 5.11. Temporal changes in soluble Potassium (K%) content of various communities

5.4 Discussion

The belowground to aboveground ratio varied between 0.37:1 and 5.1:1 in alpine communities. Similarly, because of large AGB and slower decomposition, dead components remained dominant feature of AGB in all communities except in *Trachydium* community where it was always a minor component. Therefore, the present study suggests that markedly different biomass structures may develop in different communities, located close to each other. The distribution of aboveground biomass (AGB) in herbaceous communities exhibits significant variation influenced by slope, elevation, and season along with prevalent microclimatic conditions. The continued buildup of biomass from May-September in present study indicates a favorable environmental condition for growth and accumulation. The lower values of belowground to aboveground biomass ratio indicate that the environmental conditions were less harsh at study area.

Due to the short growing season in the alpine zone of the Himalayas (from May to September), many species in this region complete their growth cycle within 3 to 5 months to ensure their survival. As a result, not all species reach their maximum biomass simultaneously, leading to the peak biomass of the community being lower than the peak biomass of individual species (Ram *et al*. 1988). Due to time constraint and difficulty of preserving and transporting individual species samples as well as destructive sampling, species biomass was not taken in the present study.

The average community AGB in present study varied between 180 to 487 g m^{-2}, which is much higher than that reported by Rawat (2007) for wet meadows of Greater Himalaya (85 to 284 g m^{-2}). Analysis of variance indicated significant differences (in all cases $p < 0.001$) between communities for both AGB and BGB except *Trachydium* and mixed *Danthonia* communities, as well as between months (in all cases $p < 0.02$) but not between the years. This is probably due to presence of gentler slopes in present study area compared to whole Greater Himalaya, as steeper slopes have lower AGB (Rawat, 2007). As a general trend AGB increased as the season progressed and attained peak in September in all communities. These findings are in common with studies conducted by Kala *et al*. (1998) for alpine regions of Valley of Flowers National Park and Khiron Valley, where the peak biomass was during September in both grazed and ungrazed sites (458 and 352 g m^{-2}), which is lower than the peak values of present study. Similarly, the peak community AGB values of the current study are greater compared to those documented in the alpine regions of Rudranath (409 and 382 g m^{-2}, Ram *et al*. 1989), Bedni-Ali (peak August 157-390 g m^{-2} Negi *et al*. 1992), Tapovan and Nandanvan (peak August 436 and 325 g m^{-2} respectively; Dhaulakhandi *et al*. 2010), Pawalikantha (217 g m^{-2}, Joshi *et al*. 1988), Bhojbasa and Gaumukh (peak August 435.4 and 472.3 g m^{-2} respectively; Dhaulakhandi *et al*. 2000; Table 5.4). When comparing the peak above-ground biomass (AGB) of the present study to previous findings in the same study area, the current average values are found to be higher than those reported for the Tungnath region by Sundriyal (1992) for both forb (195 g m^{-2}) and grass (239 g m^{-2}) meadows and Sundriyal and Joshi (1990) for protected (272 g m^{-2}) and grazed (133 g m^{-2}) meadows (Table 5.4). Keeping in mind that no protective fence was used to stop grazing in the present study sites, still the values are much higher than the protected sites. This shows that the resilience and productivity of community and species have increased in study area, possibly overall microclimatic conditions have become more favorable for plant growth.

The BGB showed opposite trend to AGB, as the biomass declined constantly till July in general, increased gradually in August, and peaked accumulation was recorded in September while peak biomass in October in present study. In *Polygonum* and *Danthonia* community peak BGB was recorded in September and August in 2017 and in September in *Danthonia* community in 2018 respectively, which might be due higher species richness during said month which might have contributed to greater biomass production for that duration (Singh *et al*. 2005). The peak average BGB varied between 470 and 590 g m^{-2} in different communities. Like present study, the different alpine communities across Greater Himalaya follow similar pattern for BGB production. The peak community BGB values for the current study are higher than what has been previously reported for alpine zones of similar altitude (3300-3600 masl) like Rudranath (470 g m^{-2}, Ram *et al*. 1989), Bedni-Ali (175-407 g m^{-2} for Negi *et al*. 1992), lower than that reported for high alpine meadows (>3800 masl) of Tapovan and Nandanvan (2264 and 2251 g m $^{-2}$ respectively; Dhaulakhandi *et al*. 2010), and Bhojbasa and Gaumukh (peak September, 2005 and 2217 g m $^{-2}$; Dhaulakhandi *et al*. 2000) respectively (Table 5.4). Comparing the peak BGB of present study with the past in the same study area, the present values are higher than that reported for Tungnath by Sundriyal (1992) for ungrazed and grazed sites in both forb (377 and 283 g m^{-2}) and grass (463 and 325 g m^{-2}) meadows and Sundriyal and Joshi (1990) for protected (505-652 g m^{-2}) and grazed (372-416 g m^{-2}) meadows (Table 5.4). This also applied to net accumulation of BGB. The increase in the BGB August onwards might be due to diversion of organic matter and nutrients by the species towards roots (Tubers, Rhizomes, Bulbs) from shoots in preparation of the winter and due to mass accumulation of dead roots. Therefore, as growing season progresses, they start to bulk up their reserve which reaches peak in October as accumulation of nutrients lowers freezing point of cells which help them survive subzero soil temperatures during peak winters. Billings *et al*. (1977) have reported functionality of roots below 5 °C, and they can resume elongation even after being frozen temporarily while Chapin *et al*. (1980) have corelated early season leaf growth with decrease in biomass of rhizomes.

Table 5.4. Comparative account of AGB and BGB (gm^{-2}) in various regions of Greater Himalaya

Study Region (Location)	AGB	BGB	Reference
Greater Himalaya (Wet meadow)	85 - 284	-	Rawat, 2007
Valley of Flowers National Park	352	-	Kala *et al*. 1998
Khiron Valley	412 - 458	-	Kala *et al*. 1998
Rudranath	382 - 409	470	Ram *et al*. 1989
Bedni - Ali	157 - 390	175 - 407	Negi *et al*. 1992
Tapovan	436	2264	Dhaulakhandi *et al*. 2010
Nandanvan	325	2251	Dhaulakhandi *et al*. 2010
Bhojbasa	435.4	2005	Dhaulakhandi *et al*. 2000
Gaumukh	472.3	2217	Dhaulakhandi *et al*. 2000
Pawalikantha	217	-	Joshi *et al* 1988
Tungnath	195 - 239	283 - 463	Sundriyal 1992
Tungnath	133 - 272	372 - 652	Sundriyal and Joshi 1990
Tungnath	180 - 487	470 - 590	Present Study

It is important to notice that about 53-75% of AGB was accumulated by the end of July while, on average more than 75% of the total biomass was accumulated by August in all communities. This is made possible because the water and temperature are not limiting factors during pre-monsoon due to early snowmelt and soil (14.34 and 12.4 °C) and air (19.12 and 11.03 °C) temperature peaks. Furthermore, on average, AGB was about 60% of BGB in alpine meadows except in *Trachydium* and Mixed Herbaceous communities, where it was higher than BGB by 30-40% in *Trachydium* community during August and September and 25-63% in Mixed Herbaceous community from June to September, respectively. The reason for the higher AGB than the BGB might be due to the dominance of species like *Trachydiym, Oxygraphis, Rannunculus, Gentiana, Carex, Juncus* and other short forbs in *Trachydium* and Mixed Herbaceous communities of which majority had fibrous roots as compared to tall forbs, tussock, and runners like Polygonum spp., Rheum, Potentilla spp., and Gaultheria spp. dominant in remaining communities which had rhizoids (Tubers, Rhizomes and Bulbs) thus amassing more biomass.

The average accumulated BGB in present study was more than 60% of total biomass. It was above 60% for *Polygonum*, Mixed *Danthonia*, and *Danthonia* communities, 55% for *Trachydium* community and 47% for Mixed Herbaceous community. These findings align with previous studies conducted by Ram and Arya (1991) and Ram and Singh (1994), which indicate that a majority of communities in the alpine region accumulate more biomass belowground than aboveground, with values exceeding 60%. However, when compared to higher latitude and arctic alpine regions, the present study's belowground biomass accumulation may be lower (Rawat, 2007). Several authors, including Kaul and Sarin (1971), Joshi et al. (1988), Nautiyal et al. (1997, 2004), Seth (1996), and Dhaulakhandi et al. (2000), have also observed significant spatiotemporal variations in biomass production, emphasizing the influence of growth forms and interactions with livestock grazing on community development in alpine meadows of the Greater Himalaya. Choler et al. (2001) and others have demonstrated species exhibiting facilitation in resource-poor alpine areas and high competition in productive or resource-rich areas, supporting the notion that adjacent species-rich communities play a facilitation role in boosting biomass production (Rawat, 2007). Furthermore, Singh et al. (2005) have highlighted the importance of species richness in maintaining ecosystem functionality and the potential consequences of species loss, leading to ecosystem impairment and degradation of meadows.

The peak net relative biomass accumulation was highest at start of growing season (May) which shows accumulated temperature sums above a certain threshold and soil water availability are most potent triggering factor for gregarious growth. This is possible by increase in soil microbial respiration which increases available soluble nutrient for plants promoting growth during early season. Callaway *et al*. (2002) did an experimental study and demonstrated higher richness increases competition in general in lower alpines, ultimately leading to increase in biomass, growth, and reproduction. The net above ground accumulation declines as growing season progresses. This may be because of increase in species richness and competition for available resources. Furthermore, many short growth cycle and early growing species may senescence by June-July leading to decrease in accumulated biomass. The total output in BGB was almost like the total input, indicating communities at study site are at equilibrium which is different from successional tropical grasslands. It is important to note that in alpine communities, snow deposition patterns and freeze thaw cycle in early growing season, and herbivory disturbance may alter vegetative development in the communities (Rawat, 2007).

Plant carbon content is an important plant trait critical to the assessment of ecological stoichiometry. The process of photosynthesis creates a huge carbon pool in terrestrial ecosystems (Schlesinger and Bernhardt, 2013) and the carbon stock sequestered can be calculated by multiplying total biomass with carbon conversion factor (C content; Thomas and Martin, 2012) given as 50 percent of biomass by multiple authors (De Vries *et al*. 2006; Keith *et al*. 2009; Lewis *et al*. 2009; Saatchi *et al*. 2011; Zhu *et al*. 2015, 2017) in both global and regional vegetation. However, many authors have shown different C content for plant organs (Yao *et al*. 2015), life forms (Feng *et al*. 2010; Cao and Chen, 2015), and biomes (Martin *et al*. 2015) which shows using default value of 50 percent may result in biases. Thus, estimating carbon stored in alpine vegetation is limited by lack of direct measurement with no estimates for C content done for alpine IHR because of larger spatial heterogeneity of alpine ecosystems. Therefore, in the present study, the global mean values of aboveground organs C content (43%) and belowground organ C content (42%; as per Ma *et al*. 2018) for herbaceous vegetation were taken as the carbon conversion factor for both AGB and BGB C content calculation. There is a need to quantify biomass carbon budgets to understand warming dynamics of ecosystems as rising temperatures (Cao and Woodward, 1998) and changing precipitation (Shen *et al*. 2011) are reportedly associated with increase in vegetation productivity leading to variation in carbon production and increase in C storage (Cao and Woodward, 1998; Smith and Shugart, 1993; Piao *et al* 2005; Shen *et al*. 2015; Shen *et al*. 2014). So far, no studies have been conducted to study carbon stock density for both AGB and BGB in alpine ecosystems in IHR but many workers have documented carbon densities of different alpine habitats in Qinghai – Tibetan plateau. In present study the mean AGB C density of alpine communities ranged between 81.1 – 160.5 g m^{-2} which is higher than alpine meadows of northern China grasslands as reported by Ma *et al*. (48.7 g m^{-2}, 2010), Fan *et al*. (41 – 103 g m^{-2}, 2008) and Ni (13.8 – 39.7 g m^{-2}, 2002). Similarly, BGB C density ranged between 109.3 – 232.7 g m^{-2} which is similar to BGB C density of alpine meadows of northern China grasslands as reported by Ma *et al*. (289.1 g m^{-2}, 2010) but lower than reported by Fan *et al*. (1.74 – 2.1 kg m^{-2}, 2008) and Ni (13.8 – 39.7 g m^{-2}, 2002). The total C densities in present study ranged between 229.4 – 361.0 g m^{-2} which is similar to BGB C density of alpine meadows of northern China grasslands as reported by Ma *et al*. (338.3 g m^{-2}, 2010) and lower than Fan *et al*. (2.17 kg m^{-2}, 2008), Ni (1 kg m^{-2}, 2002) and Ma *et al*. (1.2 kg m^{-2}, 2018) in Tibetan alpine meadows.

Several studies have explored the spatial relationship between aboveground biomass (AGB) and factors such as precipitation, temperature, and soil texture in grassland ecosystems. For instance, Sala et al. (1988) and Epstein et al. (1997) have examined the relationship between AGB and these environmental factors. Precipitation has been identified as a key determinant of AGB in grasslands and is frequently used to explain spatial variations in production (Lauenroth, 1979; Sala et al. 1988; Burke et al. 1997; Jobba´gy et al. 2002; Ni, 2004; Fang et al. 2005). While a significant relationship between AGB and temperature in grasslands has not been consistently observed, some studies have shown that AGB declines with increasing temperature, with annual precipitation held constant at 50 mm intervals (Epstein et al. 1996, 1997; Burke et al. 1997). In the context of Tibetan grasslands, Yang et al. (2009) conducted a study and concluded that moisture availability is a crucial factor influencing plant production, while temperature and soil texture also impact vegetation growth in high-altitude regions. Ram et al. (1989) investigated plant biomass, species diversity, and net primary productivity in high-altitude grasslands of Rudranath and demonstrated that alpine grassland communities maintain equilibrium through the accumulation of surplus organic matter. Additionally, De Boeck et al. (2008) found a decline in primary production in relation to increased temperature in several communities of temperate grasslands. They further stated that these negative impacts may not be alleviated at higher species richness. Namgail *et al*. (2012) have reported precipitation as an important variable in plant species distribution and variability in the Himalayas. Zang *et al*. (2010) showed the relationship between biomass, temperature, and precipitation in permafrost region of Quinghai-Tibetan plateau. Alatalo *et al*. (2016) found that stepwise warming had an accumulating effect on biomass. Sundriyal (1992) studied structure, productivity, and energy flow in the Gharwal Himalayas comparing flow and storage in grazed and ungrazed land. Furthermore, soil texture interacts with precipitation to affect aboveground biomass (AGB) in grassland ecosystems (Sala *et al*. 1988; Epstein *et al*. 1997). Liu *et al*. (2016) showed significant impact of temperature and precipitation interaction on AGB and BGB alpine carbon density during winters but had negligible impact during summer.

Numerous studies have demonstrated the influence of various soil properties on aboveground biomass (AGB) and species richness in grassland ecosystems. Soil pH, in particular, has been found to have a significant impact on AGB, with a negative correlation observed (Oztas et al., 2003; Yimer et al., 2006; Oyonarte et al., 2008; Roukos et al., 2011; Bhandari and Zhang, 2019). Cheng-Jim et al. (2014) also reported a negative correlation between soil pH and mean annual temperature in Tibetan grassland, which is attributed to the indirect effects of temperature on soil organic matter accumulation. Warmer temperatures lead to greater plant inputs and lower decomposition losses, resulting in increased soil organic carbon density and the release of more H+ ions, ultimately leading to lower soil pH at lower altitudes with warmer temperatures. However, bulk density, soil organic matter percentage, nitrogen percentage, and available phosphorus do not show significant associations with AGB production and species richness.

The soil organic carbon (SOC) stock in high-altitude and high-latitude ecosystems is a crucial component of the global terrestrial carbon reservoir (Hobbie et al., 2000; Ping et al., 2008). Soils in these ecosystems play a vital role in the global terrestrial carbon cycle due to their substantial carbon stock and their sensitivity to climate warming (Davidson and Janssens, 2006). It is expected that warming in high-altitude regions will increase litter decomposition rates, accelerating carbon turnover. However, this effect may be mitigated by changes in community composition (Gavazov, 2010) or early snowmelt, as sites with early snowmelt have been observed to have a decrease in decay rates, leading to higher carbon retention (Baptist et al., 2010). This might be the cause of increase in SOC% in early growing season in *Trachydium, Polygonum* and *Danthonia* communities as these sites in the study area had earlier snowmelt timing than that of Mixed *Danthonia* community. The alpine soils contain more liable soil organic matter because of slower decomposition and biochemical transformations (Sjogersten *et al*. 2003) and are seasonal carbon sinks and sensitive to nutrient deposition influencing plant community and ultimately nutrient cycling (Smith *et al*. 2012). Small changes in the SOC pool can have large implications for atmospheric CO_2 concentrations. A warming experiment in Tibet alpine by Li *et al*. (2011) showed contrasting behaviour of meadows in nearby communities with increase in SOC pool in wet meadow while large decrease in dry meadow while Sjogersten *et al*. (2003) did not record any changes in Swedish alpine tundra. This shows edaphic factors play a crucial role in decomposition and productivity than other environmental factors. A meta study done by Wang *et al*. (2014) showed positive response ratio between warming and soil respiration while Shen *et al*. (2015) concluded the above to be true only in presence of adequate soil moisture. Thus, warming shifts in carbon pools might show differently depending upon moisture availability and changes in summer precipitation in alpine regions.

Nitrogen (N) addition in general increase alpine ecosystem productivity (Fisk *et al*. 1998) but the recent increase in soluble N deposition in high-mountain habitats has been reported to limit plant growth and diversity in terrestrial ecosystems (Hättenschwiler and Körner, 1997; Tørseth and Semb, 1997; Vitousek and Howarth, 1991; Gong et al., 2015) and may also restrict plant growth in alpine species (Hiltbrunner et al., 2005).. Huber *et al*. (2007) have reported higher instances of available N and higher pH in high alpine meadows than low alpine meadows. A meta-analysis by Rustad *et al*. (2001) showed net mineralization increased by 9% in alpine sites while Bai *et al*. (2013) demonstrated a 32% increase in net nitrification rates in alpine meadows, with no significant effect in alpine Tibet region (Wang *et al*. 2012). However, N mineralization showed positive response to warming (Peng *et al*. 2016). Jiang *et al*. (2016) reported deceased total N as well as dissolved total N at different soil depths in response to warming but at same time plant N uptake increased, suggesting soil N status depends on plant response through different communities/physiognomic units.

Extensive grassland areas have undergone degradation primarily as a result of increased disturbances caused by livestock populations over the past five decades (Harris, 2010). During the 1990s, approximately one third of alpine grasslands were identified as degraded (Duan et al., 2013). Improved management practices, as estimated by Guo et al. (2008), have the potential to sequester 15.24–65.75 Mg C ha-1 in degraded alpine grassland soils, although the effectiveness may vary depending on the specific management approach (Wang et al., 2011; Guo et al., 2008). Presently, high mountain ecosystems are facing biodiversity loss, habitat destruction, and landscape modification due to their susceptibility to climate variables, species pool, and biogeographical region, all of which are exacerbated by the impacts of climate change (Körner, 2003; Bruun et al., 2006; Beniston, 2003; Pauli et al., 2012).These processes have attracted numerous ecologists, and a rich scientific literature extensively examines the impacts of these processes on biodiversity across various spatial and temporal scales (see Parmesan 2006; Bellard *et al*. 2012).

6. General Discussion and Conclusion

Recent research trends indicate increase in global mean surface temperature affected worldwide species richness, distribution, phenology, and physiology (Walther *et al*. 2002) hence warming is one of the bigger threats to floral ecosystem and biodiversity (Glick and Van Putton 2002). The climate change threatens survival of many organisms with fragmented habitat distribution (Peters and Darling 1985) especially species with narrow ecological ranges even go extinct due to mediated habitat alteration (Murphy and Weiss 1992) due to anthropogenic activities. This is especially true for species adapted to cold climate (above treeline) which are more vulnerable (Moritz *et al*. 2008) due to higher velocity of warming in alpine. This may exceed adaptive capability of various sensitive species, inducing extirpation in species with low adaptive capacity, leading to loss of species due to changes in altitudinal (Walther *et al*. 2005) and latitudinal ranges while species with broader distribution may locally adapt on basis of phenotypic plasticity (Lema 2008). Therefore, understanding basic ecology of species as well as communities is necessary to identify stress mechanisms and to develop effective monitoring, management, and conservation strategies.

6.1 Community response to snowmelt

In alpine regions snow and its properties like depth, density, duration, and meltwater equivalent influences ecosystem processes across wide range determining beginning of growing season and subsequent growth response and phenology of herbaceous species. It is a major driver in regulating soil temperature, decomposition and nutrient availability in addition to meltwater input, albedo and atmospheric temperature regimes in the habitats. Many studies have emphasized critical role played by snow in cold climate ecosystems beyond a major driver of ecosystem processes. In recent years, a major focus of many researchers has been on role of snow in ecosystem processes and influence of changing snow cover due to warming on species physiology and phenology. In past few decades, snow fall and snow distribution patterns have changed in the Hindu Kush Himalaya (Naegeli *et al*. 2022) which implicates thermal impact of snow cover with reduction in duration and persistence of snow cover in alpine regions introducing varying impacts on local and regional scale.

Plant growth, phenology and community composition in alpine meadows are linked intrinsicly to the depth, distribution, and duration of snow cover. These plants and habitats have evolved over a long time and their synchrony with each other is being affected due to changes in snow pattern. Various authors have strongly associated snowmelt timing with herbaceous species growth in alpine and the changes in snow duration and thickness may potentially increase the duration of growing season but at a risk of freezing damages in initial growing period and loss of winter frost resistance. Moreover, the plant species not dependent on photoperiod in alpine regions need snow cover as a protection from freezing, and can sustain frost damage in less snow.

Due to changing snowmelt regime, variation in snowmelt timing is leading to variations in species phenological events as is evident in present study, but also in duration of developmental stages as was seen in *Oxygraphis, Rannunculus, Fragaria, Swertia* and other species. Across the globe, alpine and tundra plant species are showing a general advance in phenological development with climate warming and decreasing snow cover as the colder populations are more sensitive to the temperature, indicating varying phenological behavioral response to climate change on regional scale. These modifications, in future, will disrupt 'phenological synchrony' disturbing mutualistic interactions between plants and insects putting entire communities at risk. With lot of studies dedicated to aboveground penological behaviour of plants, there are very few studies on belowground root phenology and their interactions in alpine region. A few studies suggest lesser response of root to changes in snow regimes, however root phenology cannot be inferred from aboveground phenology.

The community pattern in alpine regions strongly matches snowmelt timing in a heterogenous landscape. Many studies have pointed out encroachment of invasive species, grasses, and tall productive species (Pickering *et al.* 2014) over a time-period from one habitat to another with changes in snowmelt regimes. With changes in snowmelt regimes, there is cance of reduction in habitat for specialist species as opposed to more competitive species as they encroach into more fertile habitats in the long term. The encroachment of graminoids and shrub species into forb dominant alpine meadows is now commonly reported, reveling the more heterogeneity in alpine meadows structure than an abstract mosaic pattern due to accelerated snowmelt and drier soil conditions linked to global warming (Amagai *et al*. 2018).

6.2 Relationship between AGBM and Species Richness

In alpine systems multiple studies have shown the interconnectedness (linear, curvilinear) between temperature, precipitation, productivity, and plant interactions, as well as spatial patterns and species richness (Kikvidze *et al*. 2005). The Greater Himalaya alpine regions have comparatively milder temperature range and receive higher precipitation than other alpine regions (Trans Himalaya and Tibet) along with greater micro-topographic variations and sharper altitudinal gradient. Consequently, it becomes challenging to isolate specific variables responsible for the relationships between environmental factors and species/community response. While factors such as soil nutrients (organic carbon and soil nitrogen), snow, and site history (grazing vs. non-grazing, anthropogenic impacts) have been highlighted as important outside the Himalayan region by various authors (Atkin and Collier, 1992; Bauer, 1990; Bowman, 1992; Walker and Walker, 1991; May and Webber, 1982), less is known about the alpine regions of the Himalayas.

In recent years, researchers have examined the patterns of relationship between ecosystem biomass (AGBM) and species richness, but these patterns have been found to vary across different regions. Several authors have reported a positive relationship between AGBM and species richness at both local and regional scales (Hector, 1998; Tilman et al., 2001; Bai et al., 2007; Ma et al., 2010; Li et al., 2019), which is attributed to niche complementarity and facilitation effects among plant species. This positive relationship aligns with the multivariate biomass–species richness hypothesis, which suggests that while biomass and species richness are determined by resource abundance, species richness itself plays a role in determining total biomass (Gross and Cardinale, 2007).

Resource utilization by species depends on spatio-temporal scale (Gulmon *et al*. 1983). Different species require varying proportions of soil nutrient chemical properties (Kahmen et al., 2006; von Felten et al., 2009), and the diversification of species in a community promotes the growth of multiple species (Temperton et al., 2007), which is beneficial in the challenging habitat conditions of alpine regions for maintaining high species richness (Callaway et al., 2002). The two most common patterns observed in the relationship between species richness and biomass are a positive linear relationship (Bai, 2000; Ma and Fang, 2006; Bai et al., 2007) and a hump-shaped curve (Waide et al., 1999; Mittelbach et al., 2001; Chalcraft et al., 2004; Pärtel et al., 2007).

At the regional level, the abundance of aboveground biomass and species richness in alpine ecosystems is primarily shaped by altitude, climate, and soil fertility (Jafari et al., 2004; Maestre et al., 2006; Fornara and Tilman, 2009; Ma et al., 2010). Previous studies has consistently shown a positive correlation between precipitation and productivity, particularly in semiarid and arid ecosystems where rainfall plays a critical role (Sala et al., 1988; Ma et al., 2008; Hu et al., 2010; Bai et al., 2007). Conversely, there is a notable negative relationship between climatic factors (precipitation and temperature) and altitude, as evidenced by various studies (Mountousis et al., 2011; Roukos et al., 2011, 2017). Several studies in alpine ecosystems have shown that at higher elevations, temperature exerts a more significant influence compared to precipitation on plant growth (Liu et al., 2009; Ma et al., 2010; Tao et al., 2015; Ganjurjav et al., 2018). This observation contrasts with findings from studies conducted in central North America by Jonas et al. (2015), which highlighted the substantial role of temperature in regulating species richness and diversity variations. Moles et al. (2014) further proposed that the plant community composition is more more closely associated with mean annual temperature rather than precipitation on a global scale. These collective findings provide support for the hypothesis that temperature partially shapes plant composition in alpine regions. Additionally, Palpurina et al. (2017) have demonstrated a negative relationship between species richness and soil pH, as high phytotoxicity constrains species richness (Abedi et al., 2013) and hinder nutrient uptake (Rorison, 1980).

6.3 Conservation status of alpine meadows in Greater Himalaya

According to Rogers and Panwar (1988), the alpine zone in the Greater Himalaya region belongs to Biogeographic Zone 2, encompassing approximately 9% of the overall land area.. In Uttarakhand there are 5 protected areas encompassing alpine region namely Nandadevi National Park (NP), Valley of Flowers NP, Govind Pashu Vihar NP, and Wildlife Sanctuary (WS), Kedarnath WS and Askot WS of which except Nandadevi NP and Valley of Flowers NP, others are heavily exploited leading to habitat degradation (Rawat, 2005).

6.4 Problems faced by alpine habitats in Greater Himalaya

The anthropogenic pressure on alpine meadows is high in Greater Himalaya's alpine region. The diverse socio-economic and political landscape has led to serious exploitation, which couples with climate change endorses range of complex environmental challenges and diverse patterns of resource utilization. Unsustainable pastoral practices (Rikhari *et al*. 1993; Saberwal 1995; Mishra and Rawat, 1998) due to nuclear transhumance and transmigration by local communities, unruly extraction of medicinal and aromatic plants (MAP) leading to declining populations (Jacobson *et al*. 1991; Katariya 1998; Samant *et al*. 2001; Uniyal *et al*. 2002; Awasthi *et al*. 2003), uncontrolled tourism (mostly pilgrimage) and implementation of developmental projects without any consideration for long term impacts are major difficulties faced by alpine ecosystems of Greater Himalaya. Heavy grazing may cause palatable species loss, vegetation collapse and bare patch creation on alpine meadows. Unsustainable harvests of MAP's (uprooting entire plant, extraction before seed shedding, extraction of immature plants) may cause smaller population size due to overexploitation and habitat degradation (Rawat, 1998) as well as local extinction (Sheldon *et al*. 1998). Most of pilgrimage centers are in alpine or subalpine regions which put significant pressure on these sites for fuelwood, fodder and other non-wood forest products collected from subalpine forests and alpine scrubs. Associated impacts linked to this situation encompass the building and upkeep of transportation infrastructure such as roads and bridges, the grazing activities of mules and horses, and the accumulation of waste and litter..

6.5 Conservation and Management Practice to be adopted for study region

In order to address the aforementioned factors that contribute to stress, it is necessary to examine and implement various sustainable land use practices that have been studied and adopted by local communities, but on a broader regional scale. At state and regional scale, based on wide consultative process, a conservation and management plan (National Biodiversity Strategy and Action Plan, 2004) have been evolved and priority areas suggested in above plan needs to be implemented according to needs of particular habitats. Conservation management authorities need to formulate strategic plans to create and implement conservation measures tailored to specific sites or species, taking into account the sensitivity and stress of threatened alpine ecosystem, habitats and species. The major strategies to be applied for betterment of alpine regions are:

Management of Livestock: Since livestock grazing is main economic activity for major pastoral communities, with no clear policy guidelines for optimal use and management of the grazing area, rotational grazing of degraded habitats is best optimal solution for management. Resolving conflicts and controversies arising from grazing rights and livestock depredation by carnivores can be addressed through the implementation of self-financing compensation schemes (Mishra, 1997). Another effective management strategy involves the establishment of clear boundaries between grazing and non-grazing areas or limiting livestock presence to buffer zones to minimize conflicts (Rawat, 2007).

Regulation of MAP Harvest: Information gathered from different areas within the alpine region indicates that local communities have the potential to successfully conserve multiple Medicinal and Aromatic Plants (MAP) species. This can be achieved by empowering them and entrusting them with the task of safeguarding these species, while also granting them the opportunity to share in the benefits derived from a controlled and sustainable harvesting of such plants (Rawat, 2007).

Degraded Area Management: Heavily degraded habitats need to be protected completely from grazing for recovery process to start. Once degraded completely, the communities may take as long as 40 years to recover after complete banning of pastoral practice (Rikhari *et al*. 1993) and becomes difficult to reclaim. The importance of fast-growing opportunistic herbs in stabilizing alpine environments, including activities such as soil formation, enrichment, and slope stabilization, was emphasized by Kala et al. (1998). This process of stabilization is beneficial for the overall stability of the community. Furthermore, the recovery of numerous rare and endangered plant species has been observed in various alpine meadows following the complete cessation of grazing (Rawat, 2007), therefore utmost care is needed for management and conservation of these meadows.

Research and Monitoring: Despite the presence of multiple research and development agencies and non-governmental organizations (NGOs) working in the Himalayas, there is a noticeable absence of focused and extensive research and monitoring efforts dedicated to alpine meadows. This lack of attention extends to multiple subjects like, climate change induced effects on threatened taxa, sustainability of land use practices, carring capacity of different meadows, status of degraded meadows, secondary succession in degraded alpine habitats, status of rare and endemic species among others. Although some studies talk about grazing influence on communities no experimental initiatives have been taken for restoration of degraded meadows nor awareness is being raised for the same among local communities. Therefore, there is a need to undertake multiple long term ecological and socio-economic studies to understand alpine ecosystems and developing management strategies.

7. References

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List of Publications and Conferences

List of peer reviewed papers

Kumar R. and Adhikari B.S. (2022). Temporal changes in biomass production of different communities in Himalayan alpine meadow*. Indian Journal of Forestry* (Accepted)

Kumar R. Adhikari B.S. (2023). Natural snowmelt timing influences community structure and phenological patterns in alpine meadows, West Himalaya: A case study*. Proceedings of the National Academy of Science, India Section B: Biological Sciences* (Accepted)

List of Conferences

Internationa

Kumar R. and Adhikari B.S. (2021). Influence of snowmelt timing on temporal changes in community composition, structure and functional attributes in alpine meadow: a case study. *Assam Botany Congress (ABC-02) and International Conference on Plant Science*

National

Kumar R. and Adhikari B.S. (2019). Influence of snowmelt water on structural and functional attributes in alpine meadows. *IV Himalayan Research Seminar, Wildlife Institute of India*

Kumar R. and Adhikari B.S. (2018). Snowmelt timing regulates herbaceous community composition and phenology of alpine plants. *3rd Himalayan Research Seminar, Wildlife Institute of India*

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Date: 06/04/2023

Dr BS Adhikari
Department of Habitat Ecology,
Wildlife Institute of India, Chandrabani,
Dehradun-248007, Uttarakhand, India

Subject: Acceptance letter of research article titled "Temporal changes in biomass production of different communities in Himalayan alpine meadow"

Dear Sir,

We would like to inform you that the research article titled "Temporal changes in biomass production of different communities in Himalayan alpine meadow" by authors Rahul Kumar and Bhupendra Singh Adhikari with reg. no. M6805 for publication in Indian Journal of Forestry has been accepted.

The same would be published (online + print mode) in the forthcoming issue.

With kind regards

Abhimanyu Gahlot
(Managing Editor)

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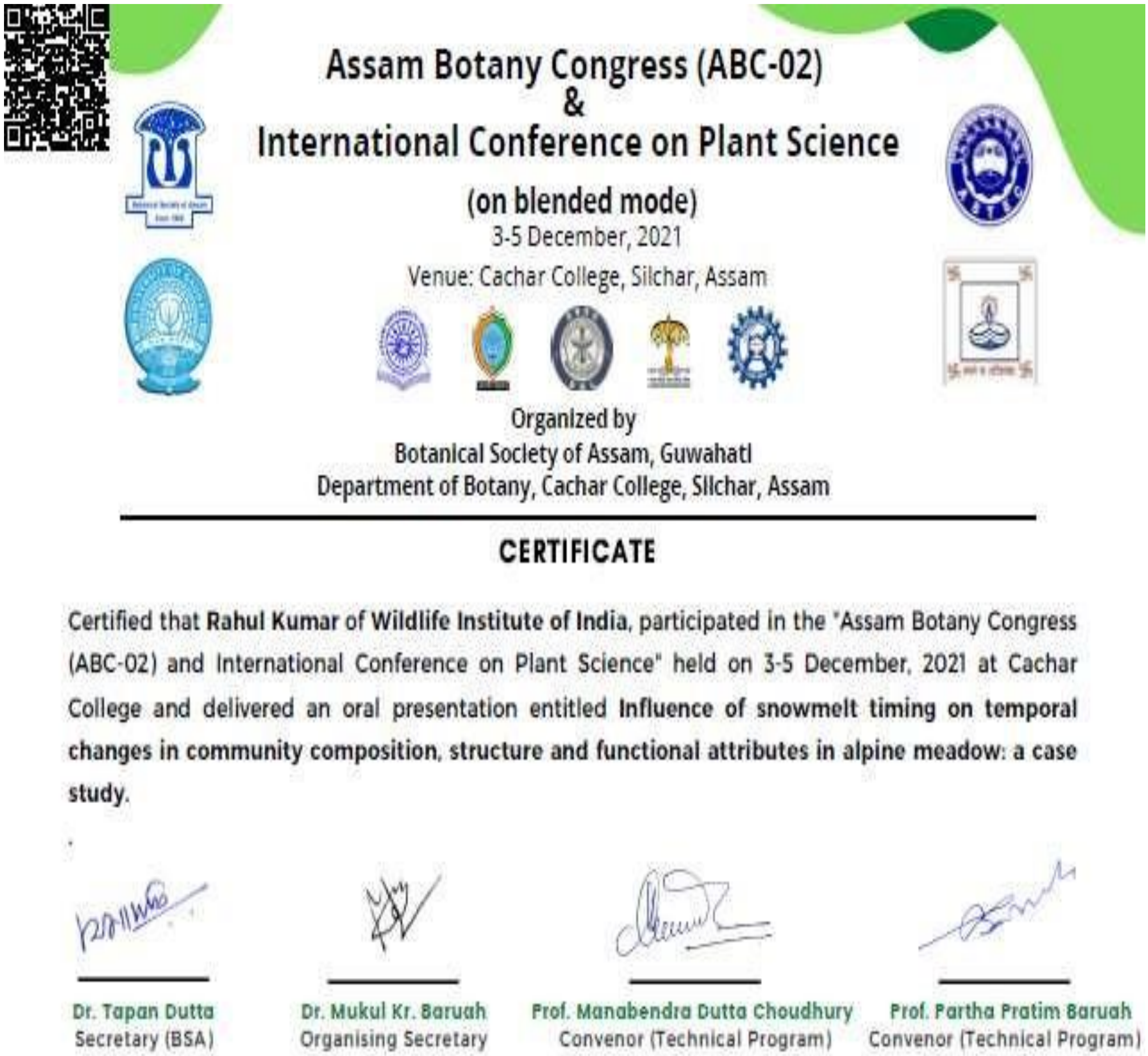


Assam Botany Congress (ABC-02)
&
International Conference on Plant Science

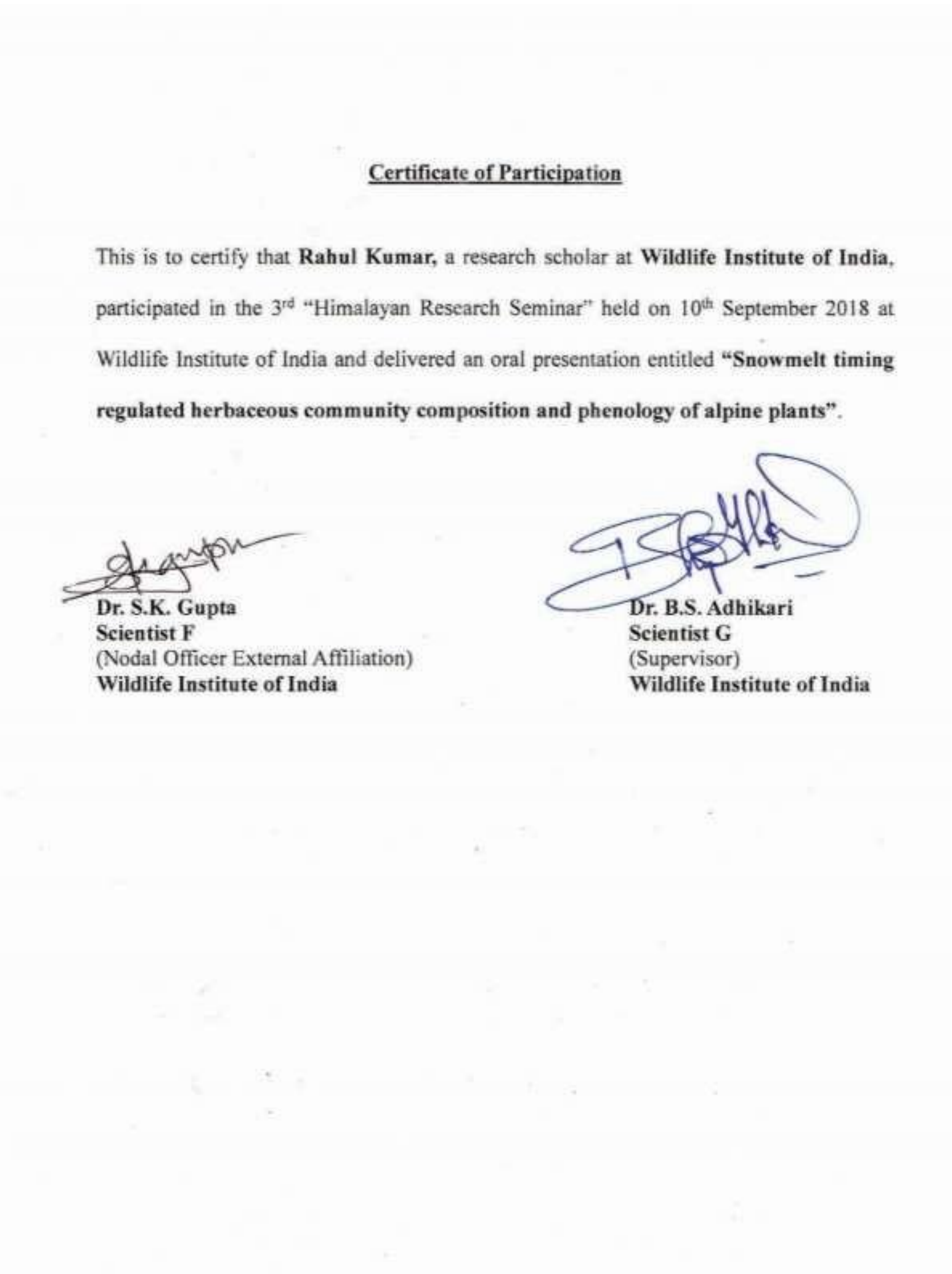
(on blended mode)
3-5 December, 2021
Venue: Cachar College, Silchar, Assam

Organized by
Botanical Society of Assam, Guwahati
Department of Botany, Cachar College, Silchar, Assam

CERTIFICATE

Certified that **Rahul Kumar** of **Wildlife Institute of India**, participated in the "Assam Botany Congress (ABC-02) and International Conference on Plant Science" held on 3-5 December, 2021 at Cachar College and delivered an oral presentation entitled **Influence of snowmelt timing on temporal changes in community composition, structure and functional attributes in alpine meadow: a case study.**

Dr. Tapan Dutta Secretary (BSA)	**Dr. Mukul Kr. Baruah** Organising Secretary	**Prof. Manabendra Dutta Choudhury** Convenor (Technical Program)	**Prof. Partha Pratim Baruah** Convenor (Technical Program)



Certificate of Participation

This is to certify that **Rahul Kumar,** a research scholar at **Wildlife Institute of India**, participated in the 3rd "Himalayan Research Seminar" held on 10th September 2018 at Wildlife Institute of India and delivered an oral presentation entitled **"Snowmelt timing regulated herbaceous community composition and phenology of alpine plants"**.

Dr. S.K. Gupta	**Dr. B.S. Adhikari**
Scientist F	**Scientist G**
(Nodal Officer External Affiliation)	(Supervisor)
Wildlife Institute of India	**Wildlife Institute of India**

Certificate of Participation

This is to certify that **Rahul Kumar,** a research scholar at **Wildlife Institute of India,** participated in the 4th "Himalayan Research Seminar" held on 21st August 2019 at Wildlife Institute of India and delivered an oral presentation entitled **"Influence of snowmelt water on structural and functional attribute in alpine meadows"**.

Dr. S.K. Gupta
Scientist F
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