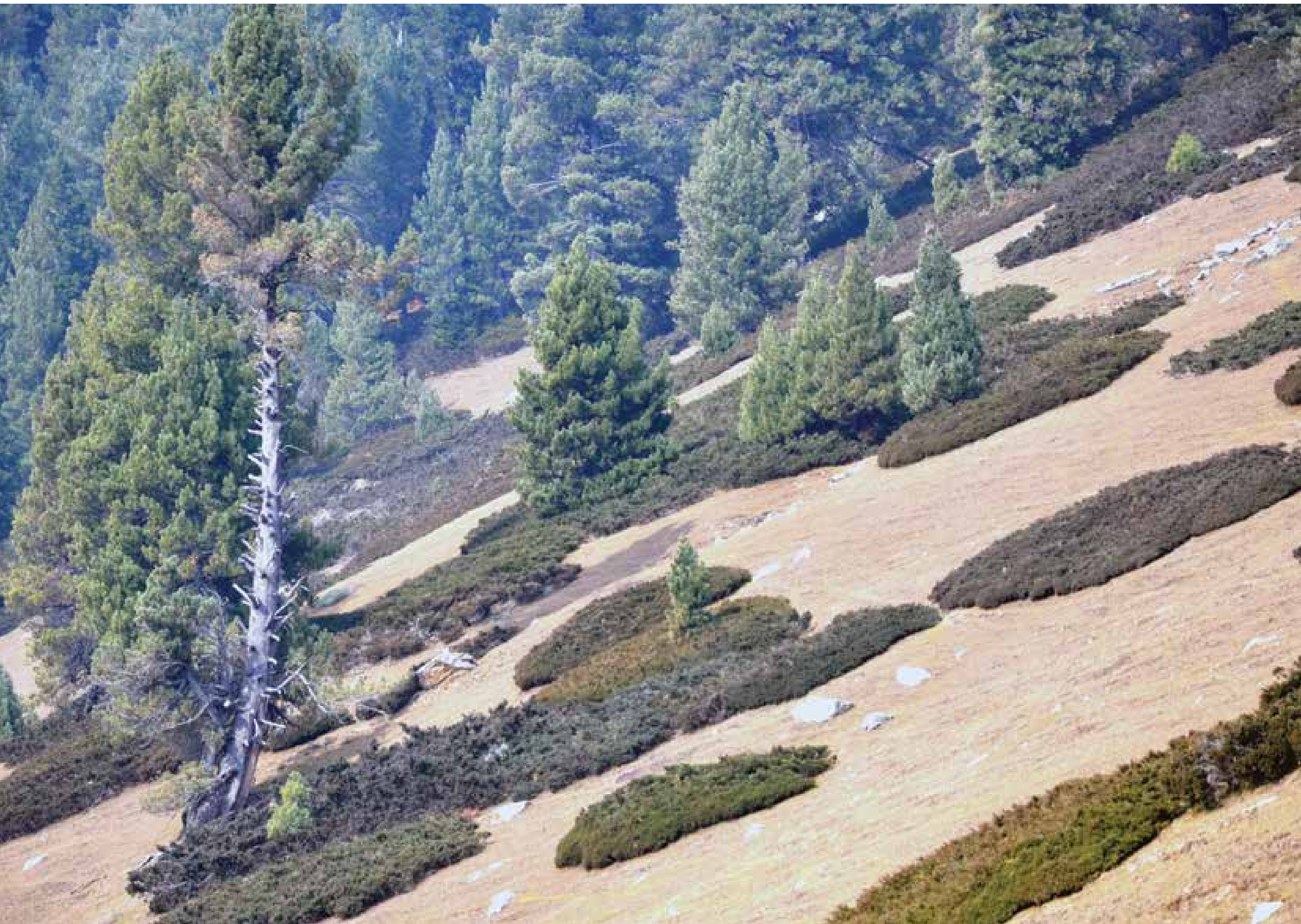
Interpreting mountain treelines in a changing world

LARGELY BASED ON THE INDIAN HIMALAYA

Surendra P. Singh

Associate editors: *Ripu Daman Singh and Surabhi Gumber*



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Cover photo

Caption: A treeline site from Kashmir. Trees emerging from the mat patches of juniper are of silver fir (*Abies pindrow*)

Courtesy: Prof. Zafar Reshi, Kashmir University, India

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Central Himalayan Environment Association (CHEA)
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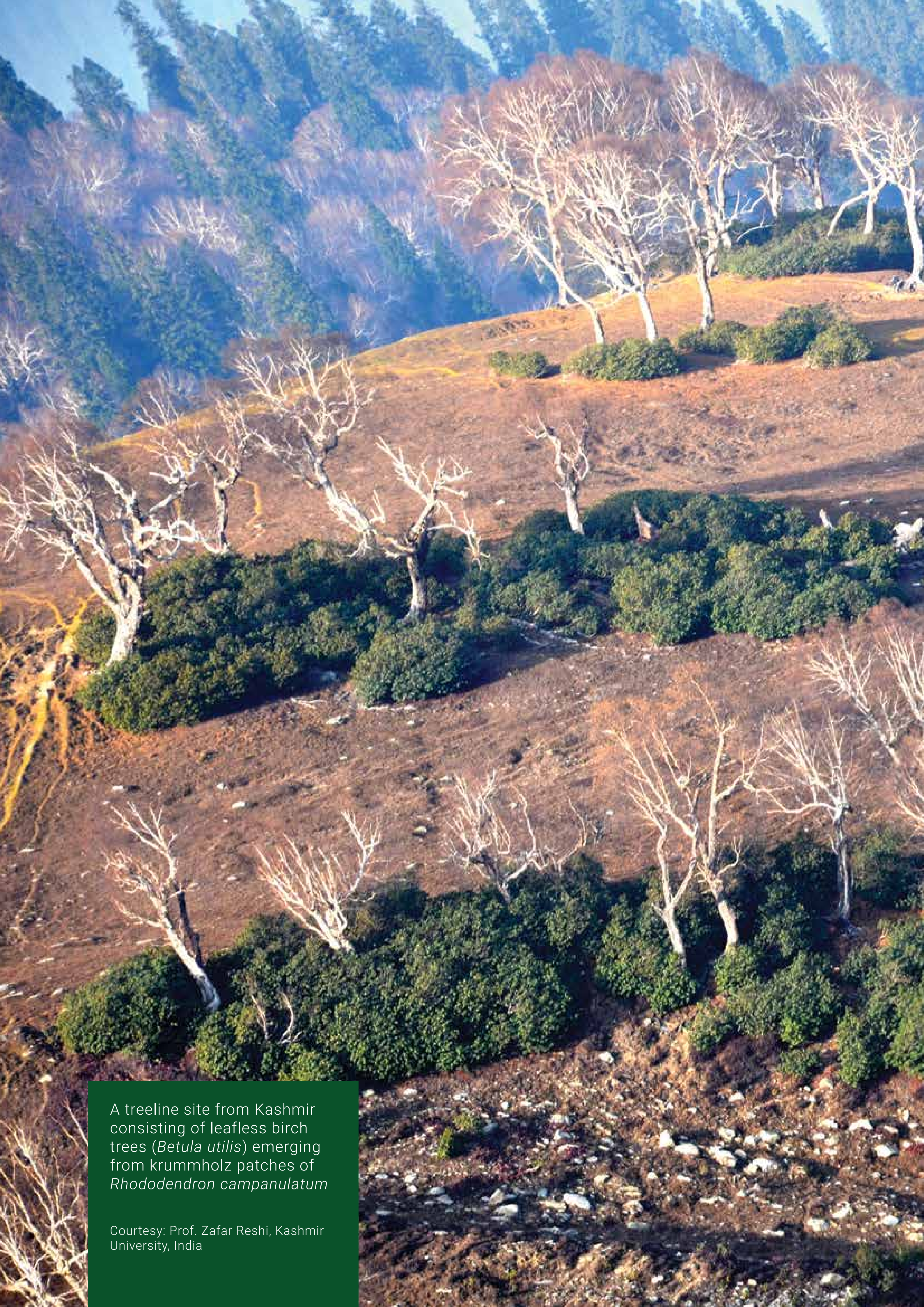
To **Ranbeer Singh Rawal** who was stealthily taken away from us by COVID-19 while he was waiting for the pandemic to loosen its grip so that he could sample treelines along with his research students

---

Dr. Ranbeer Singh Rawal was Director of the Govind Ballabh Pant National Institute of Himalayan Environment, Kosi-Katarmal, Almora, Uttarakhand, and a principal investigator on the project that provided a considerable amount of data for this book. He passed away on 24 April 2021 at the age of 55.



A treeline site from Kashmir consisting of leafless birch trees (*Betula utilis*) emerging from krummholz patches of *Rhododendron campanulatum*

Courtesy: Prof. Zafar Reshi, Kashmir University, India

Preface

In a way, treelines and timberlines represent the ‘defiance of trees’ against the constraints imposed by environmental stresses in the high mountains. Though the Himalayan treelines are thousands of kilometres long, widely spread, and unusually high — close to 5 km (the highest in the Northern Hemisphere), they are among the least investigated systems. The interchangeably used terms treeline (the line connecting uppermost trees) and timberline (upper edge of forest with at least 30% crown density) began to appear in the literature on the Himalaya only about 20 years ago.

The recent interest in treelines is largely due to global climate change. Though glacier shrinkage continues to hog much of the climate limelight, in recent decades the upward shift of mountain treelines is also considered a major indicator of climate change. Treelines in combination with subalpine forests on the lower side, and alpine meadows and nival belts on the upper side constitute a huge biotic complex, which is in flux due to climate change. Permafrost thawing, upslope migration of plants, jamming of species in some pockets towards mountain summits, and albedo alteration due to snow melt are some of the climate change induced symptoms at the top of the Himalaya.

Realizing the lack of studies on Indian Himalayan treelines, a research team undertook a study in 2016, under the National Mission on Himalayan Studies (NMHS), of the Ministry of Environment, Forests & Climate Change ((MOEF&CC) - no space), India. The study involved 11 investigators, who jointly worked to generate information about various components of Himalayan treelines: tree species which constitute treelines along the Himalayan Arc, pattern of change in species diversity along the elevation gradient leading to treelines, spatial dimensions and forms of treelines, temperature lapse rate, treeline shift due to climate change, tree phenology and tree water relations, tree-ring growth and climate relationships, effect of early snow melt on species, and treeline linked livelihoods.

This small book is intended to reach a broad audience and provide a basic understanding of treelines, largely based on the NMHS project in the Indian Himalaya. We had planned to hold several workshops and interaction sessions by developing a Treeline Interpretation Centre. However, because of the COVID-19 pandemic and related restrictions, this could not be achieved. This book is an attempt to compensate for that. Though it is largely based on our study on

Himalayan treelines, it draws frequently on two centuries of treeline research in Europe, North America, and elsewhere. Discussions within the team from time to time were always rewarding and enjoyable. Each one of the principal investigators is widely known in specific fields of knowledge about the Himalaya.

We would like to thank many individuals and academic institutions whose research publications and advice provided much needed information for developing the text, figures, and tables and facilitated the progress of the work. We are grateful to the Ministry of Environment, Forests and Climate Change for providing grants through the National Mission on Himalayan Studies (NMHS) for the Indian Himalayan Timberline Research Project (IHTRP). Advice and support were always forthcoming from Er. Kireet Kumar, Scientist ‘G’ and Nodal Officer, NMHS, G. B. Pant National Institute of Himalayan Environment (GBPNIHE), and from Dr. P. P. Dhyani and Dr. R. S. Rawal, former directors of GBPNIHE, Almora.

We extend our special thanks to the Indian National Science Academy (INSA) and the Central Himalayan Environment Association (CHEA) for providing facilities for this study. We give great importance to the research contributions of all the principal investigators and research scholars of IHTRP who worked in difficult terrains of the treeline areas of the Himalaya.

We are indebted to Dr. Gajendra Rawat (Scientist ‘SC’, USAC, Uttarakhand) and Dr. Vikram Negi (GBPNIHE) for their inputs and for providing photographs. Thanks are due to Ms. Harshita Joshi for her assistance in the preparation of figures and tables and cross checking the references.

We are thankful to Dr. Laurie Ann Vasily, Head, Knowledge Management and Communication, ICIMOD, for kindly offering to help us with the editing and design of this book, and to Mr. Samuel Thomas, Senior Editor, and Ms Rachana Chettri, Publication Coordination Officer for their editorial inputs. Apart from providing routine editing, Mr. Thomas proactively participated in improving the content of the book by raising relevant questions and pointing to weaknesses at several places. It is because of Dr. Vasily that we were able to secure ICIMOD’s partnership as publisher. We acknowledge the encouraging words of Mr. Brij Mohan Singh Rathore, who initiated the process. We are also thankful to Mr. Mohd Abdul Fahad, Mr. Sudip Kumar Maharjan, and Mr. Dharma Ratna Maharjan for designing this book.

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Note: *The editors are the authors of the rest of the chapters. They have contributed significantly to the manuscript development of all other chapters.*

Introduction

1.1 Not just glaciers, treelines too

In a world where most people live far away from mountains and more than half the global population (55.7% in 2019) is urban (World Bank 2019), it is not surprising that the terms treeline and timberline are unfamiliar. Big cities, which are the cultural, economic and scientific centres of the present day world, and the vanguard of fashion, culture, and ideas, have nothing even remotely connected to an alpine treeline (Figure 1). So, it is scarcely surprising that not many books have been published on mountain treelines.

Figure 1: Can there be a bigger contrast on earth than between the megacity and the treeline landscape?

The crisis of global climate change is now widely recognised. Shrinking glaciers in the Himalaya and other parts of the world is considered one of its major impacts. The loss of glaciers is a major threat to regional hydrology and mountain-linked ecosystems. Below the glaciers are several biotic zones, namely, alpine treelines (the uppermost limit where trees grow), alpine meadows and nival plant landscapes, and each one is being impacted by climate change. These biotic zones of different growth forms (trees, scrubs, tall herbs, cushion plants, etc.) are centres of species diversity and are highly sensitive to climatic warming. In these zones, species are no longer “sitting comfortably in their niches”. They are unsettled and often on the move under climate change impacts. Treelines are a unique resource which have stored information about climate influenced changes. Unlike glaciers, treelines are not disappearing under the influence of climate change. They are moving upslope or are stationary, but under great stress due to internal changes and volatility. Realising the need to develop an understanding of Himalayan treelines, we sent a project proposal to the Ministry of Environment, Forests & Climate Change (MOEF&CC) (MOEF&CC)under the National Mission on Himalayan Studies. A team of investigators from various disciplinary backgrounds conceptualised the study of Indian Himalayan treelines. The investigators had expertise in the following disciplines: ecology, vegetation analysis, plant taxonomy and geography, phenology, tree water relations, meteorology, high altitude biodiversity in relation to environment, dendrochronology and livelihood practices. Coordinated research through the initiative of individuals is a bit uncommon in the Indian institutional scientific environment. So, we struggled a bit to justify the topic and the mechanism of research. But once the concept and approach were communicated convincingly, MoEF&CC supported the treeline research project liberally.

A DEFINING FEATURE OF MOUNTAINS

In mountains, as elevation increases and temperature declines, vegetation changes. Generally, forest stands of tall and dense trees give way to sparse and stunted trees. With further rise in elevation, when temperature in even the warmest month drops to 9-10 °C, trees become widely spaced, and some become deformed and shrubby. One can easily notice from a distance a forest boundary separating herbaceous vegetation of short plants that occur above trees. This is called the timberline and/or treeline, above which a plant cannot be both woody and tall with a single stem (a tree).

From a distance a mountain treeline looks like a strip or a line of trees, but remote sensed maps reveal that in large mountains like the Himalaya, treelines are thousands of kilometres in length and have width with tree clusters and open habitats. A Himalayan treeline is a huge biological entity running across valleys, ridges and summits over hundreds or thousands of kilometres. Globally, treeline elevation varies widely depending on latitude, from 500 masl in Norway (69° N) to close to 5000 masl in Tibet (30° N) and Bolivia (16° S). Several mountain areas have been investigated for treeline ecosystems. Examples are Lapporten in north Sweden, Altai in Russia, White Mountains in central Alaska, Swiss Alps, Mt. Patscherkofel in Austria, Sygera Mountains in Tibet, and Mount Burns, New Zealand, among others. In the Himalaya treelines generally occur over 3000-4900 masl, but are also to be found in higher elevations adjacent to areas below alpine grasslands, the nival belt, and permanent snow.

The world over, people are concerned that glaciers are melting and shrinking because of global climate change. Interest in glacier shrinkage is understandable as they feed the major rivers that originate in mountains. Treelines may be called the poor cousins of glaciers, as they remain unnoticed, despite being an effective source of information about global climate change. In response to warming treelines tend to move upslope, lose soil moisture rapidly, and undergo change in species composition. Unlike snow, trees can fix carbon and store it for a long time, and, by growing in areas released by receding glaciers, they reduce albedo, which in turn may cause further warming. So treelines are not simply slaves of climate, they are capable of modifying climate themselves. Treelines are complex in their impact on climate. They have a cooling effect by sequestering carbon (thus helping remove CO_2 from the atmosphere) and a warming effect by reducing albedo. In comparison to glaciers, treeline roles are complex in their relationship with climate change, warranting more research. Treeline temperatures have increased in recent decades because of global warming, in response to which species have moved upslope. However, there are several other factors which influence treeline dynamics, so only about 50 percent of treelines have moved up despite decades of warming.

1.2 Trees in the treeline

Because of low temperatures, often accompanied by freezing and snow storms, only a few tree species are able to survive in treelines. Species should be cold hardy to survive in the treeline environment. That is why, of the over 60,065 recorded tree species in the world, probably not many more than 150 tree species are able to reach treelines. No genus is entirely confined to treelines. Fir (*Abies*), junipers (*Juniperus*), spruce (*Picea*), birch (*Betula*) and rhododendrons (*Rhododendron*) are some of the common treeline species of the northern hemisphere. In the southern hemisphere, the species composition is different, broadleaved evergreen species like *Polylepis* and *Nothofagus* being more common.

Heat deficiency does not allow all tree species to have normal growth. Some species become stunted and multi-stemmed, with twisted and gnarled branches (called krummholz). In a windy treeline environment, trees may have a flag-like profile, as buds directly exposed to wind get suppressed, so branches form only on one side.

Montane forests, treelines, alpine meadows and the nival belt together constitute a continuum, having many medicinal plants and species rich habitats with high endemism. The vegetational continuum provides shelter to a rich diversity of wildlife, including the snow leopard, Himalayan brown bear, Himalayan tahr, blue sheep , and pika among others. So it is an important biodiversity-rich system of the world.

Treeline researchers have been paying a lot of attention to physiological processes, trying to understand why trees are unable to grow in cold conditions where a great variety of herbs, shrubs, mosses, lichens, and other forms grow (see Körner 2012a). Only in recent years have the geography and ecology of treelines drawn worldwide interest (Holtmeier and Broll 2020; Miehe et al. 2015; Schikhoff 2005). Though the highest treelines of the northern hemisphere occur in the Himalaya, the terms treeline and timberline have until very recently been missing from the literature on this region. Ecologists in Nepal have given some importance to treeline research in the last two decades, but even there almost no investigations were made before the current century. In the Indian Himalaya, treeline research has just begun. Our treeline research (see IHTRP, Singh 2018) is probably the first major initiative with regard to the Indian Himalaya. In this treeline study, we have considered more dimensions of treeline than have been generally investigated.

Currently, treeline research is providing new insights into the study of how biota respond to climate change, the relationships between tree-ring growth and climate change in various seasons, the role of growth in relation to stress, seasonal variation in temperature lapse rate and the impact of elevation dependent warming, tree water relations and water conduits in trees, effects of early snow melt, endemism, and future changes. We know very little about several areas related to treeline tree species, such as: leaf forms specific to treelines, and wood density and bark in various tree forms.

This book is largely based on our recent research project on the Indian Himalayan Treelines, involving six research organizations (institutes, universities, and NGOs), 11 investigators, and 20 research scholars. The investigation covers ecology, tree water relations, temperature lapse rate, dendrochronology, tree phenology, distribution patterns and spatial dimensions of climate warming over the decades. We have also include research findings from other parts of the world. To make the book more readable references are sparsely used. The book is a resource for the interpretation centre on treelines that we have developed in Dehradun with the support of Central Himalayan Environment Association (CHEA).

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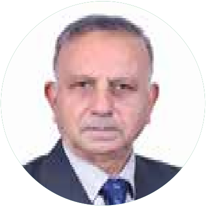

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CHAPTER 1

Treeline forms

Temperature decreases with elevation and the resultant heat deficiency limits tree growth. The timberline marks the limit of the forest, both in high mountains (altitudinal) and polar regions (latitudinal). The physiognomic (community morphology) change from a forest to grassland or scrub is so sharp that even to a casual observer the timberline is conspicuous (Wardle 1965). As we approach the treeline, the vegetation changes from closed canopy forests to patches of stunted trees, and finally to shrub-like trees, grasses, and forbs.

Decline in temperature with increase in elevation represents the basic feature of mountains (Box 1.1). Timberlines or treelines in mountains, called upper timberlines or upper treelines, result from heat deficiency. Other changes also occur as elevation increases: the air gets thinner (rarefied) inducing more evaporation loss, and CO_2 concentration in the atmosphere decreases (Box 1.1). However, low temperature at treelines seems to offset the increase in water loss in the atmosphere. Since plants grow several hundred metres above treelines, the decrease in CO_2 concentration is not a limiting factor as far as plant growth is concerned.

BOX 1.1

Pattern of environment change with increasing elevation

Barometric pressure and temperature decline with elevation	↓
Clear sky radiation increases — both incoming solar radiation in the day and outgoing thermal radiation at night	↑
UV radiation fraction in solar radiation increases with elevation	↑
CO_2 concentration (mass per volume) decreases as barometric pressure decreases, but the rate of CO_2 diffusion increases	↓
Pattern of precipitation change is unclear. It can increase as well as decrease. In Sikkim precipitation decrease with elevation is well marked	↕

Mountain summits and areas around them are often more windy and dry, or covered with thicker snow than lower areas. The wind, by suppressing the growth of vegetative buds, may deform the tree shape with no branches on its windward side. Heavy snowfall can damage branches and change the upright growth form of a plant to a prostrate growth form. Winter snowfall in the treeline areas in North America, for example, is generally between 1.3-2 m. When trees are filled high with clinging snow and ice, it may bend and break stems and branches.

However, snow cover is also beneficial to trees as it protects them from severe cold related to freezing and thawing and from the drying effect of winds. So the loss of snow due to warming temperatures can have several adverse effects on tree growth. Branches of trees which project above the snow level are often killed or damaged but those under snow survive (Arno and Hammerly 1984). The treeline habitat is exposed to several other hazards. Snow creep is common at tree bases, and scars of snow slides and avalanches on trees and landscapes are common.

Trees can also influence snow, for example, through the “black body effect”. Trees are dark objects in the backdrop of snow cover absorbing solar heat, thus, causing the snowpack to melt rapidly (Arno and Hammerly 1984). Globally, tree height decreases rapidly in all parts of the world towards treelines. However, because treeline elevation varies considerably across regions, the relationship between tree height and elevation at the global scale does not exhibit a consistent pattern.

What kinds of leaf phenology are selected in treelines? In the Himalaya, for example, *Betula utilis* (birch), a broadleaf deciduous species, *Rhododendron campanulatum*, a broadleaf evergreen species, and *Abies spectabilis*, a multi-year evergreen conifer, are common treeline species. So all main forms of leaf phenology have developed enough cold hardiness to occupy treelines in the Himalaya and other mountain areas.

Aspect is an important factor that influences temperature and moisture. Change in temperature and moisture due to the aspect in the Northern Hemisphere is given below:

Aspect	Temperature and moisture
South-west	Warmest and driest
South-east West	Warm and moderately moist
North-west East	Cool and moist

Therefore, treeline elevation is distinctly higher on the south-west aspect than north-west and north aspects. Treeline species may also change with change in aspect. In the Kashmir Himalaya, for example, while birch (*B. utilis*) forms the treeline on the cooler north aspect, *Pinus wallichiana* occupies the treeline on the warmer south aspect.

A treeline is a transition zone or an ecotone between the upper edge of continuous and closed forests and a tree species line or the beginning of alpine grassland or scrubland (Körner 1998). Above the treeline ecotone are alpine grasslands or meadows, which are followed by the nival zone consisting of short and sparsely distributed plants. Above the nival zone is permanent snow. The sub-nival and nival areas of the Himalaya are expanding with the depletion of permanent snow cover and glaciers due to climate warming.

Treelines and other plant communities are important habitats for several wild mammals and birds. The snow leopard (*Panthera uncia*) and the Himalayan tahr (*Hemitragus jemlahicus*) are common wild mammals in the Himalaya. The monal (*Lophophorus impejanus*) and the oriental turtle dove (*Streptopelia orientalis*) are common birds.

Here, we briefly discuss various aspects of treelines, based substantially on the studies that we carried out in the Himalaya under the large, multi-site and multi-partner IHTRP. However, we have also considered studies on other mountain treelines because of their scientific importance in developing generalizations about treelines. The main purpose is to communicate briefly to a wider audience about various ecological aspects of treelines and the factors which influence them.

In India, the treeline as a separate conservation and management entity has not yet been even proposed. So the aim here is to briefly analyze various aspects of treelines in a plain language. The geographical spread and elevational shifts of treelines, treeline species composition along the elevation gradient leading to treelines, species richness patterns both along elevation gradients and the Himalayan Arc, temperature lapse rate, tree water relations and phenology, climate change and tree ring relationships, livelihoods, management and policies are the main topics discussed here.

1.1 What is a tree?

A tree is an upright woody plant of certain minimum height with a single dominant stem (Figure 1.1); scientists recommend at least 2-5 m height. Perennial tall plants, bamboos, cacti and giant rosettes are not included, though they may occur in treelines.

Figure 1.1: A typical conifer forest with upright tall trees.

The alpine treeline is temperature-specific, so the treeline elevation (TLE) varies because the temperature beyond which a plant cannot biologically become a tree varies from one mountain range to another, depending on latitude and several local factors discussed below.

ADVANTAGES THAT A ‘TREE’ LIFE FORM HAS OVER SMALL PLANTS

- Trees over-shade other plant forms and, hence, have more sunlight for photosynthesis. Most of the biomass of a tree is in its stem and branches, which enables it to outcompete other plant forms. At a global level the wood density of trees (g/cm^3 or t/m^3) varies widely from 0.16 in *Ochroma pyramidale* (balsa tree) to 1.3 in *Diospyros ebenum* (Ceylon ebony). The wood density of some familiar trees are as follows: 0.35-0.85 pine, 0.43-0.45 spruce, 0.40-0.46 willow, 0.56 juniper, 0.67 fir, 0.6-0.9 oak, and 0.62-0.75 maple.
- Being tall, trees generally escape from occasional surface fires
- Being long-lived, trees generally outcompete all other growth forms, and form long lasting stable communities

THE BURDEN AND RISKS OF BEING A TREE

- A huge investment cost is required to support over a long time wood structure which does not contribute to photosynthesis. So trees have more access to light but lower proportion of tissues to conduct photosynthesis.
- Being tall, the crown of a tree is exposed to harsh atmospheric conditions, which makes trees vulnerable to drought, cold, storms, and snow. A shrub can hide much of its body below ground, but much of the body of a tree is generally above ground.

1.2 Some definitions

1.2.1 Timberline/treeline

Timberline is defined as the upper limit of forests with at least 30 percent crown cover (closed canopy) (Figure 1.2).

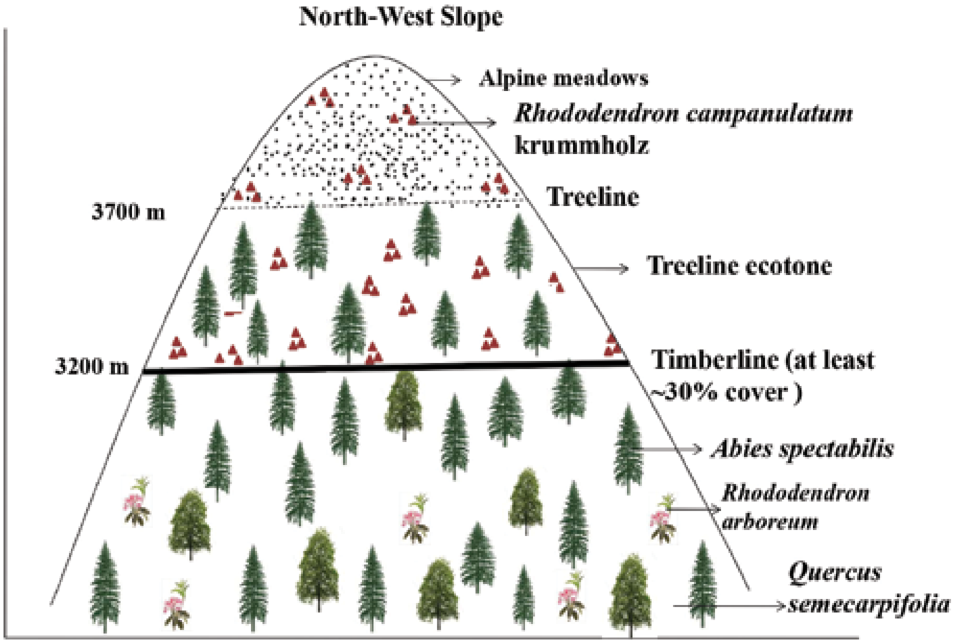


Figure 1.2: Representation of a treeline/timberline ecotone based on an Uttarakhand study site

Treeline can be called an imaginary line connecting the uppermost trees—often isolated and scattered single-stemmed trees >2m height. It is a relatively sharp boundary from trees to shrubs and herbs, but looks a line only from a distance. When you are right there, you realize it is a considerably broad ecotone.

In a way, a treeline is a physiognomic discontinuum along an environmental gradient (principally temperature). This line connects the highest forest patches within a given slope or series of slopes of similar exposure.

Tree species line connects tree species individuals which are not upright, are multi-stemmed, stunted with twisted branches, or exist only as seedlings (Körner 2012b).

The boundaries of vegetation indicated in Figure 1.2 are approximate. Even in alpine areas they are viewed as lines from the sky or the opposite slope (Körner 2012b), though uncommon broadleaf species, such as *Nothofagus* (Rosaceae) in

New Zealand and *Quercus semecarpifolia* in the central and western Himalaya form sharp boundaries.

TYPES OF TIMBERLINES/TREELINES

Holtmeier and Broll (2005) consider the treeline to be an ecotone, delimited by the tree species limit at the upper end, which is the uppermost elevation at which the species occur as trees or krummholz regardless of height, and at the lower end by continuous forests of trees >3 m tall. The strip between these two limits varies in form. Four types of treeline forms are recognized (Harsch and Bader 2011):

(i) **Diffuse type:** In this type the height and density of trees gradually decrease with elevation within the treeline ecotone. The elevation where tree density shows a sudden drop can be considered the treeline (Figure 1.3). Diffuse type timberlines are more responsive to climate change than abrupt treelines. The upward shift is observed in about 80 percent of diffuse treelines.

Figure 1.3: Diffuse timberline/treeline of *B. utilis* and *R. campanulatum*, forming the treeline at Lata-Kharak, Nanda Devi Biosphere Reserve, 4000 masl.

Photo: Dr. Vikram Negi, GBPNIHE

(ii) **Abrupt type:** In this type a continuous forest (at least 30 percent crown density) directly borders alpine grassland or scrub communities of short plants. In the Himalaya, *Q. semecarpifolia*, a broadleaf evergreen oak, generally forms the abrupt treeline (Figure 1.4).

Figure 1.4: Abrupt timberline formed by Quercus semecarpifolia (Chaudas Valley, 3800 masl).

Photo: Dr. Vikram Negi, GBPNIHE

(iii) **Island type:** In this type, above the continuous forest there occur clumped patches or finger like strips of trees or krummholz (Figure 1.5).

Figure 1.5: A timberline of dissected or finger like Betula utilis and Abies pindrow forest; a dissected forest may result from avalanche chutes which sweep standing trees and boulders in their path while adjacent slopes remain forest-clad. The long duration of snow pack prevents trees from regrowing for a long period.

Photo: Prof. Zafar Reshi, Kashmir University

(i) **Krummholz type:** Krummholz consists of stunted, crippled, and deformed multi-stemmed trees, generally above the continuous forest limit (Figure 1.6).

Figure 1.6: Treeline mosaic of vegetation. *Rhododendron campanulatum* krummholz in the foreground and birch trees with opened-up crown and fir in the background.

Photo: Prof. Zafar Reshi, Kashmir University

It may be pointed out that there is a continuum of treeline forms, so dividing them into the above discrete classes is artificial.

There is a relationship between treeline form and treeline response to climate change. About 80 percent of diffuse treelines identified globally by Harsch et al. (2009) had advanced in response to climatic warming. In contrast, only 25 percent of abrupt, island, and krummholz treelines had moved upslope.

HISTORY OF TREELINE STUDIES

Treeline studies began in the 1770s in Europe and North America, but were limited to occasional observations. Surprisingly, in studies on Himalayan vegetation, the term treeline was missing until the end of the 20th century. In the Indian Himalaya, treeline-specific studies largely began in 2016 with the IHTRP. Several Himalayan trees which occur in treelines were studied in the past but not as treeline species. Interestingly, alpine meadows which follow treelines have drawn widespread research and conservation attention, possibly because of the herding of sheep and goats and their importance as a source of medicinal plants.

Some features of the history of treeline studies at the global level are as follows:

- Studies on temperature below which or elevations beyond which trees do not occur began in the 1850s and still draw research interest (Figure 1.7)
- Tree physiology studies based on field experiments began from the 1930s onward
- Impact of climate change on treeline dynamics started from 1940
- Applied treeline research for restoration of subalpine forests and the role of local factors began from the 1980s onward

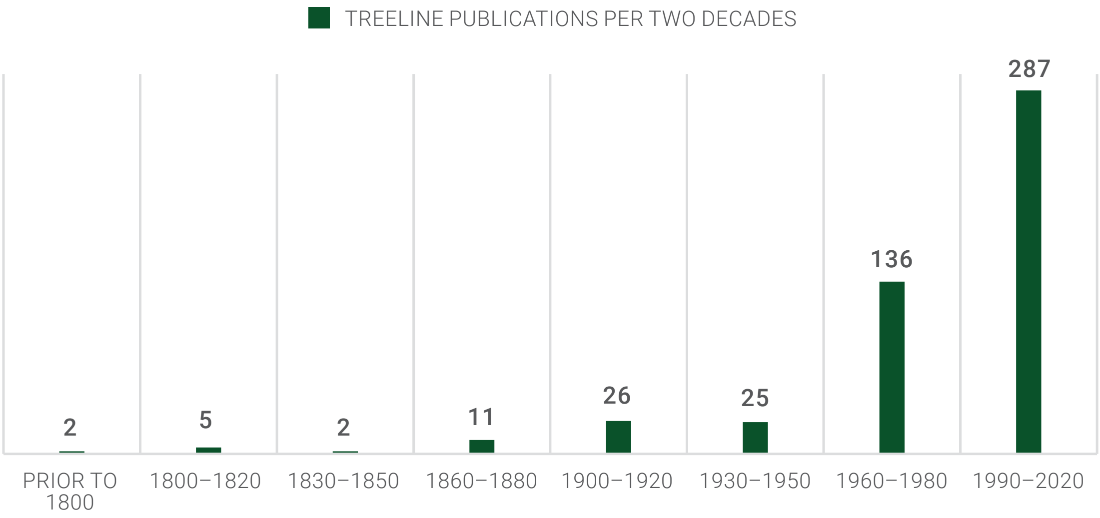


Figure 1.7: Number of treeline-related publications during consecutive 20-year periods (extracted from Holtmeier and Broll 2020).

Since a treeline is a conspicuous physiognomic boundary, treeline shifts began to draw the attention of many field based investigators. The methods used to investigate spatial and temporal changes are: traditional ground-based repeat photography, dendrochronology, remote sensing techniques (largely satellite imagery), and GIS data. In recent years a number of studies have been carried out on the treelines of Nepal and Tibet, particularly on vegetation response to climate change in terms of upward shift and drought effect (Basnet and Gaire 2018; Bhuju et al. 2016; He et al. 2013; Miehe et al. 2015; Sigdel et al. 2018). In Nepal, treeline studies began recently, with about 50 percent being conducted in the last decade (2011-2020). Treeline studies from the perspective of climate change in Nepal began in 2007.

In India treeline/timberline research began in the 1980s/1990s. Dr. R. S. Rawal used the term in the title of his doctoral thesis. He subsequently published papers on species composition. Dr. S. C. Garkoti estimated treeline biomass and productivity of forests adjacent to treelines. He showed how the biomass sharply declined from forest to krummholz of *R. campanulatum*.

A reduction in the ability of trees to retain biomass year after year might result in dwarfing of trees. This may be due to an increase in the proportion of woody litter fall in treelines. The lack of studies with a focus on treelines in the Himalaya until recently is difficult to explain. The deficiency needs to be addressed in view of the importance of Himalayan treelines in relation to climate change.

In a nutshell, the Himalayan region has almost all forms of treelines reported in literature. They generally occur at higher elevations than most other mountain ranges. The IHTRP has made a major beginning in terms of our understanding of treelines. However, several long-term studies would be required to understand climate change related issues in treelines.

CHAPTER 2

How many species are in treelines?

A couple of years ago there were reportedly 60,065 tree species documented worldwide. Of these, 8,715 are found in Brazil; 5,776 in Colombia; and 5,142 in Indonesia. There are about 3,000 species in India. The Arctic Circle has no tree species. Not many tree species reach treelines, but there is as yet no exhaustive count of all those which have reached there. According to Körner (2012), globally, the number of tree species in treelines is unlikely to be much more than 100. Globally, only 20 of about 416 families of angiosperms, and a few families of gymnosperms are capable of living in treelines. Among the families, Pinaceae has more species (of genera like *Pinus*, *Abies*, and *Larix*, the last one being deciduous, commonly known as pine, fir, and larch). Only a few species of a genus occur at treelines. Of the 113 *Pinus* species, only 20 are capable of living at treelines. Of the 80 species of *Sorbus* only two – *S. accuparia* and *S. rehderiana* (SE Tibet) – occur at treelines. No genus is confined to the treeline (Körner 2012). However, several species of *Rhododendron* in the Himalaya are centered on the treeline.

Along the Himalayan arc, ranging approximately from 70°E long. in Afghanistan to 100°E long. in Yunnan, we have counted 58 tree species, which is quite a high number given that globally the treeline tree pool is likely to be close to 150 species. The 58 tree species of Himalayan treelines are of 14 genera and 8 families (Table 2.1).

The Himalayan treeline runs in zigzag fashion, across a wide elevational range, roughly between 3000 and 4900 masl. The wide elevation range is partly because at places the treeline is depressed (being 100-300 m below the climatic treeline elevation), enabling some basically temperate forest species (*Q. semecarpifolia* and *Cedrus deodara)* to reach treelines.

Pinus, which is the most important treeline genus globally, is not a common treeline species in the Himalaya. *P. wallichiana* gets to treelines but is largely a temperate zone pine and *P. gerardiana* occurs only occasionally in treelines. However, species of the other genera of Pinaceae are common in Himalayan treelines: *Abies* (fir) and *Picea* (spruce). *Betula utilis* is possibly the most widely distributed and prominent treeline species, although it seldom forms large stretches of forest as does silver fir in sub-alpine areas. Because of overexploitation, birch is reportedly disappearing from forests around the great Badrinath shrine of Uttarakhand.

Table 2.1: Families and their treeline species in Himalaya.

(Source: Singh et al. 2020). G = number of genera, and S = number of species.

Family	Species
Pinaceae (G=5; S=18)	**Tall evergreen with multi-year leaves** *Abies delavayi, A. densa, A. faxoniana, A. pindrow, A. spectabilis, A. squamata* *Cedrus deodara* *Picea smithiana, Picea balfouriana, Picea crassifolia, Picea likiangensis, Picea retroflexa, Picea spinulosa, Picea schrenkiana* *Pinus wallichiana, P. gerardiana* **Tall deciduous conifer** *Larix griffithiana, L. potaninii*
Cupressaceae (G=1; S=10)	**Evergreen conifer with varying forms-mat, thickets and trees** *Juniperus convallium, J. excelsa, J. indica, J. komarovii, J. przewalskii, J. recurva, J. saltuaria, J. squamata, J. tibetica, J. turkestanica*
Betulaceae (G=1; S=2)	**Medium-sized deciduous broadleaved** *Betula platyphylla, B. utilis*
Sapindaceae (G=1)	**Medium-sized broadleaved deciduous** *Acer spp.*
Rosaceae (G=3; S=7)	**Broadleaved deciduous** **Small trees of the size of forest undercanopy** *Prunus rufa, Prunus cornuta* *Pyrus foliosa* **Small deciduous trees of the size of forest undercanopy** *Sorbus aucuparia, Sorbus foliosa, Sorbus microphylla, Sorbus ursina*
Fagaceae (G=1; S=1)	**Fairly large evergreen broadleaved trees** *Quercus semecarpifolia*
Ericaceae (G=1; S=15)	**Small broadleaved evergreen trees of the size of forest undercanopy** *Rhododendron aeruginosum, R. arboreum, R. barbatum, R. bhutanense, R. campanalatum, R. cerasinum, R. cinnabarinum, R. fictolacteum, R. fulvoides, R. hodgsonii, R. lanatum, R. molle, R. praestans, R. selense, R. wightii*
Salicaceae (G=1; S=5)	**Small deciduous** *Salix daphonoides, Salix microphylla, Salix denticulata, Salix karelinii, Salix lindleyana*

The total number of genera and species are 14 and 58, respectively.

Several species of fir occur in Himalayan treelines: *Abies pindrow* in the extreme west in Afghanistan, Pakistan and Kashmir, *A. spectabilis* in the rest of the western part of the Himalayan arc and much of Nepal, *A. densa* in the eastern part, and *A. faxoniana* in the Chinese Himalaya. Interestingly, though *A. spectabilis* was reported from Kashmir in the past, currently only *A. pindrow* is described from Kashmir.

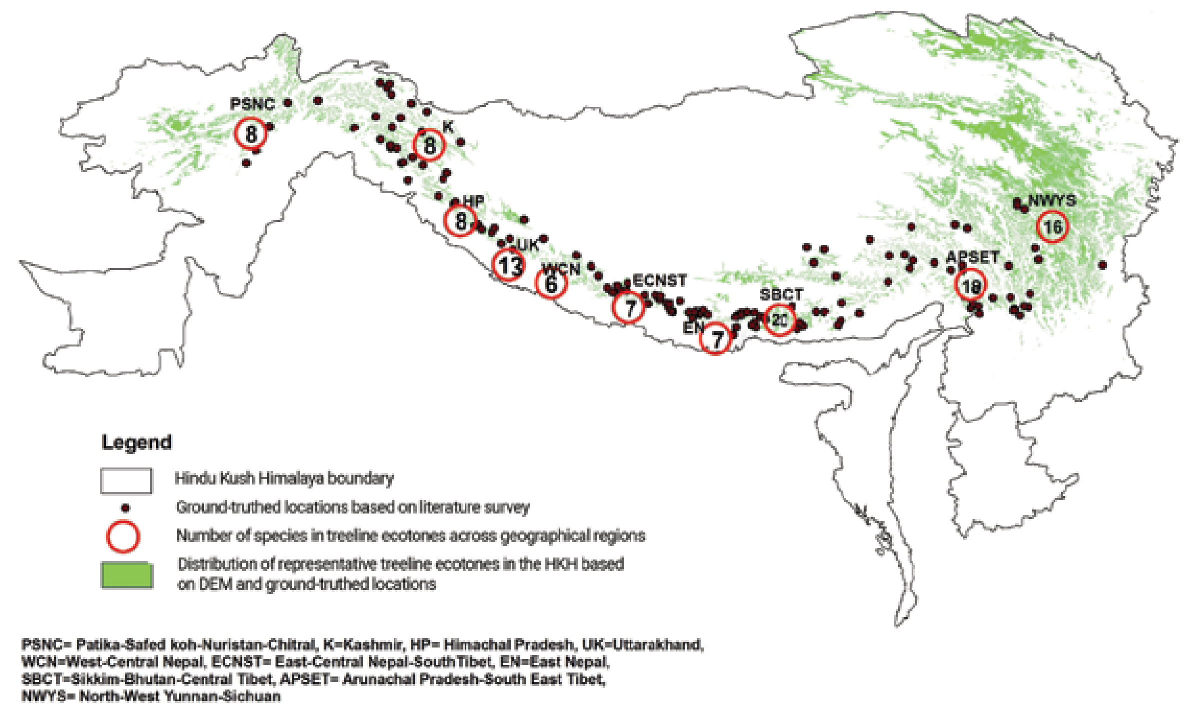
Several problems beset our estimate of the 58 species in Himalayan treelines. Several species have synonyms (a taxonomic name which has the same application as another, particularly one which has been suspended and is no longer valid), so they might be counted more than once. The distinction between the species may be unclear, such as between *A. pindrow* and *A. spectabilis* (differences between the two are discussed in another chapter).

A species may occur in treelines very occasionally, so its inclusion as a treeline species may not be justified. For example, *Cedrus deodara*, is generally a temperate forest species, but near Gangotri it climbs up to form a treeline (Figure 2.1). Further, *Rhododendron campanulatum*, which forms krummholz widely, is generally considered a treeline species.

Figure 2.1: Abrupt treeline formed by Cedrus deodara in Gangotri.

Photo: Dr. Gajendra Singh, USAC, Dehradun, India

Despite these limitations, we can safely say that the Himalayan treeline has more than 50 tree species. Since there are 1382 tree species in the Himalayan region (Rana and Rawat 2017), the treeline tree species account for about 4% of tree flora of the region. This is much higher than the percentage of global tree species which reach treelines (~160 out of 60,065 species, or 0.27%). To a considerable extent this high treeline richness is because of Hengduan and surrounding mountain areas where species differentiation was extraordinarily high (Figure 2.2, see the two easternmost sections of the arc).



This is not a GIS-accurate map but a representative illustration

Figure 2.2: Number of treeline species along the Himalayan arc. The numbers circled in red indicate the average species number of several treeline sites of a longitudinal segment. Since the data are compiled from different studies, the number of sites among the segments varies. Nevertheless, the average of species number per segment gives an approximate trend of species increase from the west to east.

Adapted from: Singh et al. 2020

The tree species number in the Himalayan treelines increases rapidly towards the eastern side of the arc, which is particularly rich in rhododendrons (Ericaceae). The two conifer families Pinaceae and Cupressaceae and one angiosperm family, Ericaceae together account for 73.3 percent of the 58 Himalayan treeline species. While conifers (37 species) account for only 2.7 percent of the total tree species

(1382) occurring in Himalaya (Rana and Rawat 2017), in the treeline they account for 48.3 percent of the species.

The high percentage of conifers in the harsh treeline environment highlights the fact that proportionally conifers are far more stress tolerant than angiosperms. Tracheids, which are the only water transport conduits in conifers are distinctly narrower (10-42 µm) than angiosperms vessels (17-150 µm). Narrow tracheids can tolerate much more water stress without getting cavitated. When water stress is severe, air bubbles form in the conduits, resulting in interrupted water flow.

ARC-WIDE SPECIES DISTRIBUTION

The Himalayan arc exhibits several notable differences along its span. From the west to east, while rainfall increases from about 500 mm to 3000 mm (excluding places with exceptionally high rainfall), the width of the mountain area decreases from 400-500 km in the Kashmir region to 150-200 km in Arunachal Pradesh. Snow cover and warming rates are higher in the western region than the eastern region. Historically, grazing and herding of livestock have been far more widespread in the west than in the east. The plant community in the eastern region is much more species-rich than the western region.

Among the treeline species, though birch (*B. utilis*) occurs throughout the arc, its importance diminishes considerably towards the eastern end (Figure 2.3). In Sikkim, for example, we did not find it at two IHTRP study sites. Birch can occur in arid areas like Chitkul in Himachal Pradesh but there it generally occurs on the cool and moist north aspect. However, it is unknown whether its choice of the north aspect also applies to moist areas. Because of climate warming, the western Himalaya could become drier and in such a situation the birch may shift eastwards (Hamid et al. 2019). However, to migrate to the moist eastern region it will have to compete with several species because of much higher species richness in the east.

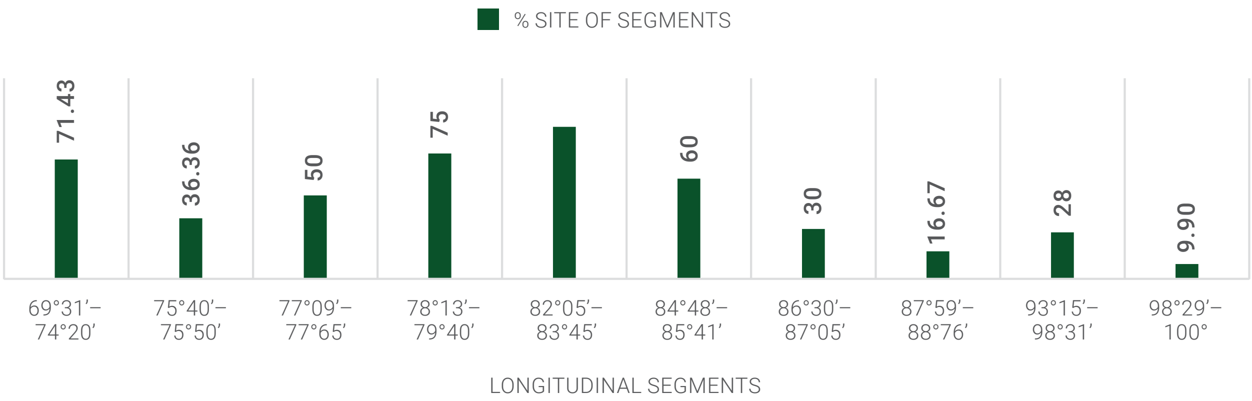


Figure 2.3: Distribution of genus *Betula* across the Himalayan arc

Source: Singh et al. 2020

Fir (*Abies*) occurs throughout the arc but the species differ. As given in Figure 2.4 six firs occur along the Himalayan arc, each occupying a distinct section of without much overlap.

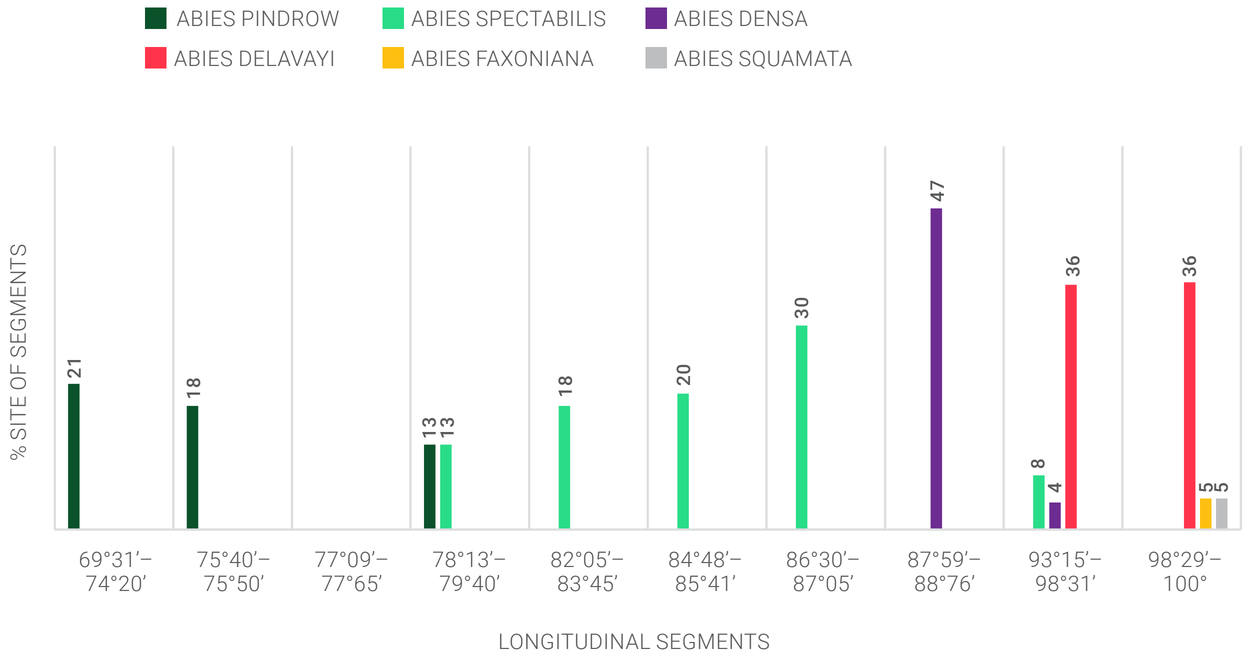


Figure 2.4: Distribution of *Abies* species along the Himalayan arc

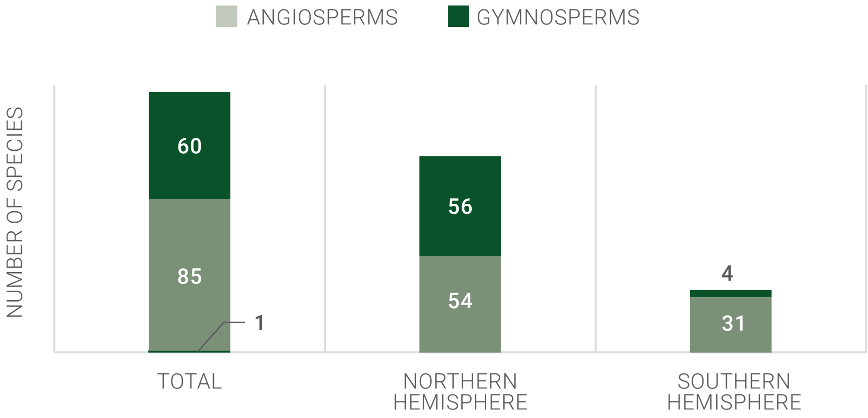
Source: Singh et al. 2020

GLOBAL AND HIMALAYAN TREELINES SPECIES POOLS

There is no estimate of treeline species richness globally, so we (Ripu Daman Singh, S.P. Singh and associates) compiled the treeline species referred to in the literature. We recorded 145 tree species, unevenly distributed between the northern hemisphere (110 species) and the southern hemisphere (35 species) (Figure 2.5). The two hemispheres differ a lot also in treeline species composition. While in the northern hemisphere, treeline species were evenly divided between angiosperms (broadleaved species) and conifers, those in the southern hemisphere were predominantly broadleaved species (88.6 percent).

In the southern hemisphere, the only conifer genera are *Podocarpus*, *Araucaria*, *Libocedrus* and *Cryptomeria*. Only the Cupressaceae family is common to both hemispheres. The Podocarpaceae and Araucariaceae are entirely southern hemisphere conifer families (Tables 2.2 and 2.3). Even the broadleaf species of the two hemispheres are different. Overall, the order of important families in the northern hemisphere is *Pinaceae* (41), *Ericaceae* (17), *Cupressaceae* (15), *Betulaceae* (11), *Salicaceae* (10), *Rosaceae* (07), and *Fagaceae* (05). In the southern hemisphere it is *Ericaceae* (07), *Rosaceae* (05), *Nothofagaceae* (05), *Myrtaceae* (04) and *Hyperiaceae* (03) (Table 2.3).

Evergreen species accounted for 82.6 percent of species in the southern hemisphere and 60 percent in the northern hemisphere (Table 2.2), the rest of the species being deciduous. As expected, the Himalayan treeline species composition resembled that of the northern hemisphere. It was evenly divided between broadleaved and conifers. In total the proportion of evergreen species in the Himalaya (72.4%) is between that in the northern hemisphere (60 percent) and southern hemisphere (82.6 percent).



Total 145 species, Northern Hemisphere 110, and Southern Hemisphere 35.

Figure 2.5: Number of treeline species globally

Table 2.2: Estimate of global treeline species and their distribution between the northern and southern hemispheres.

Number of species*	Northern Hemisphere	Southern Hemisphere	Total	Himalayan
Total treeline species	110	35	145	58
Krummholz species	55	15	71	
Angiosperms	54 (49.1%)	31 (88.6%)	85 (58.6%)	30 (51.7%)
Conifers	56 (50.9%)	4 (11.4%)	60 (41.4%)	28 (48.3%)

Source: Compiled largely from Holtmeier (2009), Korner (2012) and Singh et al. (2020) for the Himalaya. The species numbers could be an underestimation.

Table 2.3: Number of treeline tree species by hemispherical and global levels

Plant groups	Species number		
	Northern Hemisphere*	Southern Hemisphere**	Total global species (% species)
Conifer evergreen	47 (83.92%)	4 (100%)	51 (85%)
Conifer deciduous	9 (16.07%)	0	9 (15%)
Total conifers	56 (100%)	4 (100%)	60 (100%)
Angiosperm evergreen	17 (31.48%)	25 (80.65%)	42 (49.41%)
Angiosperm deciduous	37 (68.51%)	6 (19.35%)	43 (50.58%)
Total angiosperms	54 (100%)	31 (100%)	85 (100%)
Total evergreen	64 (58.18%)	29 (82.85%)	93 (64.13%)
Total deciduous	46 (41.81%)	6 (17.14%)	52 (35.86%)
Total tree species	110 (100%)	35 (100%)	145 (100%)

*Main families are Pinaceae (41 species), *Ericaceae* (17 species), *Cupressaceae* (16 species), *Betulaceae* (12 species), *Salicaceae* (10 species), *Rosaceae* (7 species), *Fagaceae* (5 species), *Sapindaceae*, and *Theaceae* (1 species each);

**Main families are *Ericaceae* (7 species), *Nothofagaceae* (6 species), *Myrtaceae* and *Rosaceae* (5 species each), *Hypericaceae* (3 species), *Rhamnaceae* and *Cupressaceae* (2 species each), *Araliaceae, Araucariaceae, Betulaceae, Pinaceae,* and *Podocarpaceae* (1 species each).

GLOBAL SPATIAL LIMITS OF TREELINES

The northernmost and southernmost treelines occur at about 72°N and 56°S latitudes respectively (Abaimov 2010; Buma et al. 2020). The lower latitude value in the southern hemisphere is because of the lack of land in much of the high latitude areas. The world's northernmost tree is *Larix gmelinii* (adeciduous conifer) in Russia (Abaimov 2010; Wieczorek et al. 2017). Here, the annual mean temperature is -12°C and the mean January temperature is -32°C and the depth of permafrost can be up to 500 m at certain places. At the extreme north point, *L. gmelinii* trees are very sparse, with tree basal area of 1-12 m^2ha^{-1}.

Nothofagus betuloides, an evergreen broadleaved species, forms the southernmost treeline in Isla Island, Chile (Buma et al. 2020). The last tree of *N. betuloides* is 42 years old and is only 2 m tall, though in favourable conditions they can be easily 12-15 m tall. Two other species, *N. antarctica* (deciduous) and *Drimys winteri* are also found on the island on a plot with 145 trees, along with *N. betuloides*.

All the three are broadleaved species. Both seasonal and diurnal temperature variations were mild for 56° S latitude because of the maritime climate. The mean minimum daily temperature was 3.6°C and the mean maximum daily temperature 7.2°C. The number of days with >0.9°C daily air temperature was between 328 and 343 days in a year, so the growth period was long like in tropical areas. On average, the number of days with daily temperature >6.4°C was from 100 to 129 between 2014-2017 (Buma et al. 2020).

The highest treeline in the northern hemisphere is at 4900 masl in southern Tibet and is formed by *Juniperus tibetica* (Miehe et al. 2007). However, the highest treeline in the world is at 5000 masl in the southern hemisphere in the Andes. It is located in Sajama, the oldest national park of Bolivia and is formed by *Polylepis tarapacana*.

In a nutshell, Himalayan treelines have, at a minimum, more than 50 tree species, which is about 4% of the total tree species in the region. This is quite a high percentage, as globally treeline tree species represent only 0.27% of total tree species of the planet. The Himalaya owes its high treeline species richness largely to species differentiation in the Hengduan Mountains of China in the eastern part of the arc. In the Northern Hemisphere, angiosperm and conifer treelines are evenly divided, while in the Southern Hemisphere the treelines have largely angiospermous flora. Treelines in the Himalaya follow the pattern of the Northern Hemisphere in this respect.

CHAPTER 3

Patterns of vegetation on the elevational gradient

– R. S. Rawal, Devendra Kumar, Zafar A Reshi, Renu Rawal, Subzar Ahmad Nanda, and Balam Singh Bisht

Though the composition of plant growth forms is similar across the sites of the Himalayan Arc, the sites vary in species composition and diversity, and to an extent are influenced by lower forest vegetation and the patterns of vegetation change on the elevation gradient. Floristically, the Himalayan region is less woody than the planet. Globally, woody species account for 45% of the total 3,08,000 vascular plants recorded (Fazan et al. 2020). Of all vascular plant species in the Himalaya (10503), 33.3% are woody (1382 trees, 1542 shrubs, and 73 lichens, total 3497; Rana and Rawat 2017). Here, we give an account of the pattern of species changes along the elevational gradient and the east-to-west Himalayan Arc based on three study sites in Kashmir, Uttarakhand and Sikkim. In the Himalaya, tree species richness peaks generally in the lower half of the elevational gradient (around 1500 masl), then declines as elevation increases up to the treeline. However, the extent changes varies from one region to another.

SPECIES RICHNESS IN THREE ELEVATION TRANSECTS ALONG THE ARC

Vegetation sampling was carried out along similar elevation ranges in three IHTRP study sites in Kashmir (2200-3800 masl), Uttarakhand (2100-3200 masl) and Sikkim (1700-4000 masl) up to treeline elevations. Each transect was sampled by 100 m elevation bands. While the tree species number in the elevation transect increased rapidly from west (6) to east (74) along the arc, the herb species increased from east (123) to west (184) (Figures 3.1 and 3.2).

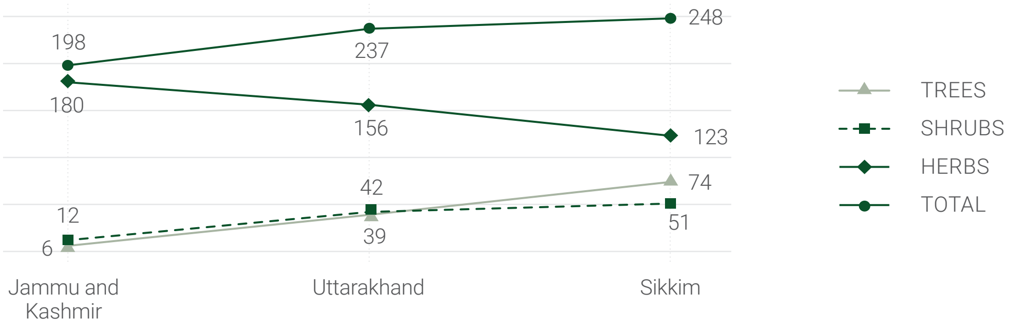


Figure 3.1: Plant species richness along the elevational gradient in three Himalayan sites

Based on FTR-IHTRP, 2021 by Zafar Reshi (Kashmir), R.S. Rawal (Uttarakhand), and Devendra (Sikkim) and their associates.

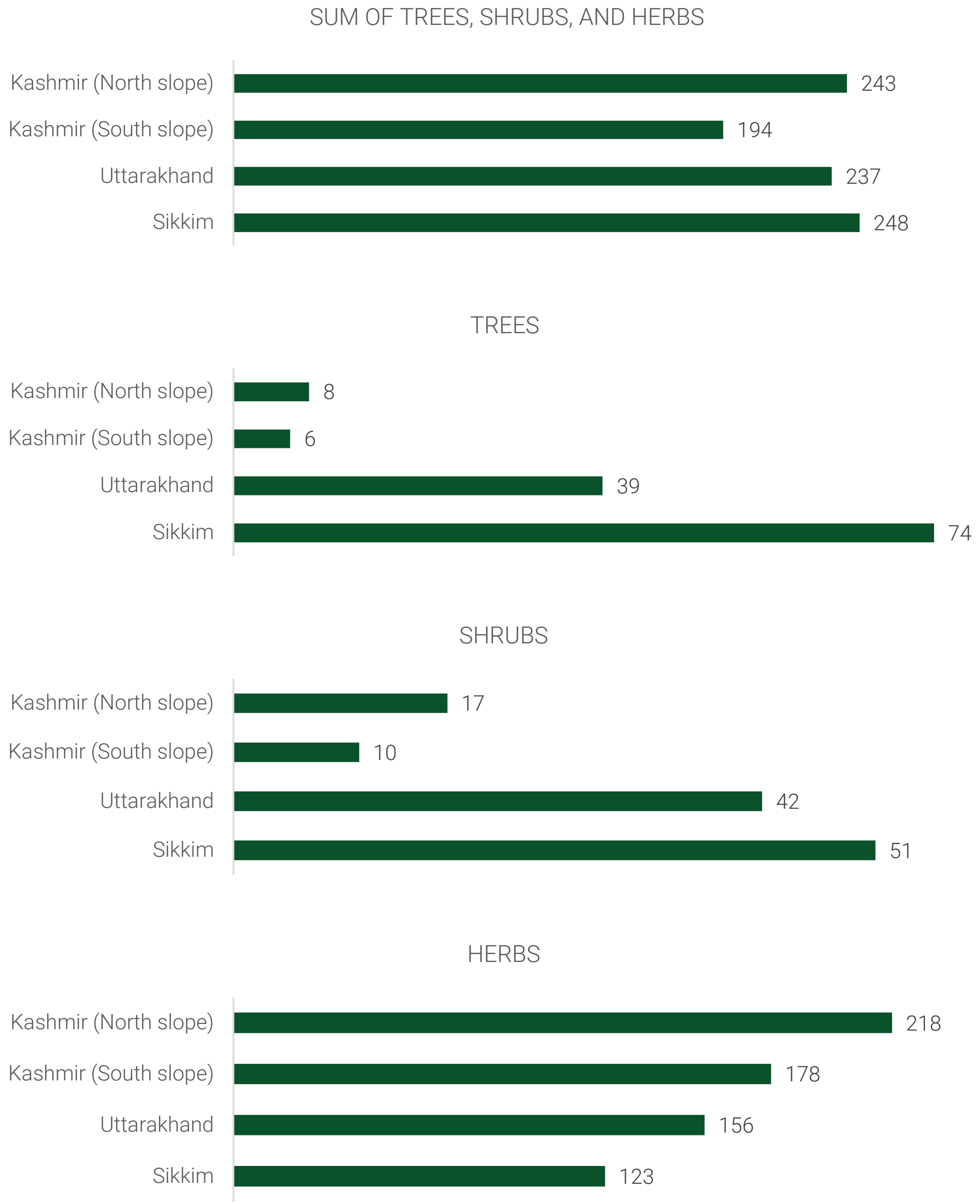


Figure 3.2: Comparison of plant species richness. The species numbers indicate the total species sampled across the elevational transects.

Based on FTR-IHTRP, 2021 by Zafar Reshi (Kashmir), R.S. Rawal (Uttarakhand), and Devendra (Sikkim) and their associates.

A comprehensive sampling of plant diversity in the Daksum-Sinthan Top site in Kashmir recorded 423 plant species (including non-seed plants) belonging to 291 genera and 120 families (Figure 3.3). At all levels, the north-facing slopes (cool and moist) were richer than the south-facing slope (warm and dry), the species, genera and family numbers being 280, 209 and 87 on the north aspect and 250, 180 and 85, respectively on the south aspect, respectively . In all, 113 species belonging to 98 genera and 52 families were common between the two aspects. The two aspects differ in dominant forest species and elevational ranges. The treeline was higher on the south aspect. On the relatively drier south-facing slope, *Pinus roxburghii* was the characteristic treeline species (Figure 3.3).

The Tungnath transect in Uttarakhand sampled at every 100 m band between 2100 and 3200masl showed a total of 237 species (39 trees, 42 shrubs, and 156 herbs) (Figure 3.4). Within this transect, the species richness of all plants (trees, shrubs, and herbs), and of trees and shrubs showed monotonic decline with elevation, which was sharper for trees than for shrubs. For herbs, species richness patterns varied among the three sites. Generally, herb species richness formed several species peaks along the elevation gradient, with an overall trend of increase in species richness with elevation (Figure 3.4).

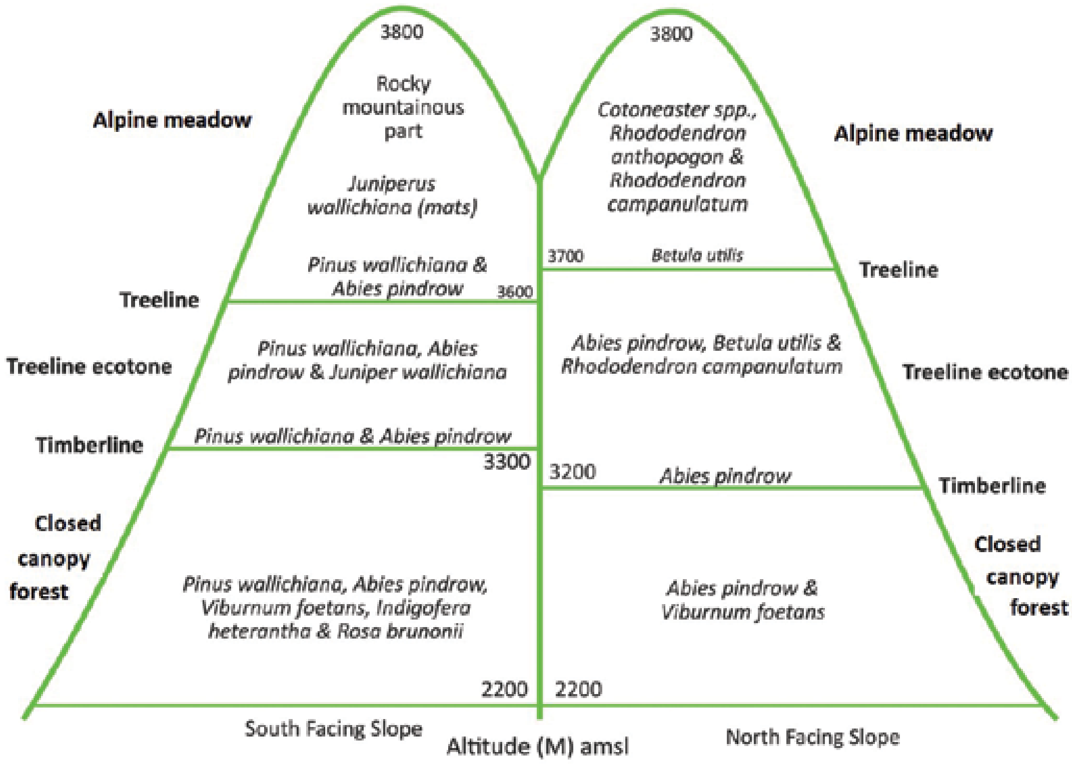


Figure 3.3: Treeline vegetation patterns on the north-facing and south-facing slopes in Kashmir

Derived from FTR-IHTRP, 2021 by Zafar Reshi and his associates.

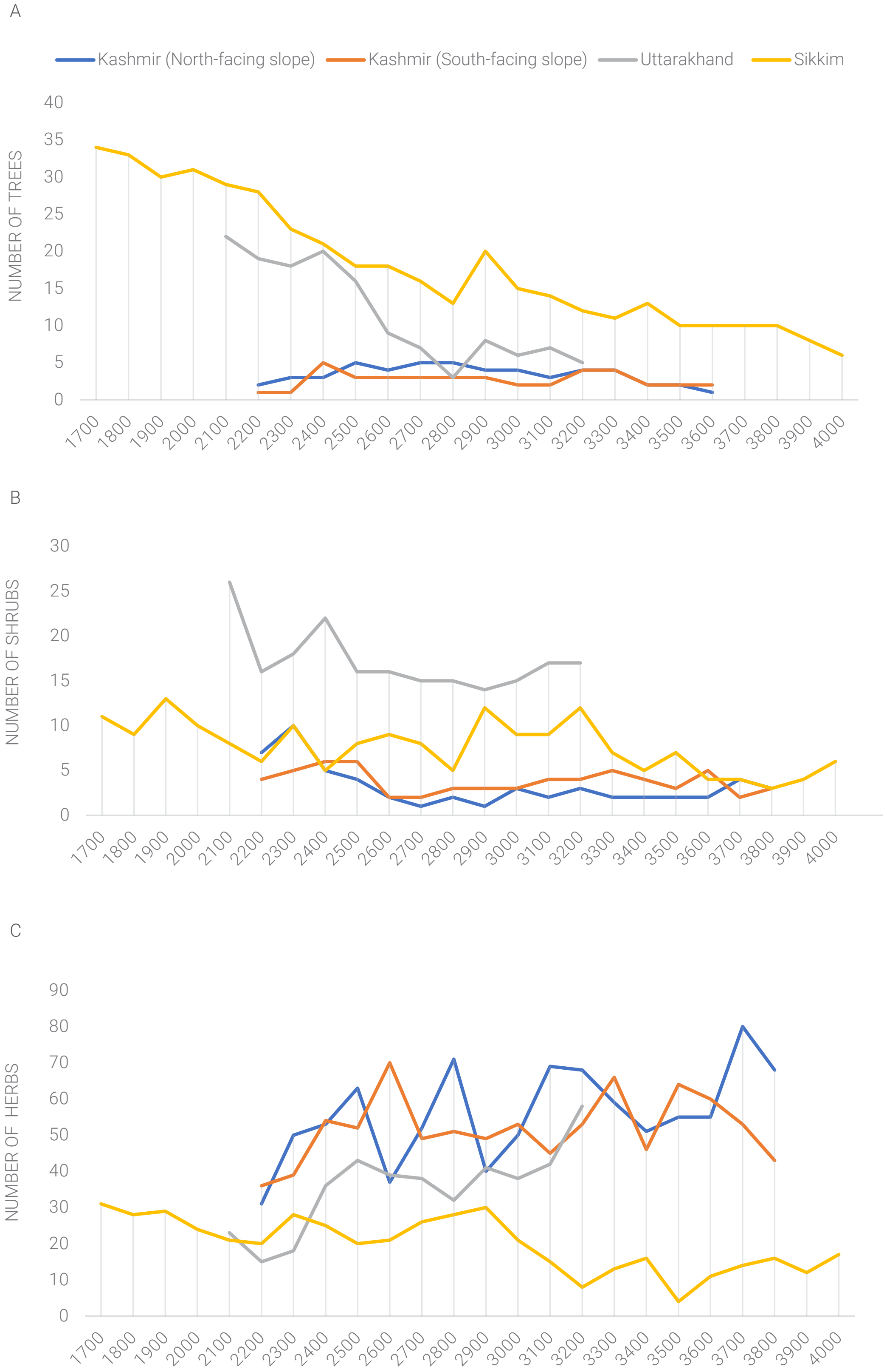


Figure 3.4: Patterns of species richness for (A) trees, (B) shrubs, and (C) herbs along the elevation gradient in the three IHTRP study sites in elevation bands of 100 m

Based on FTR-IHTRP, 2021 by Zafar Reshi (Kashmir), R.S. Rawal (Uttarakhand), and Devendra (Sikkim) and their associates.

The herb species peaks were at 1700 masl, 2900 masl and 4000 masl in Sikkim, and at 2500 masl, 2900 masl and 3200 masl in Uttarakhand (Figure 3.4).

For Sikkim, tree species richness data are available for three elevation transects (one IHTRP site and two sites studied by others). Overall, these transects show that tree species richness peaks in the lower half of the elevation transect (34-39 tree species between 1150-1700 masl), after which it declines (Figure 3.5). However, the pattern of decline varied. In Sikkim, it declined gradually to 10 species in the treeline, whereas in Uttarakhand it declined sharply to four species.

In Kashmir, the tree species richness was low throughout the gradient. Apart from present climate, past glaciation seems to be a major cause for poor tree flora in Kashmir. The tree species pool (gamma diversity—overall diversity in a region, beta diversity—species change between ecosystems in a region, and alpha diversity—species richness within a particular ecosystem) were low in Kashmir. In contrast, all values were high for herbs.

As for shrubs, Uttarakhand had high alpha diversity but low beta diversity. For all the three growth forms, Sikkim had the highest beta diversity. However, because of low alpha diversity, the gamma diversity of Sikkim was very low for herbs. The contrast in tree and herb species richness in Kashmir has not been adequately studied.
It needs to be analysed from the perspective of ecology and evolution.

Figure 3.5: Tree species richness along the elevation gradient in the eastern Himalaya

(a) Teesta Valley, Sikkim (450-4150 masl with an elevation band of 150 m; Acharya et al. 2011), (b) East Sikkim (550-3250 masl with an elevation band of 100 spacem; Sharma et al. 2019), (c) West Sikkim (1700-4000 masl—IHTRP site—with an elevation band of 100 m; Pandey et al. 2018), and (d) Subansiri district, Arunachal Pradesh (200-2200 masl with an elevation band of 200 m; Behera and Kushwaha 2007). Arunachal is distinctly richer in trees, though the values are for a 200 m elevational band.

LICHENS: SPECIES RICHNESS PATTERN

High ranges towards treeline are not species poor for all plant groups. Lichens make up one such group. The species richness in lichens peaked at 3000 masl, an elevation not far below the treeline elevation in Sikkim. Beta diversity along the elevation gradient was relatively lower for lichens, because of the wide elevational ranges of many species. In the entire transect (1700-4000 masl of Sikkim, 114 lichen species were recorded, peaking at 3000 masl). A considerable number of lichens (26 species) occurred even at 4000 masl in Sikkim (Figure 3.6).

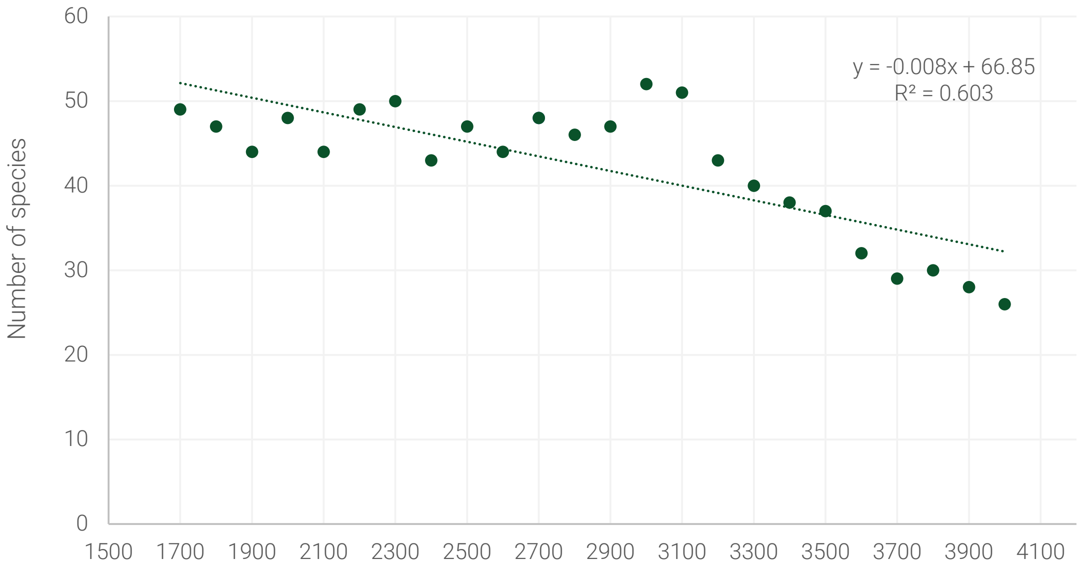


Figure 3.6: Lichen species richness along an elevation gradient in Sikkim

Based on FTR-IHTRP, 2021 by Devendra Kumar and his associates.

The peak species richness of fruticose (3200-3300 masl) and crustose lichens (3700-3900 masl) almost coincided with the treeline. Such lichen species may serve as an indicator of climate change. Across the three elevational transects, 242 lichen species belonging to 79 genera and 26 families were recorded (Table 3.1).

Table 3.1: Lichen species diversity in the three study sites.

Based on FTR-IHTRP, 2021 by Zafar Reshi (Kashmir), R.S. Rawal (Uttarakhand), and Devendra (Sikkim) and their associates

	Kashmir	Uttarakhand	Sikkim
Elevation range (masl)	2200-3800	2000-3700	1700-4000
Total species (in no.)	88	108	114
Average species per elevation band (in no.)	27.05	28.16	41.33
Beta diversity	3.25	3.83	2.75
Total genera (in no.)	45	41	50
Total families(in no.)	18	16	19

Each region seems to have a unique lichen pool, as only 12 species were common to the three sites. Common species numbers were: 21 between Kashmir and Uttarakhand, 20 between Kashmir and Sikkim, and 35 between Uttarakhand and Sikkim, showing Bray and Curtis similarity of 21.9 percent, 20.2 percent and 31.5 percent, respectively. The alpha diversity in Sikkim was much higher (41.3 average species richness per 100 m elevation band) than the other two regions. Beta diversity, which signifies species richness within the elevation transect, was the lowest in Sikkim (2.75), and the highest (3.83) in Uttarakhand. The relatively low beta diversity in Sikkim indicates that lichens in general have a wide temperature tolerance.

Treeline species assemblage was investigated in detail in Khangchendzonga National Park (KNP) by sampling nine contiguous sites. In KNP there were ten tree species, of which 6 were rhododendrons, much more than in Kashmir (4 species) and Uttarakhand (5 species). Contrary to general perception, *B. utilis* and *R. campanulatum* were rare in KNP. *Abies densa, Sorbus microphylla,* and *R. lanatum* occurred in all the nine sites sampled with an importance value index (IVI) of over 60. The treeline species generally began to occur from 3000 masl, but *R. fulgens* occurred only in the treeline.

Species migration in response to climate change is a very slow process, particularly in case of long lived tree species. However, transect level changes could be detected in growth forms like herbs, mosses and lichens, in which individuals are not long lived. Running repeat transects is a useful method to analyse species shift in response to climate change.

Unfortunately, in the Himalaya past information is limited to floristic studies, in which it is not possible to detect spatial changes. The transects established during the IHTRP study could be used at least for medium-term observations, say after 5 or 10 years. We need to improve information on spatial location of individuals using

GPS coordinates, pictures, and marks to facilitate monitoring in future. Because ecological studies began relatively earlier in universities (since the 1980s), we have more quantitative estimates for comparison for the Uttarakhand site.

In a nutshell, although Himalayan region is rich in forest types, floristically it is less woody than the planet as a whole, possibly because of several glaciations it has experienced in the geological past. Changes in species diversity in the Himalaya are impressive both along the elevation gradients leading to treelines and along the west-to-east Himalayan Arc. Elevations at which species diversity peaks varies from one growth form to another and from region to region. Tree species richness peaks well below the treeline elevation, while herb diversity tends to peak at or around treeline elevation. Woody species diversity increases dramatically from the west (e.g., Kashmir) to east (e.g., Sikkim), while herb species richness follows an opposite pattern. Many more representative sites need to be investigated to capture the heterogeneity in the vegetation characteristics in Himalayan treelines.

CHAPTER 4

Seed dispersing birds and wild mammals in treelines

Figure 4.1: Clark's nutcrackers (*Nucifraga columbiana*) cache tens of thousands of seeds (often more than 30,000 each) and can locate them as long as nine months after the original burial.

Photos: James Eaton; Andrew Spencer

No bird and wild mammal species are entirely treeline centred; they generally occur in a wide range of ecosystems from forest edge to alpine grasslands. However, not many studies have been conducted on wildlife in terms of their association with treelines. Birds can influence treeline ecotones by consuming seeds (they also feed upon buds in some cases) and dispersing them (Holtmeier 2009). Nutcrackers (genus *Nucifraga* established by Brisson, 1760) of Corvidae, close to the crow family, are closely associated with pines throughout the world. Known by three species, nutcrackers are predators and dispersers of the seeds of several pines, including Himalayan pines such as blue pine (*P. wallichiana*) and chilgoza pine (*P. gerardiana*) (Figure 4.1 and 4.2). Since chilgoza pine is almost wingless, it cannot be dispersed by wind, and is dependent on the nutcracker for dispersal. Some studies carried out in Europe indicate that nutcrackers can collect upto 30,000 seeds in a season and cache upto 32 km. Unlike other birds, nutcrackers store the seeds in a special pouch below their tongue, and carry them far away to be eaten later. The chilgoza nuts or seeds of several other pines if not eaten, get an opportunity to produce seedlings. zThe nutcrackers disperse the large wingless or nearly wingless seeds of pines, such as *P. cembra*, *P. albicaulis*, and *P. flexilis*. Among the Himalayan pines *P. gerardiana* (chilgoza pine) has the largest seeds (349 mg/seed), and is particularly favoured by birds. However, most seeds of chilgoza pine are harvested for human consumption while the cones are still green. That is why its natural regeneration is poor.

Seeds of white bark pine are a choice food source of squirrels and bears (*Ursus arctos* and *U. americanus*). Bears often plunder middens (heap of collected seeds) of red squirrels (*Tamiasciurus hudsonicus*) which like white bark pine seeds.

Nutcrackers form food caches of stone pine (*Pinus pinea*) even beyond treelines, and thus might contribute to upward expansion of the pine (Tomback et al. 1993, 1994). Stored even above treelines, stone pine forms clusters of seedlings with a high probability for survival. That is why white bark pine (*P. albicaulis*) is often found in tree clusters. Nutcrackers carry stone pine seeds over 15 km distances and 700 m elevation (Holtmeier 1974). Nutcrackers generally select convex topography, as it is free from deep snow cover. Such convex surfaces include ridges or ribs, spurs, and rocky outcrops. This contributes to an extent to the rib and trough form of timberlines. Convex surfaces without snow or with little snow would be easy for seed caching to locate later.

Figure 4.2: Spotted nutcracker (*Nucifraga caryocatactes*) at Gangotri, Uttarakhand

Photo: Nilanjan Chatterjee

Figure 4.3: Oriental turtle dove (*Streptopelia orientalis*) on the way to Tungnath, Chopta, Uttarakhand

Photo: Surabhi Gumber

Figure 4.4: Kalij pheasant (*Lophura leucomelanos*)

Photo: WII NMSHE Project, Dehradun

Endozoochoric (dispersal of spores or seeds by animals after passage through the gut) distribution is seen in junipers (*Juniperus indica*, *J. pseudosabina*). This distribution is related to animal defecation, which is accidental (Miehe and Miehe 2000). Studies also indicate that downhill dispersal of seeds is common.

Several treeline species have larger and more nutritious seeds than their lower elevation counterparts, hence they are consumed immediately after reaching the ground. Some birds are seen at higher elevations feeding on these seeds during this time (Figures 4.3 and 4.4).

Figure 4.5: Pika (Ochotona himalayana) at Gangotri, Uttarakhand

Photo: Nilanjan Chatterjee

Mamals

Burrowing animals, particularly pikas (*Ochotona himalayana* Figure 4.5) and pocket gophers (*Thomomys talpoides*), are common in treeline ecotones, where the soil is deep enough to allow burrowing so that snow does not affect them. Burrowing animals damage seedlings by gnawing and digging along roots (Schitz 2005).

However, the loose mineral material brought to the surface by pocket gophers, pikas and marmots may contribute to seedling establishment (Holtmeier 2002). During winters, wild pigs can be seen digging bulbous roots and rhizomes in treelines and adjacent grasslands. They

Figure 4.6: Himalayan tahr (*Hemitragus jemlahicus*) at 2700 masl near Chopta, Tungnath, Uttarakhand

Photo: Renu Rawal, GBPNIHE

Figure 4.7: Snow leopard (*Panthera uncia*)

Photo: WII NMSHE Project, Dehradun

Figure 4.8: Himalayan brown bear (*Ursus arctos isabellinus*)

Photo: WII NMSHE Project, Dehradun

Figure 4.9: Blue sheep or bharal (*Pseudois nayaur*)

Photo: Ranjana Pal, Researcher WII, Dehradun

must be playing an important role in the regeneration of some species. Activities like this have increased in recent years with early snow melt.

The snow leopard (*Panthera uncia* Figure 4.7) usually lives in alpine meadows and in rocky terrain at altitudes from 2,700 to 6,000 masl. In winters, they come down to forests between 1,200 and 2,000 masl. In the Himalaya, it also occupies the treeline during winters. It prefers rocky, broken terrain, and can travel without difficulty in snow up to 85 cm deep (Sunquist and Sunquist 2002).

Population and conservation status: 4678-8745 (globally); 516-524 (India) (source McCarthy et al. 2017); Endangered

The Himalayan brown bear (*Ursus arctos isabellinus* Figure 4.8) inhabits high altitude forests and alpine meadows. They are omnivores and consume grasses, roots, fruits and berries and other plant parts as well as insects and small mammals. They can also prey on large mammals, including sheep and goats.

Conservation status: Critically endangered, possibly already extinct in some parts like Bhutan.

The blue sheep or bharal (*Pseudois nayaur* Figure 4.9) inhabits treeless slopes and alpine meadows and shrubland belts above timberlines. It prefers relatively gentle hillsides covered with grasses and sedges. It feeds on grasses, herbs, lichens, and mosses.

Conservation status: Least concern

Figure 4.10: Tibetan wolf (*Canis lupus*)

Photo: WII NMSHE Project, Dehradun

The Tibetan wolf (*Canis lupus* Figure 4.10), the most persecuted species, prefers alpine forests and feeds on domestic sheep, mountain sheep, wild yaks, domestic goats, and antelopes.

Conservation status: Endangered in Jammu and Kashmir, Himachal Pradesh and Uttarakhand.

In a nutshell, wildlife studies with a focus on treelines is almost absent in the Himalaya. However, several characteristic wild mammals use treelines as habitat. Wildlife researchers in Himalaya have hardly paid any attention to the specific role of treelines and adjacent biotic zones, forests (below treeline) and alpine grasslands and scrubs (above treelines) in wildlife conservation and management. Since the communities above the biotic belts are in flux because of climate change, it is important to monitor the spatial changes on a regular basis.

CHAPTER 5

The struggle for survival at the top: krummholz and deformed trees

In the harsh treeline environment, the life of a tree seedling is a life of struggle. Treeline formation processes could be affected by three factors: growth limitation (ability to grow new tissues), dieback (biomass loss, but no mortality), and seedling mortality. Seedlings of birch, fir and other treeline species are affected by these processes, resulting in the formation of a forest boundary.

Low temperatures can result in insufficient carbon balance or directly restrict tissue formation. Freezing damage, drought and disease can cause mortality of seedlings and saplings. Freezing is common in treelines, but treelines are also formed without freezing. Repeated damage by freezing, frost and phototoxic effects is common in treelines. Interaction with neighbours is another factor which affects growth by modifying the microclimate – distribution of wind and snow, and competition for resources. A neighbouring plant can be a competitor or facilitator depending on several factors. When growth suppressing effect increases along the treeline ecotone, a diffuse type of treeline results, and when suppression is severe, it leads to a krummholz formation. A krummholz does not grow tall (it is stunted) and might shed twigs and branches more than forest trees towards the upper parts.

Treeline formation in alpine areas takes place because of heat deficiency. Therefore, contemporary climate warming is expected to shift treelines upward. However, treelines have shifted upward in only 52% of 166 sites examined globally (Harsch et al. 2009); in the rest, the treeline has remained stationary. In our Himalayan treeline study, we found that along ~85% of treeline length no change in treeline elevation has occurred over the last four decades or so (IHTRP, Latwal et al. 2018; Subrat Sharma unpubl., discussed later).

The change in treeline elevation occurs because of tree recruitment, growth and mortality (Liang et al. 2016). Seeds can arrive beyond treelines but only a few germinate and establish as seedlings. For example, during a study in 2019 in the Tungnath site, tree seedlings could be seen 400 m above the treeline.

MYCORRHIZAL ASSOCIATION AND FINE ROOTS

The treeline seedlings grow very slowly and survival is low because of a short growth period and severe abiotic stress (deficiency of nutrients, water, and heat).

Recruitment and growth of seedlings do not ensure the upslope march of a treeline, as there are several hazards like high wind speeds, drying, freezing soils, and the lack of mycorrhizal or other microbial facilitation. Mycorrhizal association – the mutual symbiotic association between a fungus and a plant – plays a key role in the survival and growth of seedlings in the harsh treeline environment. More evolved angiosperms like Betulaceae (birch family) may have evolved thin roots and fewer ectomycorrhizal mycelia, so that the carbon cost to support them is relatively lower (mycorrhizal attachment has a carbon cost, which the host tree has to bear). However, ectomycorrhizae present several advantages to trees in a harsh environment, including enhanced availability of nutrients. Ectomycorrhizae also stimulate organic matter degradation and weathering (Taylor et al. 2009). Possibly because of the high abiotic stress in treelines, Pinaceae species which have relatively thicker roots and a copious ectomycorrhizal attachment, occur at treelines worldwide. Almost no research has been done on the relative success of species with thin roots and mycorrhizal association in seedling adaptation in Himalayan treelines. There is evidence to suggest that species with thinner roots and greater specific root length (SRL, root length per unit root mass or soil root density; the higher the SRL thinner the root) like some species of *Quercus*, *Betula* and *Populus* are generally associated with relatively drier areas (Comas et al. 2012). Roots with thin diameter and long SRL seem to be less infested with mycorrhiza, and thus incur lower carbon costs. The thin root species seem to have evolved to save the carbon cost of supporting fungi. Their roots with more hairs compensate for the sparse mycorrhizae (Baylis 1972, 1975). Comas and Eissenstat (2009) found a 10-fold difference in SRL among angiosperms spanning 140 million years of species diversification. Basal seed plants of Cycadaceae and Ginkgoaceae have characteristically thick roots of low SRL. Since higher SRL is beneficial where nutrients limit plant growth, treeline species are expected to have high SRL. However, many treeline species like *Q. semecarpifolia, B. utilis, P. wallichiana,* and *A. spectabilis* are known for their ectomycorrhizal association. Information on fine roots of the treeline trees is almost absent for the Himalayas.

PATHWAYS AND BARRIERS TO THE UPWARD MOVEMENT OF TREELINES

Since heat deficiency is the main cause of treeline formation, climatic warming may lead to the upward movement of treelines, densification of trees, and encroachment of trees into alpine meadows (Korner and Paulsen 2004; Lenoir et al. 2009).

There are many biotic factors which influence treeline dynamics, including species interactions, pests and diseases, and invasive alien species. Recent investigations shed light on the role of species interactions and tree-to-tree interactions in upward shift of treelines.

Figure 5.1: More seedlings, saplings and young trees of *Abies pindrow* grow inside krummholz patches of *Rhododendron campanulatum* than outside in this treeline in Kashmir

Photo: Zafar Reshi, Kashmir University, India

In Kashmir, more tree seedlings and young trees were found inside the patches of *R. campanulatum* krummholz and juniper mats than outside in open areas (IHTRP, Prof. Reshi and associates, Figure 5.1). In *R. campanulatum* patches, the tree seedlings, saplings and young trees were of silver fir (*Abies pindrow*), and birch (*B. utilis*) and in juniper mats they were of blue pine (*Pinus wallichiana*). While the birch and *R. campanulatum* occurred on the north aspect, the blue pine and juniper mats were largely present on the south aspect. So these observations of the Kashmir treelines suggest that a plant species can facilitate upward movement of tree species. The patches of *R. campanulatum* and juniper seem to have protected seedlings from desiccation caused by wind action and browsing.

In contrast, Sigdel at al. (2020) reported that young trees which formed clusters near the treeline in dry conditions restricted upward treeline movement. The warming-driven increase in evaporation loss may result in the desiccation of soil, and such a condition is likely to favour clusters rather than isolated solitary individuals.

In another study conducted on the Tibetan Plateau (28.4°-38.5°N), Liang et al. (2016) reported that warming results in the densification of rhododendron shrubs next to treelines and thereby limits the establishment of treeline species. This comprehensive study based on 14 sites indicates that the upward movement of treelines under the influence of climatic warming (by 1.2-1.5°C over a century) is restricted by the densification of rhododendron.

The above observations indicate that species relationships in treelines can shift from positive (e.g. facilitation) to negative (competition). In Kashmir, the tree recruitment seems to have been enhanced by krummholz and juniper mats, but in Tibet the shrubs restricted the upslope movement of trees. Had temperature been the sole limiting factor, climate warming should have advanced treelines by 200 m during the last 5-6 decades on the Tibetan Plateau. While tree density increased because of recruitment of new individuals during the past 100 years both in fir (*Abies georgii*) and spruce (*Picea crassifolia*) treelines, the upslope treeline advancement was far less than the warming rate indicated. On average, the treeline shift was 2.9±2 m per decade, compared to 6.1-11 m per decade as indicated in earlier meta analysis. This was largely because of the formation of rhododendron (regular text) thickets (1-3 m tall). In these thickets, tree seedlings and saplings were not in a healthy condition. In general, the thicker the rhododendron cover, the slower the upward treeline shift. In brief, the response of treelines to climatic warming in terms of upward shift is modulated or controlled by inter-species interactions.

DETERMINANTS OF TREELINE ELEVATION

- Treeline is caused by heat deficiency, therefore treelines occur at certain temperature e.g. 10°C mean temperature in July in the Northern Hemisphere, or soil mean temperature of 5-7°C during the growing season.
- In humid mountains, the mean soil temperature is 6.1±0.7°C/ 6.7±0.8°C during the growing season (Hoch and Körner 2009).
- However, many local factors affect treeline formation: topography, aspect, snow accumulation, grazing, overall altitude of the area, rock type, and tree species composition.
- Across the bioclimatic zones, the mean growing season temperatures are similar, 4.7-7.8°C (commonly between 5.1-7.4°C), but the length of growing season varies widely, from 90 days to year round growth conditions (Körner 2012). A growing period longer than 90 days cannot compensate for the temperature threshold required for treeline formation. The growing season in Himalayan treelines ranges from 100 days to 160 days (Table 5.1). It depends on temperature as well as cold hardiness of treeline species. Depending upon interpretation and the elevation of the site, the growing season could be up to 200 days in the Central Himalaya (Ram et al. 1988).

Table 5.1: Growing season temperature and length in some Himalayan treelines

Location	Latitude and altitude	Growing season length (days)	Mean growing season temperature (°C)	Species with common names in parentheses
Yuksam, Dzongri, Sikkim	27°N; 3900 masl	135	7-8.4	*Abies densa* (Eastern fir)
Langtang, Nepal	28°N; 4010 masl	142	5.8	*Picea asperata* (Spruce)
Sygera Mountains, Tibet	29°N; 4500 masl	122	6.8	*Betula utilis* (Birch); *Juniperus tibetica* (Juniperus)
Tungnath, Chopta, Uttarakhand	30°N; 3360 masl	160	10.3	*Rhododendron campanulatum* (Rhododendron)
Daksum, Sinthan Top, Kashmir	33°N; 4000 masl	100	7.5	*B. utilis* (Birch)
Sichuan, China	37°N; 3750 masl	143	7.1	*Picea spp.* (Spruce)

- Global mean temperature for growing season is 6.4°C±0.7°C (general range being 5.5-7.5°C; Korner and Holtmeier 2009), with minimum growing season of 90 days.
- The relationship between treeline elevation and latitude is not uniform. Treeline elevation declines sharply between temperate and boreal latitudes, but is constantly high from ~32°N to 20°S.
- Treelines are parallel to the permanent snowlines in elevation pattern, indicating that temperature is a common influencing factor for both.
- Variation within latitudinal bands suggest that other climatic factors not related to latitude influence treeline elevation.

Tropical treelines are characterized by higher mean annual temperatures (but not mean growing season temperature), lower seasonal variation but higher diurnal variation (soil may freeze every night), longer growth periods (up to the entire year), and higher solar radiation.

From low to high elevation within the temperate belt, temperature and growing season length often decrease, while precipitation, cloudiness, and wind speed tend to increase.

Treeline species may encroach upon alpine meadows, thus changing not only the physiognomy of alpine meadows, but also species richness, albedo, and soil carbon. It is likely to lead to a reduction in soil carbon and grazing area, and the densification and increase in vegetation cover can lead to a reduction in albedo (reflectance), which may in turn lead to further warning.

FACTORS LIMITING HIGH ELEVATION EXISTENCE OF TREES

Stress: Frost can damage cells by freezing or photoinhibition, particularly in tall trees. Frozen soils can limit water availability causing desiccation of tree tissues. On a sunny day, such trees would lose water from leaves without water supply from soils.

Disturbance: Mechanical damage due to wind, herbivory, snow loading, and fungal infection.

Reproduction: Decreased pollination and seed development leading to reduced seedling and sapling establishment. Low temperatures can limit seed development and germination. In general, there is a deficiency of data on tree reproduction in treelines.

Carbon balance: A tree will not survive if photosynthesis is lower than respiration because of a short growing season. However, research shows that in the treelines, photosynthesis during growing season is quite high and there is a surplus carbon reserve because of slower tissue formation. The sink (tissues formed) is not large enough to take care of carbon reserves resulting from photosynthesis.

In summary, heat deficiency is the primary cause limiting tree growth and hence the formation of a treeline. However, the struggle for survival of seedlings, saplings and young trees is also influenced by several other biotic and abiotic factors. Here, tree to tree interactions and regrowth play an important role. Thickets of woody plants may facilitate or restrict growth and upslope movement of treeline species.

KRUMMHOLZ AND ELFIN-WOOD

Krummholz and elfin-wood, to an extent, are the products of struggle that a tree has to undergo to remain a tree in the harsh environment of high mountain areas. Individual trees are deformed in both.

Krummholz is a German word applied to genetically determined scrub-like contorted woody growth forms of species like *Pinus mugo prostrata* and *Alnus viridis* (green alder) (Holtmeier 1981) (Figure 5.2), occurring in and around treelines. In English speaking countries, the term has been also used to refer to climatically stunted and distorted trees.

On the other hand, elfin-wood (crippled trees) is a phenotypical response to harsh climate influences (Holtmeier 1981). When conditions become favourable for growth the deformations disappear in elfin-wood, which is not the case with genetically determined krummholz.

The krummholz belt is particularly well developed along avalanche tracks, dry infertile boulder fans, or around local bogs (Pitschmann et al. 1970, 1973). Both *P. mugo prostrata* and *Alnus viridis* (Figure 5.2) are multi-stemmed (polycormic growth) with asymmetrical canopy. On steep slopes, they are often pressed down to the soil surface by snow and deflected downhill.

Holtmeier (2009) recognizes three pine species, three alder species, one *Picea* species and one *Podocarpus* species as krummholz.

Pinus mugo also has an arboreal form, called *P. mugo arborea*. The two varieties of *P. mugo* overlap in distribution in the Central Alps. Both forms also occur at the same site, with a range of transitional forms. It is unknown whether the transitional forms represent their hybrids or have resulted from environmental influences.

Figure 5.2: *Pinus mugo prostrata*

Source: Morris Arboretum, Philadelphia, PA, USA;

Photo: Valentino Liberali

In comparison, elfin-wood has varied deformed growth forms under the influence of local environmental stresses. Examples include flagged trees with no branches or twigs on the windward side (Figure 5.3), table trees, matgrowth, wind-trimmed ribbons, and hedges (Holtmeier 1981) (Figure 5.3).

Figure 5.3: Stunted subalpine fir (***Abies lasiocarpa*** (Hooker) Nuttall) on a ridgetop at 5,900 feet (1798.32 masl) in Mount Rainier National Park, Washington, USA.

Source: Arno and Hammerly 1984;

Sketch by Harshita Joshi, Research Scholar, IHTRP

When an elfin-wood species is transferred to a place with favourable climate, it can develop like a normal tree, while a krummholz species (genetically determined) would grow like a scrub even under favourable conditions. *Rhododendron campanulatum* is a common Himalayan krummholz species, particularly in the western and central parts (Figure 5.4). As the Sikkim treeline data indicate (Pandey et al. 2018), *R. campanulatum* is rare in the eastern parts, where *R. wightii*, *R. fulgens* and *R. thomsonii* are the main krummholz species. At Tungnath, Uttarakhand *R. campanulatum* has not become upright despite decades of warming, so it can be referred to as a genetically krummholz species (Figure 5.4).

Figure 5.4: An individual of ***Rhododendron campanulatum*** at Tungnath, Uttarakhand. It is possibly the most common krummholz species across much of the Himalaya, with average height of 2-4 m.

Photo: Surabhi Gumber

Figure 5.5: An avalanche slope near Kwoiek Creek containing herb and deciduous shrub-dominated communities of ***Alnus viridis*** order. Avalanche tracks can span up to 1200 m in elevation.

Source: Brett et al. 2001

The common krummholz pine (*P. mugo var. prostrata*) of the Central Alps is generally 1-3 m tall (occasionally upto 5 m), with a base spread of up to 10 m on the ground. *P. pumila* which forms krummholz in the mountains of North Korea, northern Mongolia, Siberia, China and others shrubby form with creeping branches of 10 m is generally below 6 m tall. *P. albicaulis*, native to the USA and the Canadian Rocky Mountains in Alberta, British Columbia is relatively tall, upto 21 m. But its needles (5 per fascicle) are short at 3-7 cm.

Alnus viridis, called green alder (Figure 5.5) is a short-lived deciduous small tree or shrub from 0.5 to 5 m tall often colonizing landslide sites in central mountainous parts of Europe (1600-3000 masl). *A. maximonizii*, is a deciduous krummholz alder native to Japan, growing up to a height of 9 m. *Podocarpus nivalis* is a prostrate or semi-prostrate evergreen shrub of the timberlines in New Zealand.

Apart from these, there are several tree species of *Juniperus* which form mats of varied sizes. *Salix* and *Sorbus* also occur in treelines, particularly in the Himalaya.

The shrubby woody plants can form clones with layering branches that form adventitious roots (Körner 2020). These shrubby trees could become upright in a warming climate.

FLAG TREE

In a flag tree or banner tree, branches on the windward side are killed or deformed by the persistently strong winds, giving the tree a characteristic flag-like appearance. Where the lower portion of the tree is protected by snow cover or rocks, only the exposed upper portion may have this appearance.

In a way, a flag tree is environmentally induced krummholz. In the Himalaya, we have not yet seen flag trees, but this could largely be because the region does not have many windy areas, since the massive mountains have kept winds in check.

GROWTH LIMITATION AND DIEBACK

While growth limitation constrains biomass gain, dieback is a loss in biomass. Both occur because of stress, such as water scarcity or low temperatures. However, growth limitation occurs because of prolonged chronic stress, while dieback is due to short-term but severe stressors like wind, frost, and snow load. It may be pertinent to mention here that limited growth may result in upright growth of trees, while dieback deforms the tree, resulting in a krummholz form.

In established individuals, photosynthesis and carbon reserve are not limiting factors (Körner 1998; Piper et al. 2000). Low temperatures, however, limit tissue formation or carbon use or cause sink limitation (Körner 2008; Hoch and Körner 2009). The low growing season temperature (<5°) leads to nutrient deficiency. The other stressors are high snow load, frost, excess radiation, high wind, and frozen soil, among others. These may cause photo damage, desiccation of tissues, mechanical damage, and breakage.

A considerable number of treelines occur at relatively higher growing season mean temperatures (8-11°). Such temperatures have been observed even in the Himalaya. It shows that there can be other factors, such as water scarcity or the lack of seedling establishment (not growth) which affect treeline formation. Higher mortality could be because of smaller root development, low stature and biomass, summer or winter desiccation, and limited carbon storage for replacing damaged tissues. However, seedling mortality can be very high, generally 90% in the first year, after which the rate declines (Smith et al. 1991; Maher and Germino 2006).

In a nutshell, treelines feature deformed trees of several forms. Their deformation may be genetically determined (called krummholz or result from environmental stressors that cause prolonged wear and tear. How many species occur as deformed trees in mountain treelines is not known. In the Himalaya, *R. campanulatum* is a common species that exhibits deformation.

CHAPTER 6

Stunting of trees, leaf crowding, and cold hardiness

TREE STATURE

As elevation increases, tree morphology changes, as do the characteristics of their organs. Here we discuss how trees change with elevation. In other words, this chapter is about tree adaptation to changing environments associated with elevation. Apart from the cold, solar radiation, wind speed, availability of water and soil nutrients, forms and amount of precipitation, and other factors change with elevation. One of the major changes associated with an increase in elevation is the shift from liquid (water) to solid (snow) in the form of precipitation. Treeline areas are known for winter snow cover, which is now decreasing because of climate warming.

A tree in the treeline differs from a tree at lower elevation in several ways. In the treeline, a tree form is characterized by a thicker stem for a given height, bigger and longer lower branches, and more inward growth in tree crowns, resulting in a compact canopy often with a cushion shape. The tapering of tree stem in the treeline is distinctly more than at lower elevations.

Marked changes in trees also occur with age. How morphological features and allocations to different parts change with age can be investigated by planting species in treeline and recording changes in relation to age. In one such study of planted treeline species (Körner 1999), namely of *Pinus cembra*, *P. uncinata*, and *Larix decidua*, the following changes were observed with age. From the age of 6 to 22: (i) the proportion of leaves decreased from 35-47% to 15-17%, (ii) that of branches remained relatively stable (from 14-19% to 14-21%), (iii) the proportion of stem increased considerably from 17-25% to 52-60%, and (iv) root proportion decreased from 21-22% to 11-12%.

With increase in elevation, herbs become rootier (unlike trees, which become less rooty), leafier, and allocate less to stems. In a way, tree seedlings are like herbs, allocating more dry matter to leaves and less to stems.

Stem diameter is less sensitive to low temperature than height growth, resulting in stunted trees at the treeline – a universal trend. In other words, cambial growth in stems is relatively less adversely affected by low temperature, while apical meristem is quite sensitive to it (Figure 6.1).

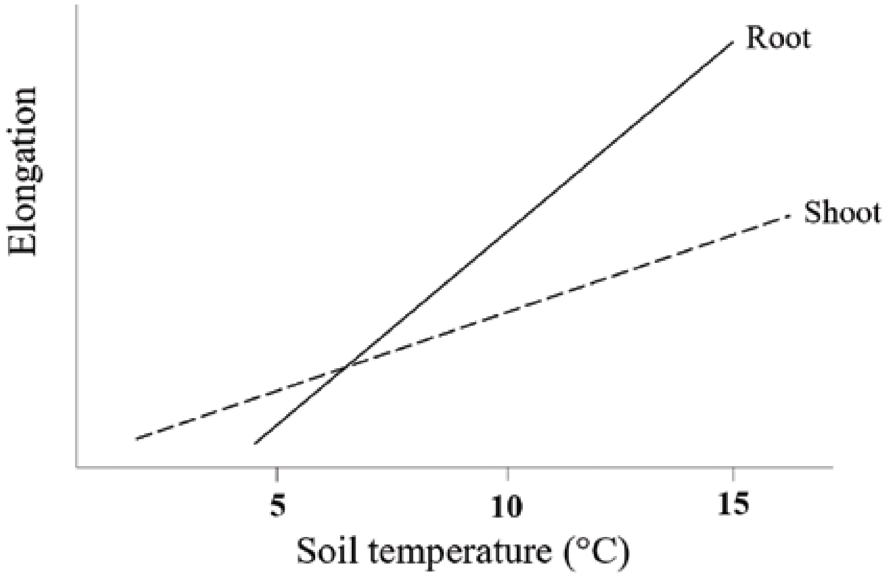


Figure 6.1: Soil temperature when below 5°C adversely affects seedling growth, but the effect is more on roots than shoots (Hasler et al. 1999). The graph simply indicates the trend; it is not based on actual data. Like herbs, tree seedlings become rootier as elevation increases.

At high elevations, near the treelines, temperature lapse rate is substantially lower for tree stems (-0.41°C/100 m) than for air (> 0.54°C/100 m). It means that, along an elevation gradient, stems cool much slowly than the air does, which explains the substantial gain in stem girth contrasted with the little increase in height and resulting in the stunted nature of trees in treelines (Figure 6.2).

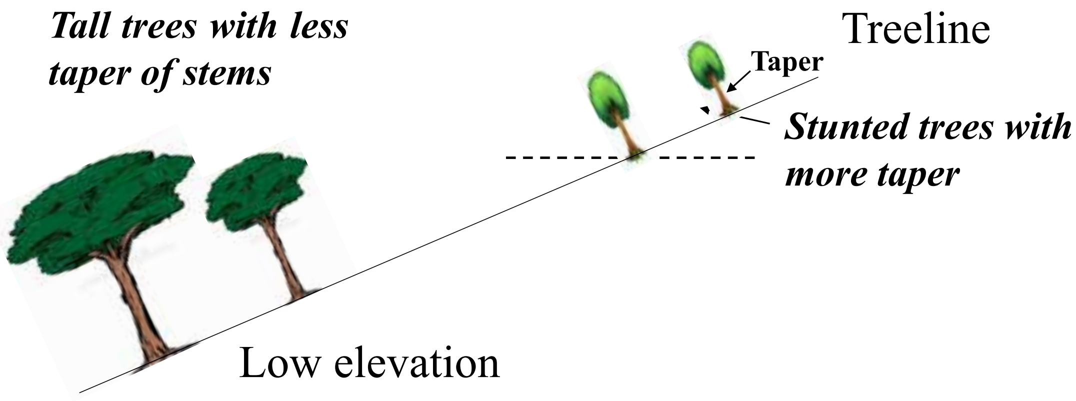


Figure 6.2: Stunting of trees at higher elevations is common. Here, stems are thicker in relation to height.

There is hardly any root growth when the soil temperature is below 5°C. A convex ground is warmer, enabling a tree to produce more roots. In contrast, in cold treeline ecotones, where tree canopies are close, rooting zones get covered and shaded, resulting in poor root growth.

The spring development of plants is controlled first by chilling, second by photoperiod, and third by low temperature.

WOOD PROPERTIES

It seems that generally treeline species have intermediate level of tree density. In the Indian Himalaya, treeline wood density (based on 12 species) ranges from 480 kg/m^3 (in *Abies spectabilis* and *Pinus wallichiana*) to 870 kg/m^3 in *Quercus semecarpifolia*. Apart from *Q. semecarpifolia,* high wood density is found in *Juniperus wallichiana* (820 kg/m^3), and *Betula utilis* (705 kg/m^3) and *Pinus gerardiana* (729 kg/m^3). Species with heavier wood are likely to survive more than species with lighter wood in treelines as the sites are windy and in stressful environments survival rather than rapid growth is a suitable adaptation.

Width of conduits (tracheids and vessels) influences water conductivity, while their wall thickness affects mechanical strength and wood density. Though water is generally not a limiting factor, cavitation because of cold conditions can be quite common. This leads to embolism or blockage (breakage of water columns due to the entry of bubbles as a result of the freezing and thawing of the xylem sap) within the conduits. Tracheids, which are generally narrower than vessels, are more resistant to cavitation. This is why the proportion of conifers (which have only tracheids) in Himalayan treelines is vastly greater the proportion of angiosperm trees, which have vessels (~50% in Himalayan treelines and 1.7% at the global level). The lumen of tracheids in the crippled trees of treelines is relatively narrow. Surprisingly, the species which form the highest treelines – *Juniperus tibetica* (4900 masl) and *Polylepis tarapacana* (4800 masl) – were found to have no change in tracheid diameter (Körner 2010). It seems that short tree stature and wood density are not correlated, but there is not enough data to generalize.

LEAF FORM AND SIZE IN TREELINES

In Himalayan treelines, leaves vary widely: junipers have scale leaves, firs and pines have needle leaves, the birch is a broad-leaved deciduous species, and rhododendrons and *Q. semecarpifolia* are broadleaved evergreen species. Larch (*Larix*) is a deciduous conifer. The leaf size at the Tungnath treeline, Uttarakhand, India varies from 0.29 cm (*Abies spectabilis*) to 55.37 cm (*R. campanulatum*).

The growing period length at the treeline, which varies from about 90 days to the whole year, and other climatic conditions influence leaf formation. Since the growing period shortens with increase in elevation, leaf size should decrease with elevation. Cold temperature can directly limit leaf size. However, large leaves with a large boundary layer (still air around the leaf surface) are warmer than small leaves, particularly near the ground surface. The largest leaves at Tungnath are of *R. campanulatum*, which has a short stature (generally <4 m height) and bent stems.

In broadleaf species, leaf size decreases with elevation, but in conifers the decline is indistinct and difficult to estimate as cross-sectional shape of the leaves also changes with elevation. With increase in elevation, apart from leaf area, petiole length also decreases, and internodes become shorter resulting in a dense packing of leaves. The number of leaves per unit length of twigs increases with elevation. Leaves become thicker resulting in higher specific leaf mass (SLMW) or lower specific leaf area (SLA). In Mt. Emie (29°N China), the average SLA (specific leaf area, which is the opposite of specific leaf mass) of broadleaved sclerophyllous species (88 species) declined from 133 cm^2g at 600 masl to 76 cm^2g at 2500 masl (Shi et al. 2008).

When the growing season is short (<135 days), spells of inclement weather may not allow new leaves to mature sufficiently, resulting in a thin cuticle, and hence more water loss (Körner et al. 1988). But leaf life span in conifers may not change with elevation.

There is a direct correlation between leaf size and the rate of leaf expansion regardless of elevation (Figure 6.3). This relationship is surprising as leaves vary so much in specific leaf mass, time period of the leaf expansion, and their protective structures.

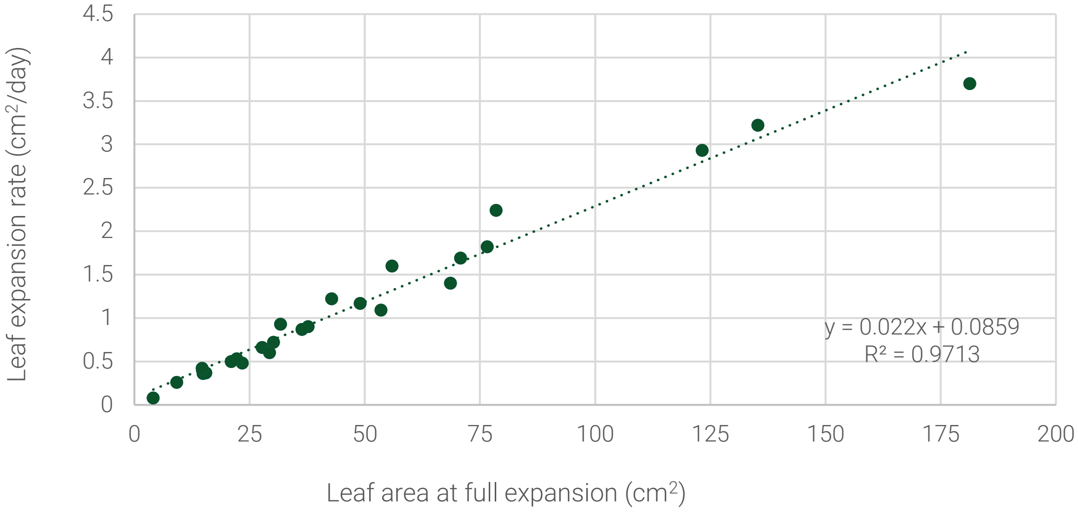
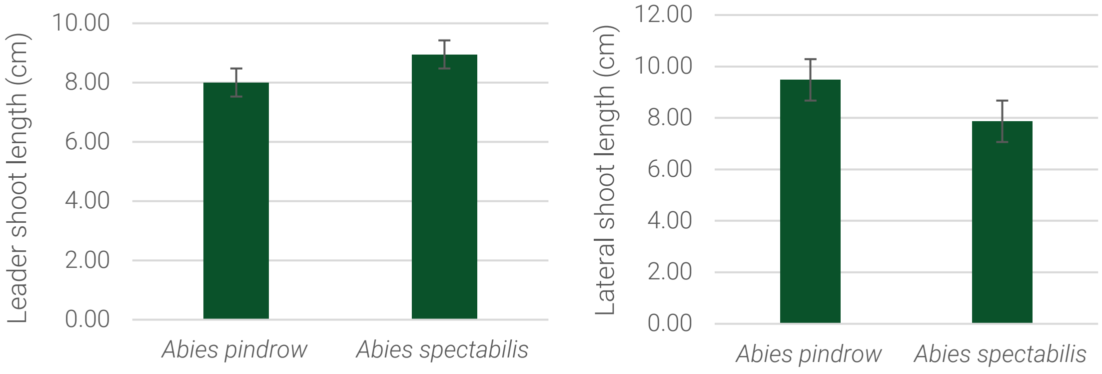


Figure 6.3: Correlation between leaf area at full expansion (cm^2) and leaf expansion rate (cm^2/day) based on data of temporal Himalayan tree species. The common species were ***Quercus semecarpifolia, Rhododendron arboreum, R. campanulatum, Q. floribunda, Q. leucotrichophora*** and ***Shorea robusta***.

Despite a short growth period at the Tungnath treeline site (Uttarakhand), the start of leaf expansion varies considerably between tree species. In *Abies spectabilis,* leaf growth started in the first week of May when the weekly mean temperature was 5.27°C, while in *R. campanulatum* it occurred in early June when the temperature was 10.99°C.

A COMPARISON OF TWO WESTERN HIMALAYAN FIRS TO INDICATE THE EFFECT OF ELEVATION

In the western Himalaya, *A. pindrow* and *A. spectabilis* often occur together in treelines, with the latter invariably occurring above the former. A comparative study of these two species was made at the Tungnath site to examine the adaptation of leaves and twigs of firs in relation to treeline environment. Taxonomists often find it difficult to detect differences between the two species when trees are of similar size. Detailed study and measurements by Pradeep Singh and G.C.S. Negi have recently addressed this difficulty (IHTRP). The most obvious difference between the two firs was in shoot thickness and number of leaves per shoot. Both were higher in *A. spectabilis* for both leader and lateral shoots. The number of leaves in *A. spectabilis* was roughly three times more that in *A. pindrow* (Figure 6.4). The leaves of *A. spectabilis* were comparatively shorter, but not thicker than the leaves of *A. pindrow*. In *A. pindrow,* the lateral shoots were longer than leader shoots, while in *A. spectabilis* they (lateral shoots) were shorter. The leader shoots of *A. spectabilis* were longer than those of *A. pindrow* (Figure 6.4). Leaf life span was 4 years in both, but in lateral shoots of *A. pindrow* it was close to 3 years. A higher proportional leaf drop can be seen in *A. pindrow.* However, not all leaves seem to survive up to four years, as the number of leaves per shoot declined in shoots from year 1 to 4 in *A. spectabilis,* while in *A. pindrow* the leaf drop began from year three and, in the fourth year, only about one-fourth of leaves were left on old shoots (Figure 6.4).



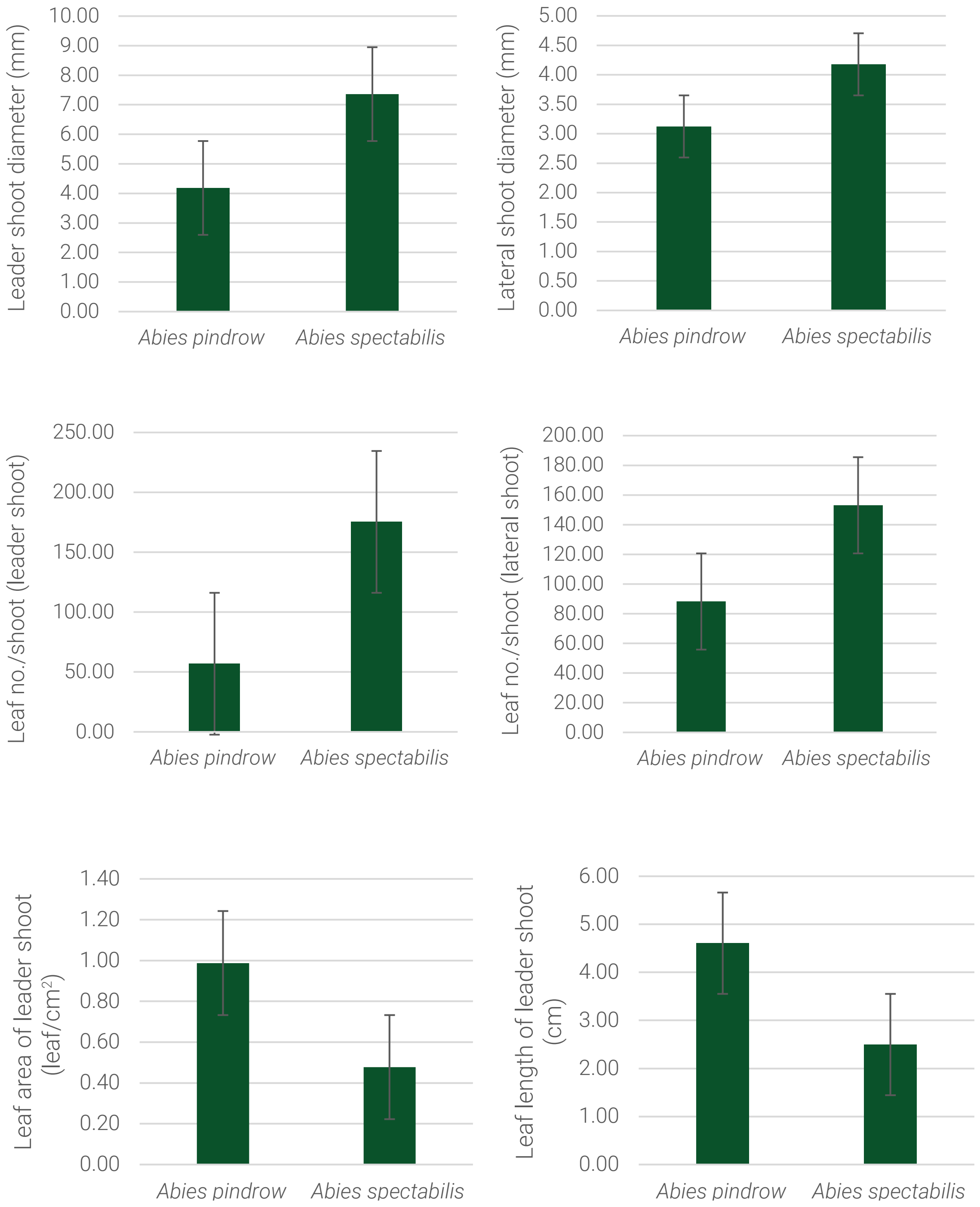


Figure 6.4: A comparison between leader and lateral shoot length, leader and lateral shoot diameter, number of leaves per shoot on leader and lateral shoots, and leaf area of leader and lateral shoots of *A. pindrow* and *A. spectabilis*

Source: Pradeep Singh and GCS Negi, unpublished

COLD HARDINESS

Our understanding of the cold hardiness of Himalayan trees is largely based on Sakai and Malla (1981). Cold hardiness of Himalayan tree species (based on hardiness of leaves, buds, stem, xylem and cortex) on average (-24.8°) is markedly lower than for treeline tree species of temperate zone mountains in the Northern Hemisphere (-53°, Figure 6.5; see Holtmeier 2009).

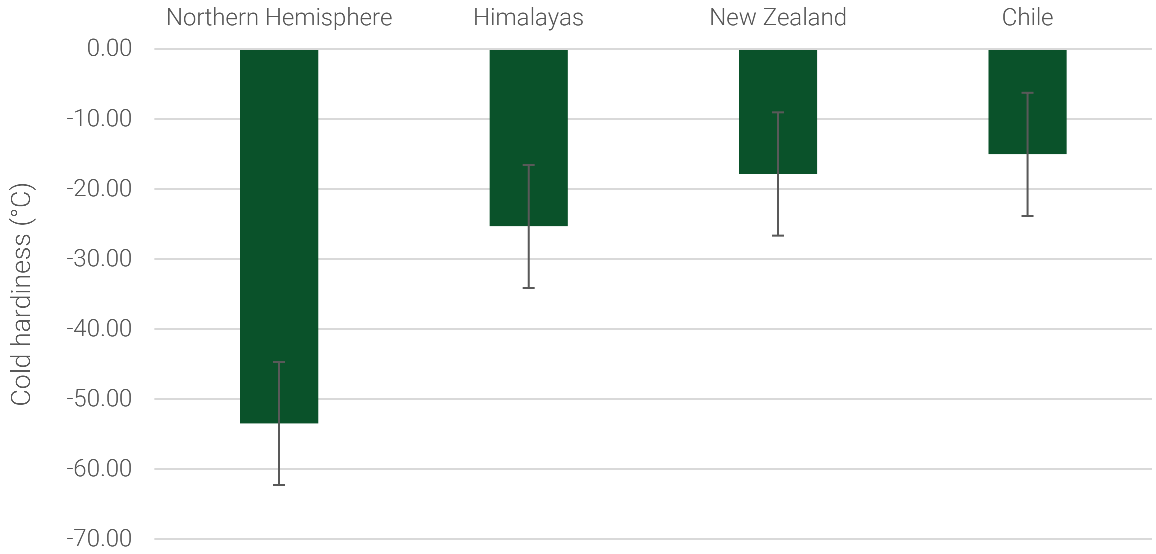


Figure 6.5: Average cold hardiness of different zones (derived from Sakai and Malla 1981; Holtmeier 2009).

Source: Pradeep Singh and GCS Negi, unpublished

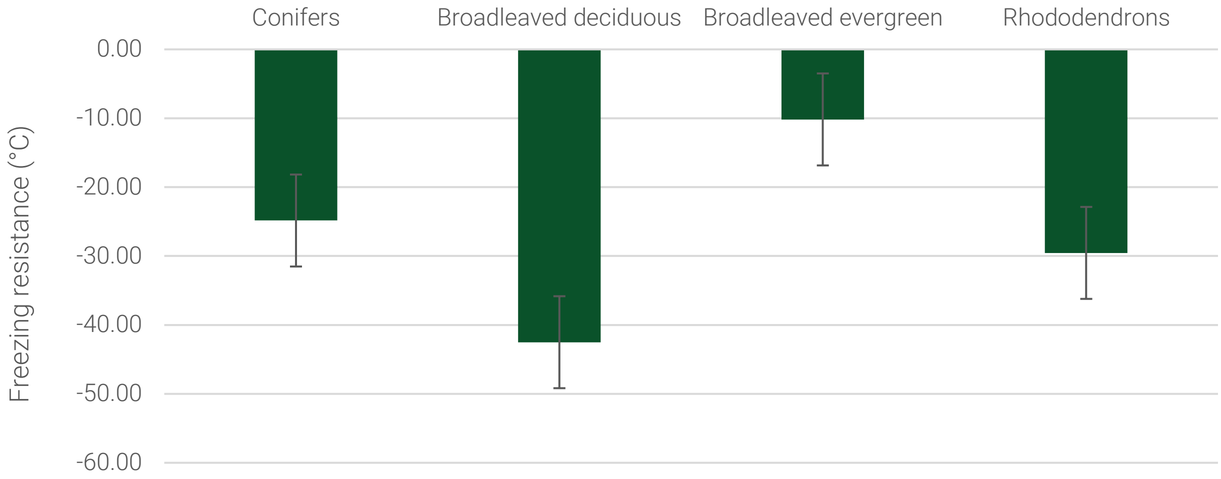


Figure 6.6: A comparison of freezing resistance of trees of different forest types in the Himalaya (based on Sakai and Malla 1981). The conifers included ***Abies spectabilis, Tsuga dumosa, Pinus wallichiana, Juniperus recurva*** and ***Cedrus deodara***; ***Betula utilis*** represents broadleaved deciduous trees; ***Quercus semecarpifolia***, ***Q. lanuginosa, and Q. lamellosa*** make up the broadleaved evergreen category; and rhododendrons include ***Rhododendron arboreum, R. barbatum, R. arboreum subsp. cinnamomeum, R. campylocarpum, R. hodgsonii, R. campanulatum, R. lepidotum, R. anthopogon,*** and ***R. setosum.***

Winters are milder in the Himalaya (sunny and fairly long days) than in mountains of temperate latitudes. In this respect, the Himalayan trees are closer to those of the Southern Hemisphere (Figure 6.5). Sakai and Malla (1981) are of the view that the Himalaya, particularly the eastern Himalaya, has oceanic climate (mild temperatures with less seasonal extremes) despite being continental in location.

Within the Himalaya the temperature that the tree species can tolerate becomes increasingly colder with increasing elevation. For example, it is between -5° and -15° in evergreen oaks (*Quercus lanuginosa*, *Q. lamellosa* and *Q. semecarpifolia*) generally occurring below 3000 masl, between -18° and -30° for conifers (*Abies spectabilis*, *Pinus wallichiana*, *Tsuga dumosa*, *Cedrus deodara*, *Juniperus recurva*) growing between 2800 and 3800 masl, and -40° and -50° for deciduous species *Betula utilis* (bhojpatra/birch) occurring from 3200 to 4200 masl (Figure 6.6). It may be pointed that freezing is not necessary for the formation of a treeline. The cold hardiness is relatively more for small tree species/shrub-like species of rhododendrons (-29.51°), like *R. campanulatum* than for tall canopy species. Among small trees/shrubs, plants such as *Salix* spp. are more cold hardy. In canopy tree species, cold hardiness is markedly more in cortex and xylem than in buds and leaves. However, in rhododendrons it does not vary much from one organ or tissue to another (Figure 6.6).

How could the information on tree cold hardiness contribute to understanding treeline dynamics under the influence of climatic warming in the Himalaya? As data from the Nepal Himalaya indicates, at the treelines mean minimum temperature of the coldest month is between -6.1° and -11.3° and the extreme minimum between -15.6° and -17.9°. Nevertheless, it seems that extreme treeline temperatures in the Himalaya are warmer than the cold resistance of treeline trees of the region (Table 6.1). The western Himalaya is expected to be relatively colder. As our study (IHTRP, Sah and Sharma 2018) indicates, treelines in many areas of the Himalaya are stationary/arrested, so their environment is getting warmer. In a stationary and warmer treeline, the species with warmer temperature requirements like *Rhododendron* spp. may densify, and species of lower elevation like evergreen oaks, burans (*R. arboreum*) and maples may arrive, thus making the Himalayan treelines crowded with species.

Table 6.1: Treeline response to climate change depends on the combined effects of various spatial (space) and temporal (time) scales (derived from Holtmeier and Broll 2020).

Global/zonal scale	Regional scale	Landscape and smaller scales
Temperature – elevation dependent warming Precipitation CO_2 fertilization and pollution	Regional climate Mass Elevation Effect (MEE) Exposure to wind Temperature Lapse Rate -°C decrease per 100 cm elevation increase (e.g., 0.53°/100 m rise in elevation for Tungnath, Himalaya) Treeline orientation	Landform, topography Microclimate Snow deposition – depth and duration Landslides, avalanches (sliding snow) Disease and pathogens Wild animals and livestock (pastoralism) Fires Ecological succession Tourism

In a nutshell, stunting of trees (a thicker stem) for a given height is a characteristic feature of treelines. Stem diameter is less sensitive to cold temperature than tree height. Other changes in treeline areas include crowding of leaves on twigs and, in general, wood density above a threshold. Winters in the Himalaya are relatively mild, despite the continental locationof these mountains. That is why the Himalayan tree species are relatively less cold hardy, and in this respect they are closer to the species of the Southern Hemisphere.

(a) (b)

(c)

(d)

(e)

Table 6.7: Leaves of some important timberline tree species: (a) ***Abies pindrow;*** (b) ***A. spectabilis***; (c) ***Rhododendron arboreum***; (d) ***R. campanulatum;*** and (e) ***Betula utilis***

Photos: Pradeep Singh and Surabhi Gumber, IHTRP

CHAPTER 7

Temperature lapse rate in the Himalaya

– Rajesh Joshi and Ninchhen Dolma Tamang

The near surface temperature decreases with elevation as atmospheric pressure decreases and air expands, drawing heat from the air. That is why higher elevation areas are cooler than lower areas. This rate of decline in temperature with elevation is called temperature lapse rate (TLR) and is a controlling factor in many environmental and ecological processes, such as change in moisture regimes, climate-vegetation interaction, glacier mass, glacier melt, and runoff. TLR to an extent, determines the elevation at which a treeline is formed. So it is important to estimate TLR while studying treelines.

Climate change can substantially influence TLR, particularly because of elevation dependent warming (EDW), which implies that the rate of warming is amplified with elevation and high mountain areas experience more rapid temporal changes in temperature than environments at lower elevations. Because of this, a cool site at a high elevation is predicted to warm more than a warm site at a lower elevation, resulting in a relatively lower temperature difference between them or a lower TLR. Now we are learning that TLR varies a lot across seasons within a year, and TLR values are different for the maximum and minimum temperatures. Since meteorological stations are sparse in treeline areas of the Himalaya, there are limited observed data-based TLR estimates. For the Indian Himalaya, the study of Tungnath (IHTRP, Joshi et al. 2018) is possibly the first one based on properly designed observed data along an elevational transect (Box 7.1).

BOX 7.1

Outline of the field data measurements (based on Tungnath site)

To estimate the TLR 10 portable V2 micro-bloggers and 6 tipping bucket rain gauges (8" dia.) were installed along an elevational transect from 1500 to 3680 masl at two different aspects (N-W and S-E) (see Joshi et al. 2018). The temperature loggers were covered with radiation shields to protect the sensors from direct incoming shortwave radiation on exposed sunlight. On the N-W slope, a more advanced Automatic Weather Station was installed at an altitude of 3360 masl (see figure 7.1) which consisted of a Campbell

SR50A sonic ranging sensor, an ARG-100 tipping bucket (rain gauge) with a simple event data logger, and a temperature probe, and the other sensors for measurement of temperature, soil moisture, wind speed and direction, and net radiation. Station data from all the sensors installed at different locations were recorded at 15 minute intervals and the data collected over a three-year (from 2017 to 2020) period.

Figure 7.1: (a) Location map of the installed loggers within the study area; (b) Automatic Weather Station installed at a high altitude site (3360 masl; 30°29.57`N, 79°12.95`E), Tungnath, Uttarakhand, India.

The annual mean Temperature Lapse Rate (TLRmean) is between -0.50 and -0.53 °C/100 m elevational rise in the eastern and central Himalaya (which included Arunachal Pradesh, Sikkim and Uttarakhand of India, and Bhutan), -0.57°C/100 m in the western Himalaya, and -0.73°C in the cold desert of Ladakh (Figure 7.1(a)). To an extent this is why treelines are relatively lower in the western than in the eastern Himalayan region.

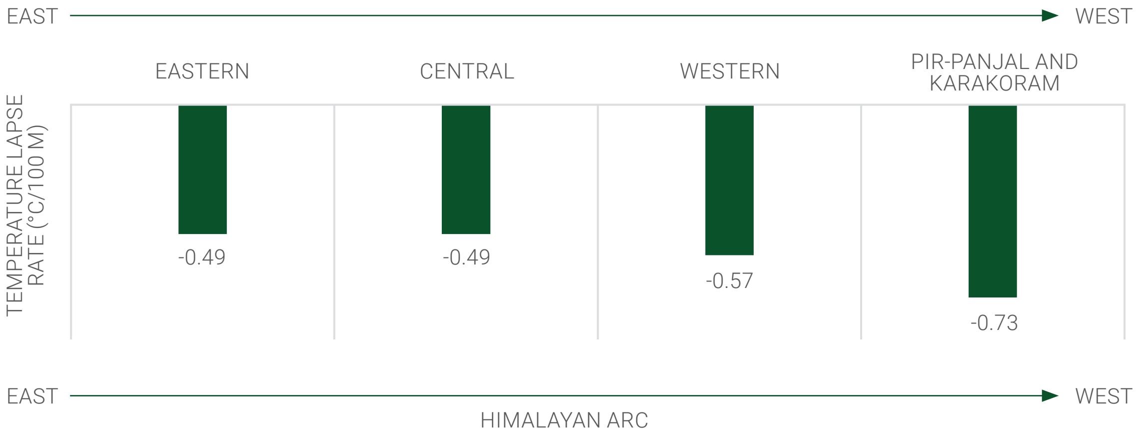


Figure 7.1a: Change in annual mean TLR from East to West along the Himalayan Arc

TLR roughly follows similar seasonal pattern for maximum and minimum temperatures; however they differ in finer details as indicated below for Tungnath, Uttarakhand (India) and Langtang, central Nepal (Kattel et al. 2013) (Figure 7.1(b) and Table 7.1).

Generally, the lowest TLRmean in the Himalaya is in winter or monsoon. The winter TLRmean is unusually low (-0.20°C/100 m) in Langtang, Nepal and Daksum-Sinthan, Kashmir (-0.31°C/100 m). The low winter TLRmean may be because elevation dependent warming is more during winter months (Figure 7.2(a) and (b)). It may also be related to winter air pollution at lower elevation which results in a cooling effect.

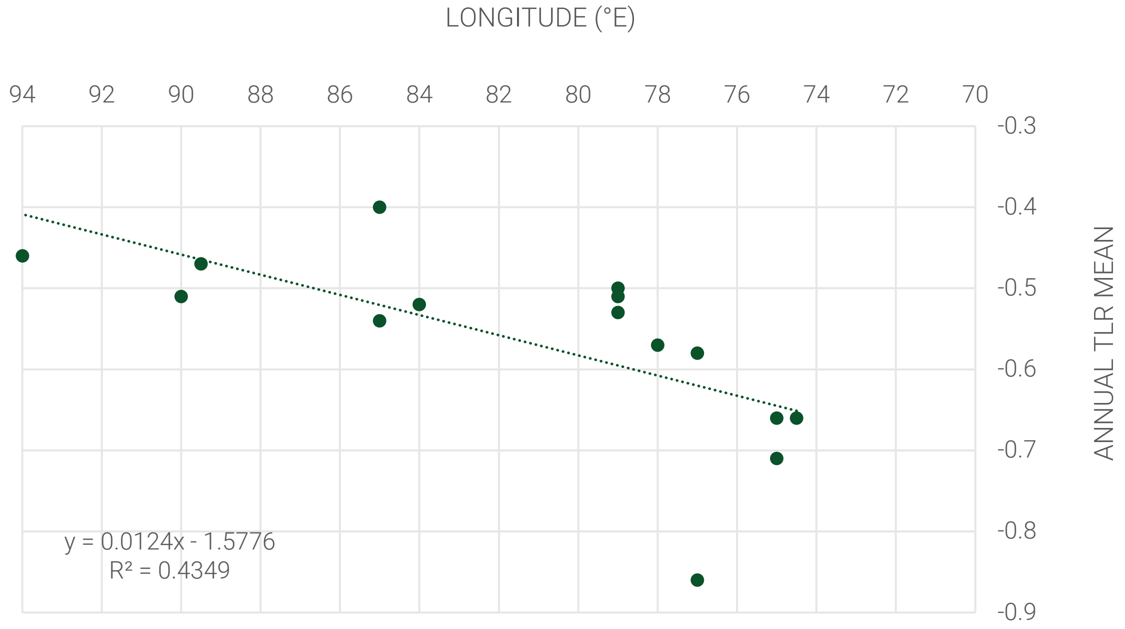


Figure 7.1b: Temperature Lapse Rate (TLR) increases (becomes more negative) along the Himalayan Arc, from east to west with increasing aridity, being extraordinarily high (negative) at Ganglas catchment site, Ladakh

Sources: Ashraf 2020; Bandyopadhyay et al. 2014; Dorji et al. 2016; Hayat et al. 2019; Henyen et al. 2016; IHTP Report 2020; Immerzeel et al. 2014; Joshi et al. 2018; Joshi R. 2020; Kattel et al. 2013; Kattel et al. 2018; Pratap et al. 2013; Thayyen and Dimri 2014; Thayyen and Dimri 2016; Romshoo et al. 2018.

Between maximum and minimum temperatures, the TLRmax is higher. It might be partly because of the greater time warming in higher ranges. The greater night time warming in higher elevations decreases TLRmin.

At both sites TLRmax and TLRmin were low during winter and monsoon seasons and high during pre-monsoon season. The difference between TLRmax and TLRmin varied with season and site. In winter, the difference was low at Tungnath and high at Langtang, during pre-monsoon it was high at both sites, and during monsoon it was negligible at Langtang and moderate at Tungnath. The subsequent seasonal change was similar at the two sites, after each season. They plateaued during the monsoon, but while TLRmax and TLRmin were similar at Langtang, they showed moderate difference at Tungnath.

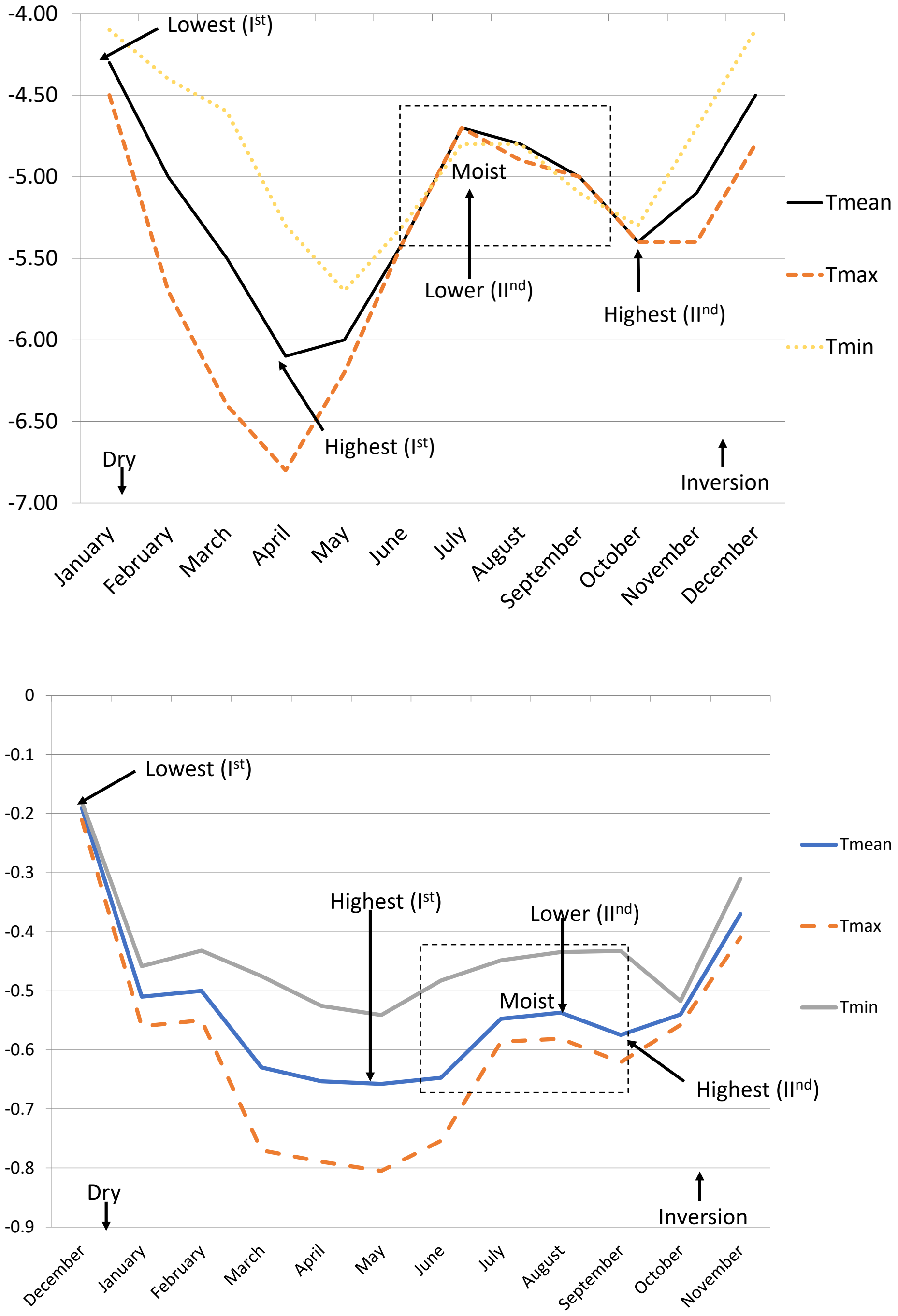


Figure 7.2: (a) Annual cycle of maximum, minimum, and mean TLR values for central Nepal Himalaya, and (b) Chopta-Tungnath transect, Uttarakhand, Western Himalaya.

Source: (a) Kattel et al. 2013 (b) IHTRP, Joshi et al. 2018

TLRmax was either markedly higher than TLRmin or similar. Low TLRmin might be because of more elevation dependent warming (EDW) in the night (minimum) under the influence of climate change.

Relatively low winter (December, January, and February) TLR must be seen in view of the fact that winters in Himalaya are already mild. If the trend persists, evergreen broad leaved forests are likely to increase in dominance. In contrast, the higher TLR during pre-monsoon season (April, May, and June) than mean annual TLR, indicates that treelines are relatively cooler during summers.

Table 7.1: A comparison between the seasonal patterns of maximum and minimum temperatures for Tungnath, Uttarakhand (India) and Langtang, Central Nepal.

Seasons	TLR		Difference between TLR_{max} and TLR_{min}		Subsequent seasonal change in TLR	
	Tungnath	Langtang	Tungnath	Langtang	Tungnath	Langtang
Winter (December, January, February)	Low	Low	Low	High	Sharp rise	Sharp rise
Pre-monsoon (April, May, June)	High	High	High	High	Moderate difference	Moderate decrease
Monsoon (July, August, September)	Low	Low	Intermediate	Negligible	Plateau	Plateau

Low and almost invariant TLR during monsoon months suggests the occurrence of stable and favourable (moist and warm) conditions over an extended period, which might have contributed to the occurrence of relatively longer growing season in the Himalayan treelines (up to 200 days). TLR fluctuates widely on a daily basis too (Figure 7.2), particularly during the pre-monsoon period. The monsoon period was relatively stable even on a daily basis. So, for plant growth, the pre-monsoon is a period of uncertainty, and the monsoon a period of stability.

In a nutshell, across much of the Himalaya under the influence of the monsoon, TLRmin is low at around -0.5°C/100 m elevation; however, in arid regions it sharply increases (more negative) and generally exceeds -0.6°C/100 m elevation. TLR fluctuates seasonally and on daily basis (Figure 7.2) indicating highly turbulent condition along an elevation gradient. This atmospheric turbulence might have increased because of global climate change. TLR is useful to understand treeline/timberline formation and dynamics. There is a need to investigate the effect of seasonal differences in TLR on vegetation distribution and plant and ecosystem processes. Elevation dependent warming is likely to further increase under the influence of global climate change, which may threaten the survival of species growing close to mountain summits. In fact, it could drastically alter the composition of alpine ecosystems, particularly the carbon dynamics and carbon stock.

CHAPTER 8

Timberline elevation, length, and upward shift in response to climate change

– Priyanka Sah, and Avantika Latwal

Are treelines/timberlines moving up in mountains in response to climatic warming? This question has generated considerable interest among researchers and is considered a major indicator of climate change impacts in the mountains. A global analysis shows that about 50% of the treelines have not shown upslope advancement (Harsch et al. 2009). Most studies on treeline shifts in mountains are based on one or two sites. In IHTRP, possibly for the first time, a regional-level analysis (of the Himalaya) was made using remote sensing technology (FTR-IHTRP, 2021 by Subrat Sharma and his associates).

TIMBERLINE ELEVATIONS

Here we focus on treeline elevations and changes in them, measured using remote sensing and dendrochronogical methods. The major revelation of our study is that treelines in the Himalaya are huge, running thousands of kilometres across the region (FTR-IHTRP, 2021 by Subrat Sharma and his associates).

In a given region, timberline elevation varies considerably because of several factors in addition to temperature. The proportional altitudinal distribution of timberlines by elevational bands of 200 m (e.g., 3400-3600 masl and 3600-3800 masl, FTR-IHTRP, 2021 by Dr. Subrat Sharma and his associates) shows a unimodal curve along the elevational gradient, with peaks getting increasingly higher eastwards.

In other words, as we move eastward, a greater percentage of timberlines occur in higher elevation bands. The percentage of total timberline length peaks at 3200-3400 masl in Kashmir, 3400-3600 masl in Himachal and Uttarakhand, and 3800-4000 masl in Arunachal Pradesh (FTR-IHTRP, 2021 by Dr. Subrat Sharma and his associates). Increase in elevation from the west to east has also been noted at species level (for birch and fir) in Nepal.

This pattern confirms that timberline elevation increases with decreasing latitude. The treeline altitude changes at the rate of 130 m/degree of latitude over the subtropical-temperate transition (Körner 1990). The western Himalaya have much larger and thicker snow cover than the eastern Himalaya, which reduces the timberline growing season, resulting in the occurrence of timberline at relatively lower elevation in Kashmir and other similar regions in the western Himalaya.

In the north facing slopes in the western Himalaya and much of Nepal, *Rhododendron campanulatum* gets to the highest elevation followed by *Betula utilis* and *Abies spectabilis*. Where *Sorbus microphylla* occurs, it is present next to *R. campanulatum.*

A depressed treeline occurs at an elevation lower than a climatic treeline, i.e., the treeline elevation determined by temperature. It could be because of drought and aridity, grazing, and the lack of space for species to move up. A treeline that is unable to shift upward in spite of decades of warming is a kind of arrested treeline. In that situation trees may become large, and form dense forest stands, which in turn may render soils cool.

HOW MUCH PRECIPITATION IS NEEDED?

Generally, water stress is not among the likely factors controlling treeline elevation (Körner 2012). At treelines, however, water stress may constrain tree growth periodically as anywhere else. It may cause seedling mortality in certain habitats of treelines as it does in lower areas. It should be remembered that the highest treelines are located in relatively dry regions, like Tibet and Bolivia, where annual precipitation ranges from 200-300 mm. In the inner valleys of the Himalaya, near the main ranges, trees form higher treelines than in the outer ranges that are moist and often cold (Figure 8.1 Singh SP and Singh RD, unpublished).

Timberline elevations are distinctly higher in dry inner ranges and along the main Himalayan ranges than in the outermost ranges (Figure 8.1). Apart from dry conditions, mass effect of high mountains on temperature accounts for this elevation difference in the timberline. Between the moist north aspect and dry south aspect, timberlines are higher on the latter because of warmer conditions.

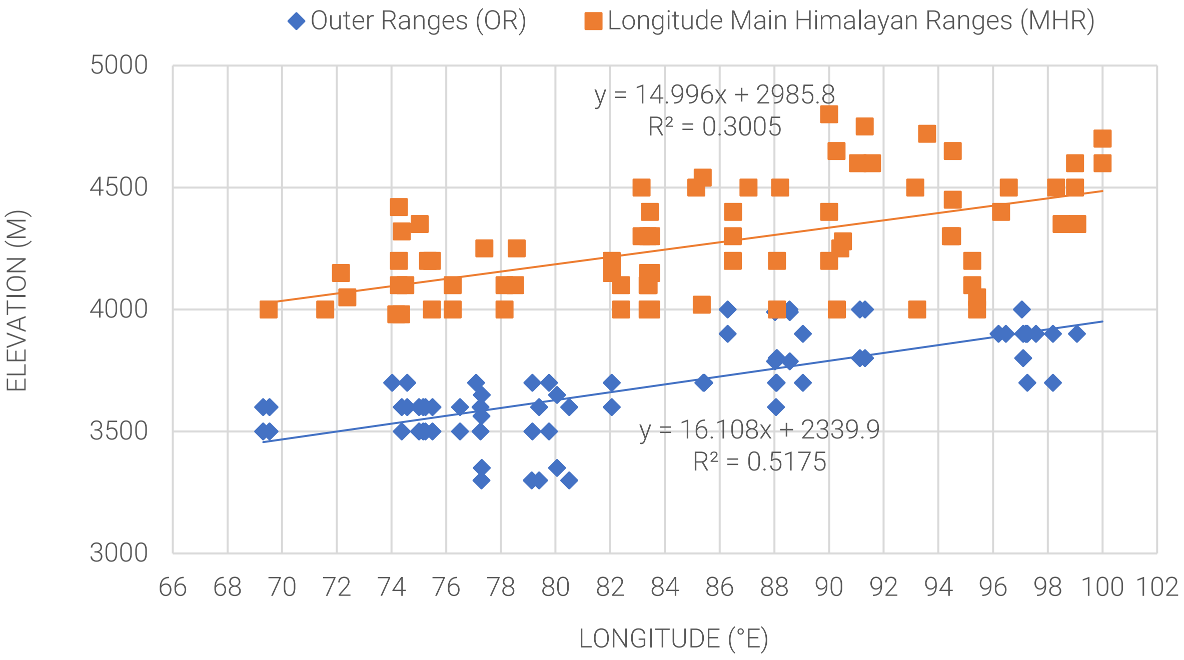


Figure 8.1: Relationship of altitudinal position of timberline of sample sites of Outer Ranges (OR, n=73) and Main Himalayan Ranges (MHR, n=80) (in each case n is number of sample sites) in relation to longitude along the Himalayan Arc (they were significantly positively correlated, r=0.54; p≤0.05 for OR, and r=0.72; p≤0.05 for MHR).

LENGTH OF TIMBERLINES

Timberlines are highly zigzag in distribution covering a length of over 8-10 km per km in horizontal length. It seems that along the 2500 km long Himalayan Arc, timberlines stretch roughly 20,000 km. In Sikkim, the elevation of the timberline ranges from 2620 to 4390 masl, of which 60% is between 3400 and 4000 masl, 27.4% is below 3,400 masl, and 12.8% is above 4,000 masl (Sah et al. 2021, in press). About half of the timberline length in Sikkim occurs at a relatively moderate slope (20-35°). Though timberlines look continuous from a distance, they are broken into segments because of landslides, rocks, and other topographic barriers. In Sikkim, the timberline was shown to have 534 segments, with 37.6% less than 500 m and only 6.4% or 34 segments more than 5 km long (Sah et al. 2021, in press). Between the timberlines and permanent snowlines there occur several broad biotic belts consisting of alpine meadow, and subnival and nival plants. All these are under the impact of global climate change. By advancing upward, timberlines are expected to deplete communities of short statured plants like forbs, grasses, mosses, and lichens. Because of increasing snow melt, the areas under subnival and nival communities have already expanded in the Himalaya. Changes in these remote mountains under the influence of climate change is worth monitoring using remote sensing techniques.

BOX 8.1

Analysing treeline shift, and tree-ring-growth and climate relationship

Because of the favourable conditions resulting from climate warming, forest boundaries at high elevations are moving upslope. The following methods are used to measure treeline or species shifts: dendrochronogical, diameter measurement based method, repeat transect sampling, and remote sensing and photography (Hansson et al. 2020). Because trees of treelines vary in their response to climate change, they are useful proxy climatic sources (Fritts 1976).

DENDROCHRONOLOGY

In year-to-year variations of tree ring width, lies the story of climatic variations. Dendrochronology is based on the principle that trees form annual growth rings which can be counted to determine the ages of individual trees. The differences in ring width are responses to year-to-year variations in climate. Studies which use tree rings to estimate age of individual trees are considered dendrochronological. Dendroclimatological studies, on the other hand, pertain to reconstructing past climate by checking the response of trees to climate variables (Gaire et al., unpublished). Dendrochronological studies are most common among treeline studies. For example, in Nepal they account for about half of the treeline studies (Gaire et al., unpublished).

The population structure of trees in a treeline ecotone is determined by counting tree rings. Generally, a belt transect of 20-30 m width and a length that covers the entire ecotone (100-300 m) is used to survey the population. If tree ring data indicates that trees are getting progressively younger towards higher elevation, it can be assumed that treeline is expanding upwards. By recording the year in which a tree was established, it is possible to calculate the rate at which the treeline is moving upwards. We can also estimate treeline recession (decline in treeline elevation) by noting the presence of older tree trunks above the present day treeline (Saezer et al. 2014). Treeline recession would indicate that climate is likely to become less favourable.

The tree-ring width and climate relationship of past (upto several thousands of years) would indicate how a given species responds to adverse or favourable conditions, and the data could be used to predict future changes. The method is quite effective but is limited by some factors. For example, in certain hardwood species, such as Himalayan oaks, getting wood cores from trees is very difficult. Now electric drills are being used in place of manual turning of the cores (Sleer Kamp et al. 1999). In several species annual ring formation is unclear. In some species false rings are frequently formed, and in some annual rings are not formed or are missing in some years. Not all species are good for cross dating. In the Himalaya, *Cedrus deodara* (deodar) is an appropriate species as tree ring responses across the individual trees are fairly uniform. In other words, tree ring width is narrow or wide across all trees in a given year.

TREE DIAMETER MEASUREMENTS

Although less commonly used than the above method, it works well for species in which significant correlation between stem diameter and age is established. Among the Himalayan species, this method has worked well for *Betula* (Shrestha et al. 2007) and *Rhododendron* (Prabivirana et al. 2017). Tree growth decreases with elevation, therefore correlation between diameter and age varies rapidly, particularly in species which get stunted towards the treeline. Therefore, this method does not work in such a situation.

REPEAT TRANSECT

Treeline movements have been investigated through repeat vegetation surveys along elevation transects, particularly in the Swedish Scandes (Kullman 2000, 2002, 2003, 2007; Oberg and Kullman 2012). Since treeline changes are very slow, past studies with which comparison is to be made should have been conducted hundreds of years before (Hansson et al. 2020). When we take a long elevation gradient, and consider different groups of organisms, there are more chances of detecting changes. In the Himalaya, such studies are absent. Through the IHTRP we conducted a thorough transect study, establishing species distribution data for several plant groups. We need to store this data properly so that changes could be detected accurately in repeat sampling efforts into the future.

REMOTE SENSING AND REPEAT PHOTOGRAPHY

Because of the remoteness of treelines and the fact that documenting treeline migration is a time-consuming work, remote sensing methods are now being increasingly applied in treeline studies. Repeat aerial photographs have been particularly useful for areas with old photographs. Remote sensing methods can quickly detect treeline changes over a large area. However, in remote sensing the present spatial resolutions of images are high (0.5-4 m), but past images are generally coarser (30-60 m), so one has to depend on coarser images for making comparisons.

COMPARISONS OF METHODS

Dendrochronological method: This method has several advantages. It is a simple and proven technique, is the only method which establishes relationship between treeline shift and climate change, does not require historical data, and can indicate year of tree establishment, and year when shift of treeline started. However, it is labour intensive and cannot be applied to all tree species. Tree rings in many species are not clearly formed, or they may be missing. Also, the method requires physical access to the study site of study, and provides information only for a small area, such as a treeline site or mountain slope (Table 8.1).

Repeat transect: Repeat transect can give an idea of change in species composition over time and, if done frequently, can indicate future trends based on regeneration data. However, this method works only when historic and quality data are available and physical access to a study site is possible. It is a time consuming method. (Table 8.1)

Remote sensing and photography: This effectively tracks changes over large scales. Data collection and processing are quick, and access to a local study site is not required. However, remote sensing and photography require the support of historic data, and shadows and time of day can make it difficult to interpret images. Satellite images of high resolution (≤ 6 m) improve timberline data by about 10% over the medium spatial resolution (25-30 m), but past data based on high resolution are seldom available and are more likely to be affected by clouds (Sah et al. 2021, in press). In the IHTRP study, the remote sensing methods gave an estimate of changes in treeline elevation at a regional scale, covering hundreds and thousands of kilometres.

Table 8.1: A comparison of three important methods used to study treeline shift (Hansson et al. 2020).

	Dendrochronology	Repeat transect	Repeat remote sensing and photography
Spatial scale	Small	Small	Large, of regional scale
Requirement to visit study site	Yes	Yes	No
Requirement of historic data	No	Yes	Yes
Provide climate correlation data	Yes	No	No
Provide data when migration started	Yes	No	No

TIMBERLINE WARMING AND ELEVATION SHIFT

Currently, in the Himalaya, treeline ecotone communities are impacted by climate change, livestock herding (sheep, goats and cattle) and wild mammals (See Box 7.1 for methods used to measure treeline shift). The two groups of animals compete with each other for resources. Tourism is gradually emerging as a new factor. Apart from damaging habitats, tourists disturb and stress wild animals by pushing them to less habitable areas.

Timberlines in general are not going up in spite of rapid climate warming in the Indian Himalaya (Table 8.2). They are stationary along 76.5% to about 95% of theirlength in the Himalayan states of India (some site based studies however indicate that treeline areas are moving up). Even some of the short timberline strips are stationary. So, they are “arrested timberline ecosystems”, and must be under stress because of the temperature rise. We guess that trees would be advancing their growing season, litter would be decomposing at a higher rate, and more seeds would be viable than before.

Will stunting of trees decrease under the warmer temperatures? Biologists need to capture the treeline pulses in several ways. Only long term studies can address these questions. The temperature driven upward march of trees could be restricted by grazing, cutting of trees for local needs or to cater to the needs of tourists, lack of enough space between timberline and mountain summits, erosion, and landslides.

Table 8.2: Changes in timberline from 1976-2015 (Sah et al. 2021, in press).

	Sikkim
Continuous timberlines	
Total timberline length (km) in 1977	707.3
Length (in percentage) that has remained stationary	76.5%
Upward shift (since 1977) over timberline length (km); height (m)	97.1 km; 100 m ± 89
Timberline downward shift	56 m ± 54
Mean upward shift	23.5%
Upward shift average of entire timberline (including stationary)	18 m

** In Sikkim, there was downward shift over about 22.3 km by 56 m height*

Recently, Latwal et al. (in press) have intensively investigated changes in timberlines of Sikkim between 1977 and 2015 (close to 4 decades) using remote sensing techniques (Box. 8.1). The study also considered a comparison between island type timberline (ITL) and continuous type timberlines (CTL). Here ITLs occurs around mountain summits in outer ranges which are directly exposed to the monsoon. It is thus more moist than the CTLs, which occur in inner ranges shielded from the monsoon (and are hence drier). ITLs are short strips, at lower elevations, hence warmer than CTLs (Table 8.3). The study found that CTLs were drier than ITLs. In both rainfall declined with elevation, but this decline was only moderate in ITL and sharp in CTL. Consequently, high CTL sites were very dry.

Both stationary state and increase in elevation under the climate change effect were observed. Among CTL sites where timberline shifted upward, temperatures were already warmer than the sites where treelines were stationary (0.93°C vs 0.89°C), and they showed higher average temperature rise from 1977 to 2015 (0.93°C) than stationary sites (0.89°C). The CTL sites showing upward treeline shift were also more moist with annual rainfall between 597-1790 mm in 2015, compared to 651-1203 mm at stationary sites.

Compared to CTL sites, the ITL sites showed more increase in temperature and precipitation (Table 8.4). The upslope shift of treelines is related to several factors, including treeline form. Globally, about 80% of diffuse treelines are moving up, compared to 22% of abrupt treelines.

In brief, sites showing upward shift in timberlines warmed up more than the sites which did not and they were also more moist. So more warming is required for upward movement of timberlines and it should be accompanied by increase in precipitation.

Table 8.3: Summary of Sikkim study of timberline (Latwal et al., in press) based on comparisons between 1977 and 2015, island type and continuous timberline (CTL)

	ITL	CTL	Remarks
Elevation range across sites	Narrow (500 m), lower in elevation (up to 3300 masl)	Wide (1800 m), higher in elevation (up to 4400 masl)	ITLs are around summits; CTLs are along permanent snowlines
Data points at 30 m intervals			
- In year 2015	598	21,903	-
- In 1977	660	21,042	-
Mean annual temperature (range) across sites	12.7°C-14.9°C (average=13.8±0.7)	2.3°C-14.7°C (average=8.6±3)	For the same elevation ITL is 3.3-4.5°C warmer than CTL
Change in rainfall with elevation	Moderate decline	Sharp decline	-
Rainfall range	2099-2396 mm (2253±90 mm)	500-2378 (1397±451 mm)	-
On average	-	-	ITL gets 438-655 mm more rainfall than CTL
Mean temperature warming between 1977-2015	0.21°C/decade	0.23°C/decade	-
Average increase in rainfall between 1977-2015 (37 years)	187 mm/decade	93 mm/decade	For the same elevation, average rainfall in 37 years increased by 529 mm at ITL sites (compared to CTL sites)

Table 8.4: A summary of the differences between Island Timberlines (ITL) and Continuous Timberlines (CTL) (Sah et al. 2018; Sah et al., in press; Latwal et al., in press) are listed below:

ITL	CTL
Short, isolated, in outer ranges	Long, with fragments of up to 5 km, and more in inner/main ranges
Lower in elevations	Higher in elevations
Moist with moderate decline in rainfall with elevation of timberline Warming at a relatively higher rate	Dry with steep decline in rainfall with elevation of timberline Warming at a lower rate
More responsive to climate warming in terms of upward movement of timberline	Less responsive to climate warming in terms of upward movement of timberline
More livestock, grazing, and tourism	Less grazing and tourism
Lower in elevation	Higher in elevation

ASSESSMENT OF UPWARD TREELINE SHIFT BASED ON CLIMATE AND TREE RING GROWTH RELATIONSHIP

We analysed 30 studies on dendrochronology of treeline species in the Himalaya in recent years to assess climate and tree growth relationship in the upward of treelines. In 15 of them, tree ring growth was found to be negatively correlated with pre-monsoon temperature and positively correlated with pre-monsoon rainfall. The 15 studies were generally on tree ring growth of *A. spectabilis*, and *B. utilis*. Some prominent sites are Gangotri in India, and Annapurna Conservation Area, Langtang National Park, Sagarmatha National Park, and Rara National Park in Nepal. Generally, pre-monsoon (March-May) is a warm and dry period of the year. However, occasional rains (about 10-20 cm) are common and they contribute significantly to tree growth. When rains are excessive, temperatures in pre-monsoon period may become too low to be favourable for tree growth. The positive relationship between pre-monsoon precipitation and tree ring growth and negative correlation with high temperature suggests that pre-monsoon drought is an important limiting factor in treelines. Climate change is thus likely to adversely affect tree ring growth by intensifying pre-monsoon drought, particularly when snowfall declines. Snowmelt water keeps soil moist when trees begin growth, but is not always enough to sustain growth during the entire pre-monsoon period. In a treeline, leaf development is not completed during pre-monsoon period, so any abiotic stress during that period can suppress growth. In fact leaf area, leaf mass and nitrogen mass all reach their peak during August and September and incompletely developed leaves remain vulnerable to abiotic stress during the pre-monsoon period. In the temperate forest belt, tree leaf expansion ends by June, just before the arrival of the monsoon.

Apart from increasing tree ring growth, climate change accounts for upslope movement of treelines. In the Himalaya, the upward shift of treelines has been investigated in 34 studies, based on tree ring growth analysis and remote sensing techniques. In about 70% of the cases, the upward shift ranged for a few metres to 30 m/decade (Figure 8.2). However, in several studies the upward species shift is because of decrease in land use intensity or abandonment of annual grazing. The conclusion from these studies runs contrary to the analysis of the IHTRP study, which indicates that across over 80% of their length treelines have not moved up in recent decades. It is difficult to reconcile these conflicting inferences. While dendrochronological studies span centuries, the remote sensing based IHTRP studies dealt with only three to four decades.

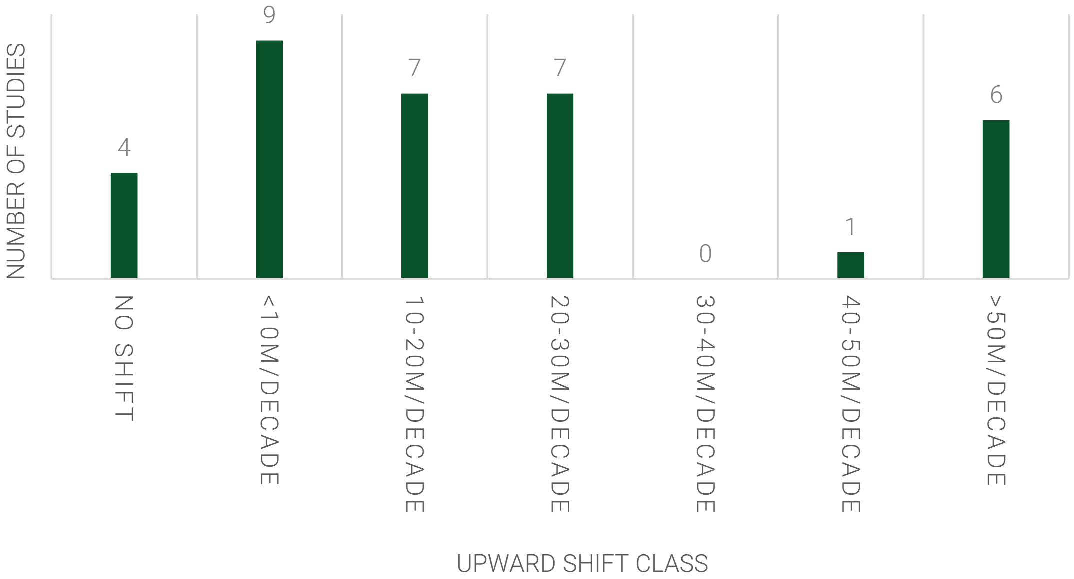


Figure 8.2: Treelines have moved upward in recent decades due to climate warming. The upward shift of treelines varies widely, but a majority of them are 30 m or less (based on several studies carried out in India, Nepal, China and other Himalayan countries). Most studies are based on *Abies spectabilis* and *Betula utilis*.

In a nutshell, in the Himalaya, two types of timberlines are distinguishable: (i) those which are located in outer ranges around mountain summits (ITL) and (ii) those occurring in inner ranges (CTL) (Sah et al. 2018). Compared to the former, the latter are much longer and appear at much higher altitudes. Additionally:

- ITL sites are warmer and also more likely to face a greater increase in temperature (for a given elevation) than CTL sites. They are hence more responsive to climate change in terms of upward shift of species.
- An upward shift is related to temperature. We have observed that sites showing upward shifts were already warmer and showed a greater increase in temperature than sites not showing an upward timberline shift.
- In Sikkim, rainfall has generally increased between 1977 and 2015. However, the increase in rainfall is much higher in ITLs than in CTLs. Eventually, this will result in a greater difference in tree species composition between the two timberline types.

CHAPTER 9

Tree water relations in the treeline

– Ashish Tewari, Shruti Shah, Nandan Singh, Krishna Kumar Tamta, and Amit Mittal

Throughout the world treelines are not associated with water stress, as evapotranspiration losses are low at low temperatures (Körner 2012). That is why not many treelines have been studied for tree water relations. Contrary to this, several studies that have examined the relationship between tree ring growth and climate indicate that treelines can be adversely affected by drought (Gaire et al. 2014). In the Himalaya, and across much of the rest of the Indian subcontinent, the pre-monsoon period (March to June) is particularly dry and warm, and may adversely affect tree growth (Singh et al. 2006). Our study (IHTRP, Tewari et al. 2018) is the first on tree water relations in Himalayan treelines. The study was largely conducted at Tungnath site, Uttarakhand which is located in the outer Himalayan ranges and is directly exposed to the monsoon. However, we also collected data on the trees of an inner, drier valley in Himachal Pradesh. To characterize treeline species (TLS) we compared them with lower elevation species (LES) studied earlier (Tewari 1998; IHTRP, Tewari et al. 2018).

ARE HIMALAYAN TREELINES WATER STRESSED?

The lethal level of water stress varies widely across trees. For example, the tree water potential which induces 50% mortality is -1.75 and -1.45 MPa for poplars and beech, respectively (Barigah et al. 2013). In the Himalaya, tilonj oak trees (*Quercus floribunda*) stopped producing leaves at -5 MPa water potential during the 1999 drought (Singh et al. 2000). At Tungnath, severe water stress was not encountered by any treeline species (TLS), as across all seasons of the study years the Ψpd (water potential measured at predawn) of trees was never below -1.0 MPa. The minimum values of Ψpd for all species were observed during the summer season (pre-monsoon, May-June). This is consistent with the generally held view that Ψ in treeline species in different parts of the world does not reach critically low levels as to affect normal plant functions during the growing season (Anfodillo et al. 1998; Körner 2012). For example, in a treeline in the NE Italian Alps, predawn tree water potential ranged from -0.29 to -1.0 MPa, and between -0.45 to -1.49 MPa at mid-day (for *Pinus cembra*, *Picea abies,* and *Larix decidua*) (Anfodillo et al. 1998). We compared TLS species and lower elevation species (LES) to analyse the water stress condition (Figure 9.1 and 9.2). LES species included most of the dominant species occurring from 300 to 2200 masl. The average values of all study species indicate that both the lowest and highest predawn water potential were higher (less negative) for TLS than LES. Likewise, the mid-day water potential was less negative for TLS than for LES (Figure 9.1). Increased evapotranspiration rates with rising global temperature and uncertainty associated with precipitation, earlier snow melt, and more rain than snow may combine to intensify drought in a warming climate, and hence the water stress in treelines.

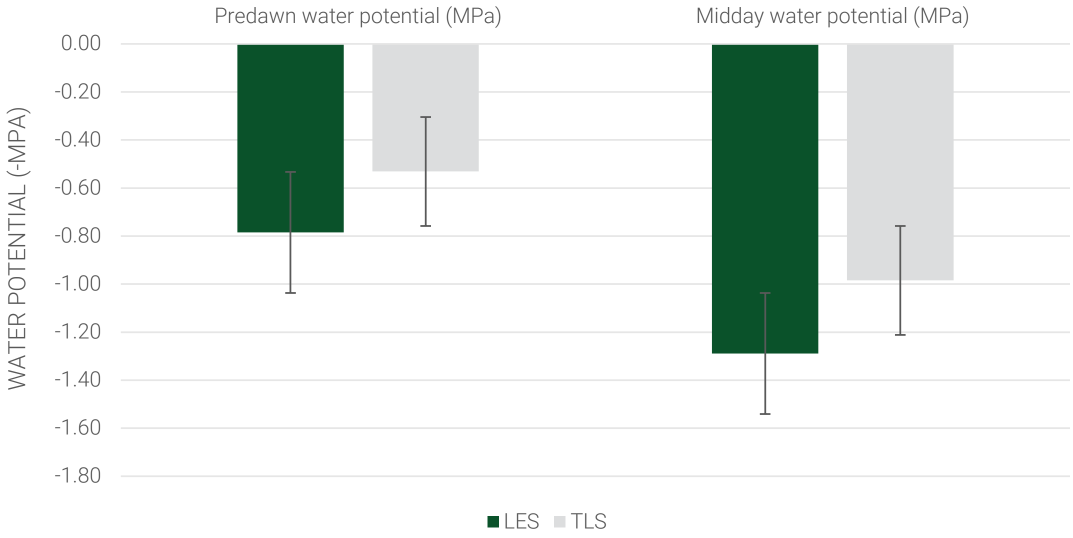


Figure 9.1: A comparison between average tree water potential of lower elevation species (LES) and timberline species (TLS). The LES (occurring from 300 to 2200 masl) species were ***Shorea robusta, Pinus roxburghii, Quercus leucotrichophora, Rhododendron arboreum, Q. floribunda, Carpinus viminea, Machilus duthei, Fraxinus micrantha, Cupressus torulosa, Q. lanata***, and ***Cornus macrophylla***, and the TLS (Tungnath, Uttarakhand >3000 masl) specieswere ***Q. semecarpifolia, Abies spectabilis, R. campanulatum*** and ***Betula utilis***. Averages are values for all seasons and all sites.

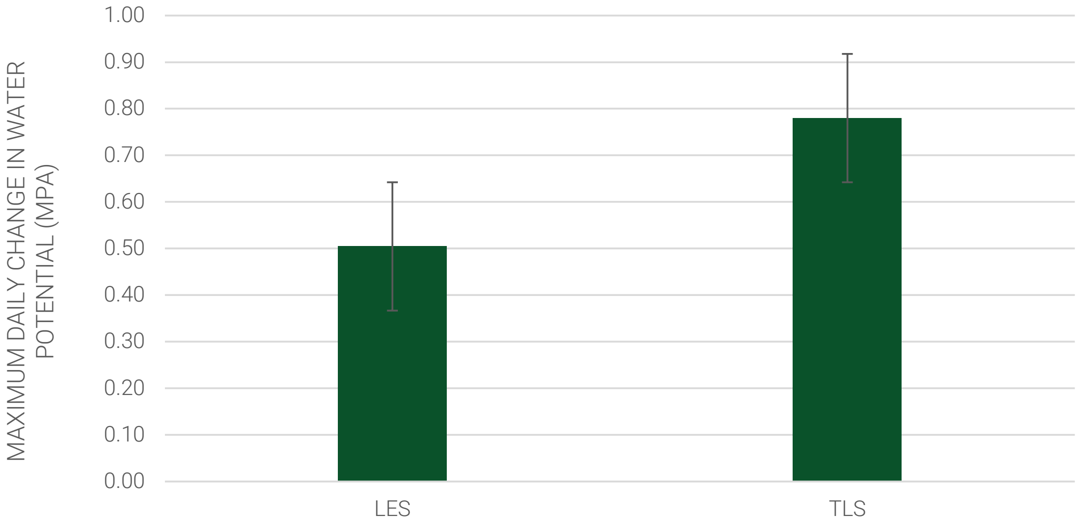


Figure 9.2: A comparison between low elevation species (LES) and timberline species (TLS) in the maximum seasonal daily change in tree water potential (difference between predawn and mid-day on a given day ;for species see explanation of Figure 11.1). The LES value is of pre-monsoon and TLS of monsoon period.

At this stage, however, at the treeline the melting snow seems to keep the soil water potential higher than the threshold required for the commencement of phenological activities during summer. All the treeline species substantially decreased their osmotic potential (Box 9.1, Table 9.1) from winter through late spring, which coincided with the onset of phenological activities. By lowering water potential, trees are able to access soil water, as water moves from higher potential to lower potential. Thus, in all the tree species at Tungnath, treeline water potential did not reach lethal levels so as to curtail phenological and physiological activities (Box 9.1). The snowmelt water during pre-monsoon has a key role in keeping the soil moist (Table 9.1).

BOX 9.1

Water potential and osmotic adjustment

Water potential, generally indicated by the Greek letter Ψ, is a measure of the free energy of water of plants or soil in comparison with free energy of pure and free water. The energy that is available to do work in a system is called free energy. Water potential is generally measured in a pressure unit, megapascal (1MPa= 10 bars). Movement of water into and through a plant occurs from higher to lower water potential, for example from - 0.7 MPa to - 1.6 MPa. In simple terms, the more negative the value of water potential the higher is the water stress in plants. One of the common mechanisms that plants employ to derive water from soil is to decrease the plant water potential below soil water potential through osmotic adjustment.

Osmotic adjustment is an effective adaptation that trees employ to overcome drought, as it can contribute in the maintenance of turgor during periods of drought and therefore enhance the chances of competing with other species in treeline areas (Badalotti et al. 2000; Tewari et al. 2018). Osmotic potential can be lowered both passively by concentrating the existing tissue solutes via dehydration and by actually increasing the amount of solute in cells (Tyree and Jarvis 1982; Teskey and Hinkley 1986). It involves uptake, internal production, or transfer of osmotically active substances such as inorganic ions (K, Mg, Cl, Ca, NO_3), sugars and amino acids (such as proline). Generally osmotic adjustment is calculated as the decline in osmotic potential over the drought period (difference between the value at the beginning of drought and peak of drought).

In broad terms, the relationship between predawn tree water potential and daily change in water potential was similar among the TLS species at Tungnath – decline in daily change in water potential with decreasing water potential or increasing water stress. The decline was continuous from rainy season to summer, with intermediate values in spring, autumn, and winter. There was a striking similarity among TLS species in several other features as well. For example, the highest predawn water potential across the species occurred within a narrow range, -0.16 and -0.5 MPa; likewise, the lowest water potential did not differ much, and ranged between -0.70 and -0.99 MPa (Table 9.1).

The afternoon leaf conductance in each TLS species was higher than in the morning, which is contrary to that of LES species. It shows that in TLS, the low morning temperature was a limiting factor, and afternoon tree water potential was high enough to sustain a high rate of leaf conductance. Predawn water potential values of trees at Chitkul site (drier inner ranges) were relatively lower, falling below -1 MPa, particularly in seedlings. It ranged between -0.94±0.05 MPa and -1.1±0.02 MPa for trees and between -0.80±0.04 MPa and -1.4±0.01 MPa for seedlings. These values indicate that both trees and seedlings at this inner Himalayan site were at least moderately stressed. Water stress in dry inner valleys is a common feature, and a factor in suppressing the upward movement of species.

Table 9.1: Summary of tree water relations of treeline species (TLS) at the Tungnath site (Uttarakhand).

Species	Water potential		Full turgor osmotic adjustment (MPa)	Max. daily change (MPa)	Leaf conductance (mmol m^{-2} sec^{-1})
	Predawn water potential (MPa)	Mid-day water potential (MPa)			
Quercus semecarpifolia	0.25-0.99	1.02-1.37	0.76	0.81 MPa (spring)	204-268.6
Abies spectabilis	0.16-0.89	0.99-1.24	0.82	0.82 MPa (rainy)	175.9-243.5 (summer)
Rhododendron campanulatum	0.22-0.80	0.99-1.50	Low	0.77 MPa (rainy)	247.5-268 (rainy)
Betula utilis	0.18-0.76	6.63-1.06	0.57	0.72 MPa (rainy)	319.6-314.8 (rainy)

CONTRASTING SEASONAL PATTERN OF THE RELATIONSHIP BETWEEN PREDAWN AND DAILY CHANGE IN WATER POTENTIAL

The TLS (Tungnath site) and LES provide contrasting pictures (Figure 9.3 and 9.4) with regard to the relationship between predawn tree water potential and daily change in water potential (the difference between predawn water potential, the highest water potential of day and mid-day water potential, the lowest water potential of the day). As expected, the predawn water potential was the highest during the rainy season (particularly July-August) both in TLS and LES. While in LES the highest daily change in water potential was observed during pre-monsoon (i.e. summer, May-June), when predawn water potential values were the lowest or close to that, in TLS the highest daily change in water potential occurred during the monsoon (July, August, September) when soil potential was the highest (Figure 9.3). Interestingly, the monsoon was the time when daily change in water potential of LES was the minimum (Figure 9.2). This difference is partly related to leaf phenology. In the TLS species, leaves attained full expansion and full leaf mass only in rainy season, so the physiological activities during pre-monsoon were still low. On the other hand, in the LES species, leaves were fully expanded and mature during pre-monsoon, resulting in the high water loss through transpiration and hence a high daily change in water potential (Figure 9.2). But what stops LES species from keeping stomata open and maintaining high leaf conductance during monsoon period, and why does this not apply to TLS species? TLS trees occur in an open habitat with intermittent exposure to sun during rainy season. In LES, eight out of the 10 lowest daily change values across all species were during the rainy season, when the predawn water potential was mostly greater than -0.5 MPa. In them the highest daily change (~0.8 MPa) occurred during pre-monsoon months (Figure 9.3), when predawn water potential ranged from -0.8 to -1.2 MPa (Figure 9.2). The monsoon predawn water potential was high in TLS species too (greater than -0.3 MPa), but during that period daily change was also high hovering around 0.7 to 0.8 MPa (Figure 9.3).

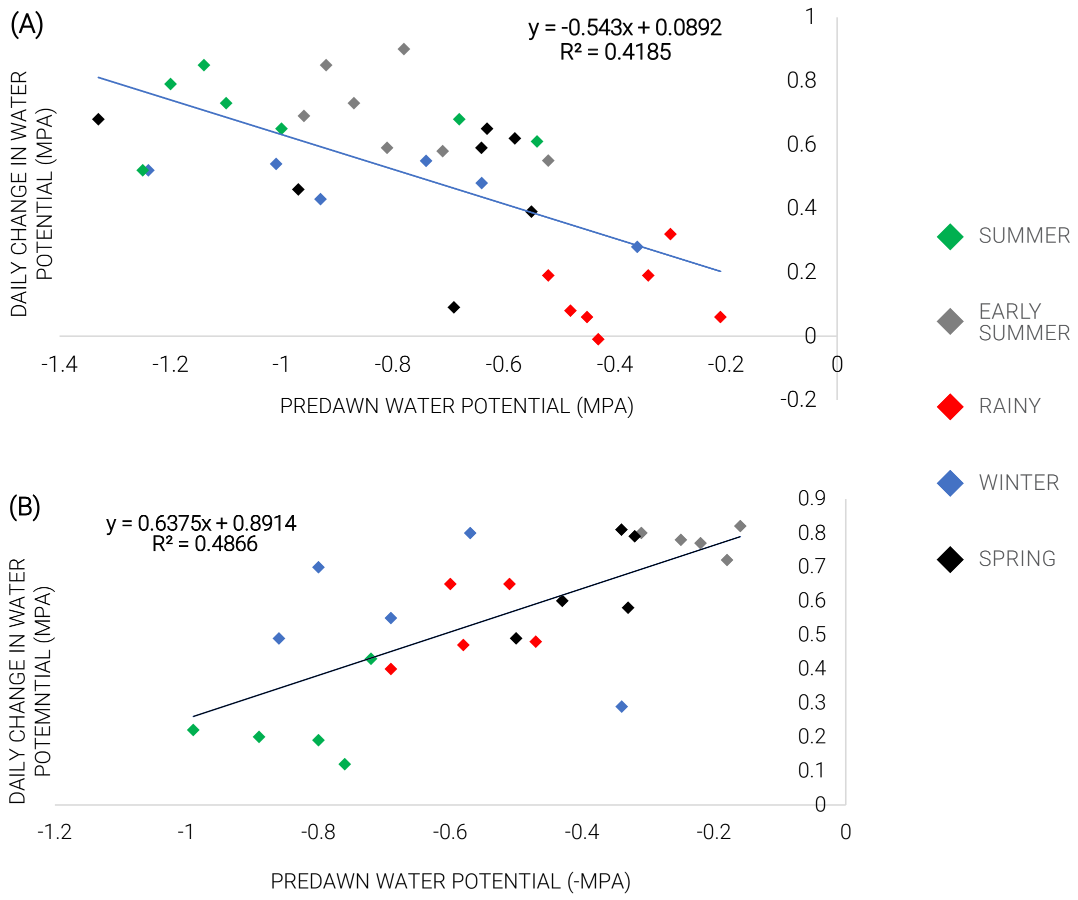


Figure 9.3: Seasonal pattern in the relationship between predawn water potential (-MPa) and daily change in water potential (MPa) in tree species (A) of lower elevation (LES) (***Shorea robusta, Pinus roxburghii, Quercus leucotrichophora, Rhododendron arboreum, Q. floribunda, Carpinus viminea, Machilus duthei, Fraxinus micrantha, Cupressus torulosa, Q. lanata;*** and ***Cornus macrophylla***), and (B) of treeline species (TLS) (***Quercus semecarpifolia, Abies spectabilis, Rhododendron campanulatum***, ***R. arboreum,*** and ***Betula utilis***).

WATER RELATIONS AT CHITKUL, A DRY INNER VALLEY SITE

We collected data on certain parameters of water relations at a representative site of the inner Himalayan valley (Chitkul, Himachal Pradesh) where birch, fir (A. spectabilis) and rhododendron (*R. campanulatum*) were common treeline species. The data were collected during the transition period between monsoon and autumn (September) and summer (May). The striking feature was extraordinarily high leaf water conductance values in the morning hours in September, which surprisingly was more for seedlings than adult trees (Figures 9.4a and 9.4b).

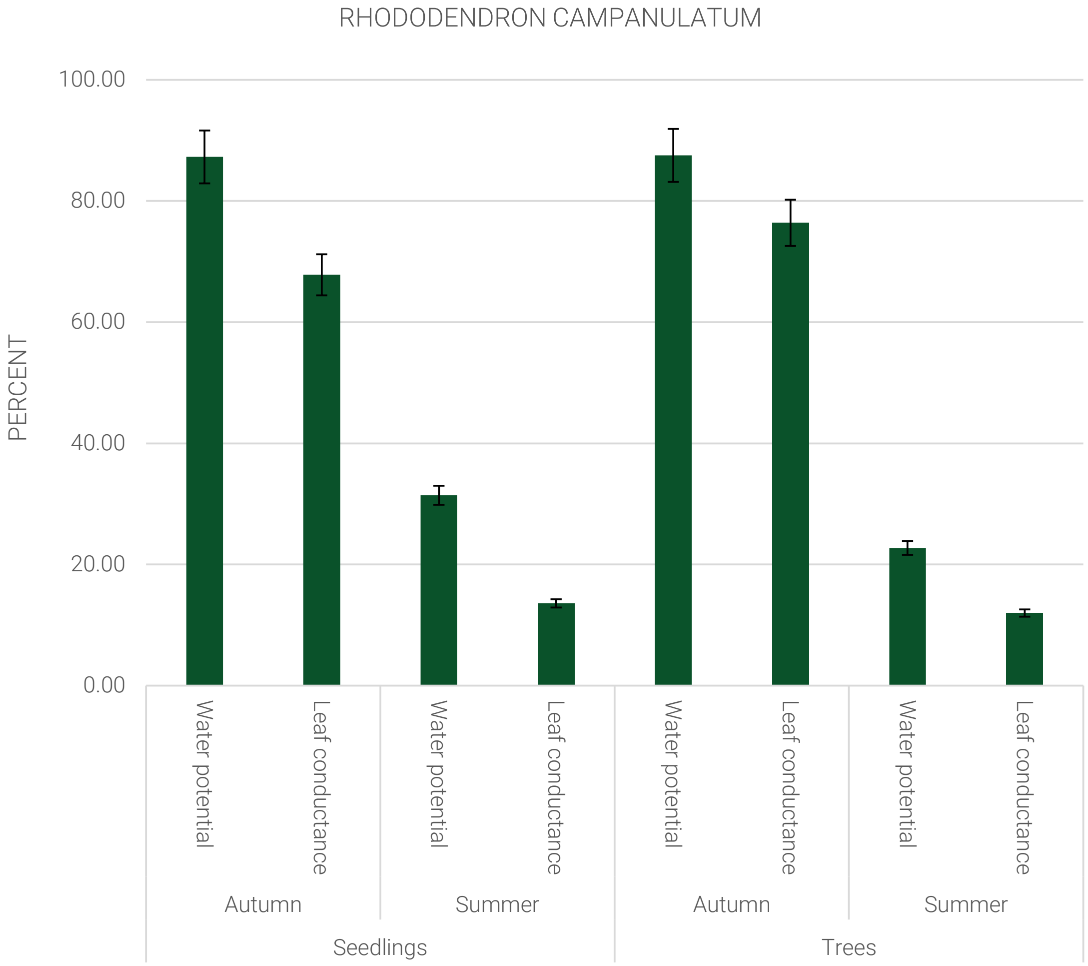


Figure 9.4a: The extent of drop in water potential and leaf conductance of trees and seedlings of ***Rhododendron campanulatum*** in autumn (September) and summer(May). Values of water potential and leaf conductance were as given in Table 9.2.

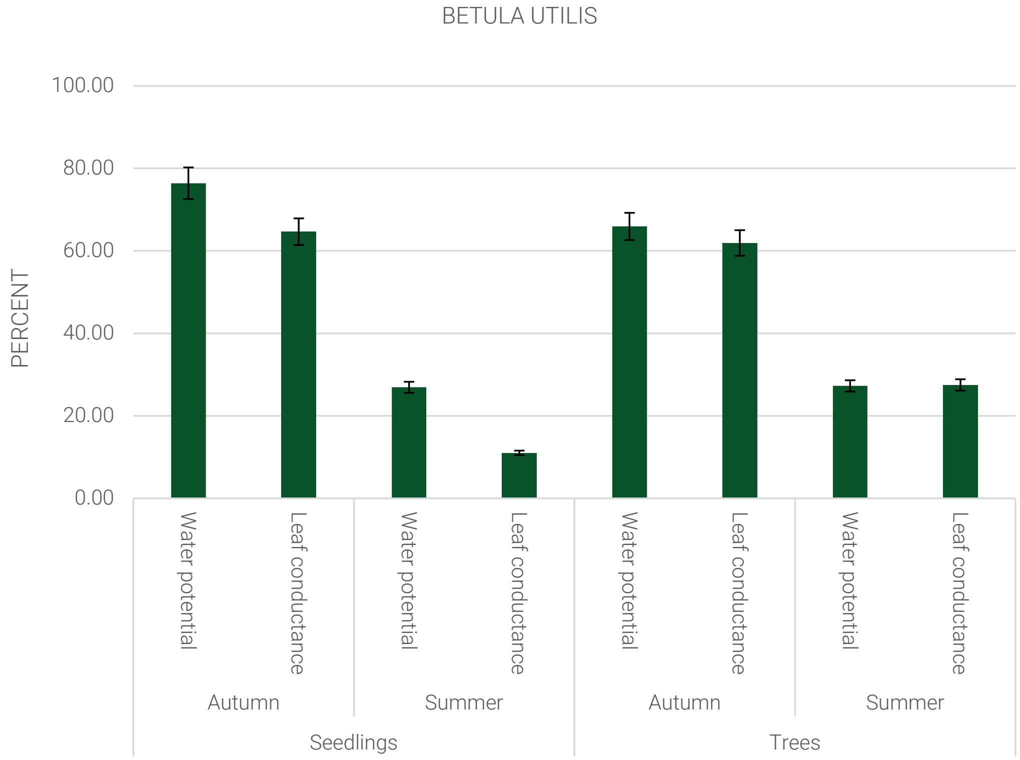


Figure 9.4b: The extent of drop in water potential and leaf conductance of trees and seedlings of ***Betula utilis*** in autumn (September) and summer(May). Values of water potential and leaf conductance were as given in Table 9.2.

During the three study years, the tree leaf conductance in the morning hours ranged between 502.6 and 783.8 mmol m^{-2} sec^{-1} for rhododendron and between 321.2 and 667.0 mmol m^{-2} sec^{-1} for birch. For seedlings, the values were between 577.4 and 1147.7 mmol m^{-2} sec^{-1} for rhododendron and 591.8 and 1323.3 mmol m^{-2} sec^{-1} for birch (Figure 9.5).

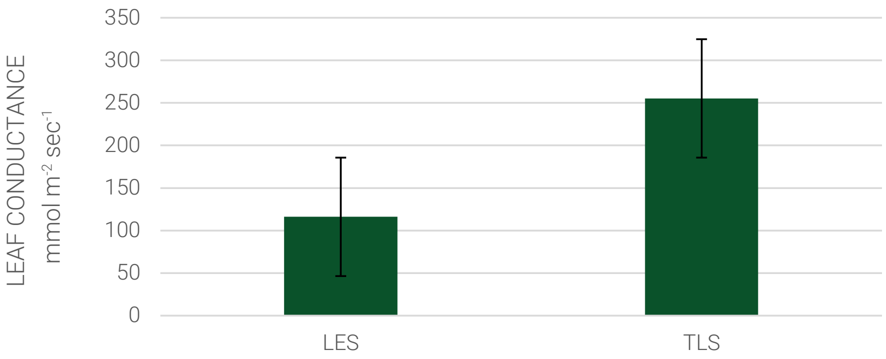


Figure 9.5: A comparison between the averages of leaf conductance of lower elevation species (LES) and timberline species (TLS, Tungnath, Uttarakhand). The LES species were ***Shorea robusta, Quercus leucotrichophora, Rhododendron arboreum, Q. floribunda, Carpinus viminea, Machilus duthei, Fraxinus micrantha, Q. lanata,*** and ***Cornus macrophylla,*** and the TLS were ***Q. semecarpifolia, R. campanulatum*** and ***Betula utilis***.

What made leaves conduct so much water in a dry climate? It was high temporarily, and then dropped off rapidly to a low level in the afternoon, the percentage decline being 63.2-78.6% for rhododendron and 58.9-73.7% for birch. The drop in leaf water conductance was associated with sharp drop in tree water potential, which ranged between 85.9-88.8% in rhododendron and 54.4 and 87.5% in birch (Figure 9.5). In summer, both leaf conductance and tree water potential values were low, and so were drops in the afternoon values.

Table 9.2: Water potential and leaf conductance in tree species of Chitkul, HP (values are averages for three years; data of IHTRP, Ashish Tewari and research scholars).

Species	Growth form	Water potential (-MPa)				Leaf conductance (mmol m^{-2} sec^{-1})			
		Predawn		Mid-day		Morning		Afternoon	
		Autumn	Summer	Autumn	Summer	Autumn	Summer	Autumn	Summer
A. spectabilis	Seedling	0.28	1.40	1.11	1.90	-	-	-	-
	Tree	0.38	1.20	1.17	1.80	-	-	-	-
R. campanulatum	Seedling	0.15	0.96	1.15	1.40	772.47	87.70	228.30	75.80
	Tree	0.19	0.85	1.48	1.10	626.02	101.80	146.40	89.60
B. utilis	Seedling	0.37	1.90	1.51	2.60	839.17	162.40	274.70	144.50
	Tree	0.34	1.60	0.98	2.20	470.19	216.00	170.49	156.60

In a nutshell, our study of tree water relations in the treeline shows that the treeline species (TLS) are characterized by: predawn water potential above -1 MPa, strikingly high daily change in water potential during the monsoon months, and high leaf conductivity (all in comparison to lower elevation Himalayan species). However, even mild water stress may limit growth during summer (pre-monsoon) by restricting leaf expansion as leaves are not fully developed.

CHAPTER 10

Treeline phenology of Tungnath, Uttarakhand

– G.C.S. Negi, Pradeep Singh, and Sahil Joshi

The growth period in the treeline is generally short because of low temperatures. A tree requires a 90-95 day growth period at least, during which it can complete its growth cycle. Several phenophases and processes have to be accomplished during this growth period, e.g., emergence of new leaves, leaf expansion, leaf mass accumulation, and leaf-senescence, during which leaf nutrients are withdrawn to be used again as new leaves put forth in the following season. Flowering and fruiting are other important phenophases. Our analysis of tree phenology in this chapter is based on five species occurring in the Tungnath treeline ecotone. The study treeline species include all tree growth forms: broadleaf deciduous (*Betula utilis*), broadleaved evergreen (*Quercus semecarpifolia*, *Rhododendron arboreum* and *R. campanulatum*) and an evergreen conifer (*Abies spectabilis*) with multi-year leaves (Figure 10.1). The broadleaved evergreen group included a tall tree species (*Q. semecarpifolia*), an undercanopy small tree species (*R. arboreum*), and a krummholz (*R. campanulatum*). *A. spectabilis* is a fir species (> 30 m), comparable with the other fir (*A. pindrow*) which seems to remain below the elevations of *A. spectabilis*. The five study species differed in their elevational centres at Tungnath:

Figure 10.1: A representation of main tree growth forms in Himalayan treelines. (a) Broadleaf deciduous mature birch (***Betula utilis***) trees emerging from ***Rhododendron companulatum*** krummholz; (b) Broadleaf single-year evergreen (***Quercus semecarpifolia***); (c) Multi-year evergreen conifer (***Abies spectabilis***)

Photos: (a) Prof Zafar Reshi, Kashmir University; (b) Ms. Meenakshi Negi; (c) Dr. Pradeep Singh, IHTRP

Q. semecarpifolia, 3020 masl; *A. spectabilis*, 3133 masl; *B. utilis*, 3265 masl, and *R. campanulatum*, 3290 masl. The annual rainfall here is 2411 mm and soil moisture across the species sites is strikingly similar (mean monthly value being 20.23±1.61% - 20.48±1.93%). On average soil is about 4° cooler than the air, except during the peak of the monsoon in August when the difference narrows (Figure 10.2). To characterize the treeline phenology, we compared the observations with mid-elevation forests (1500-2200 masl) in Uttarakhand.

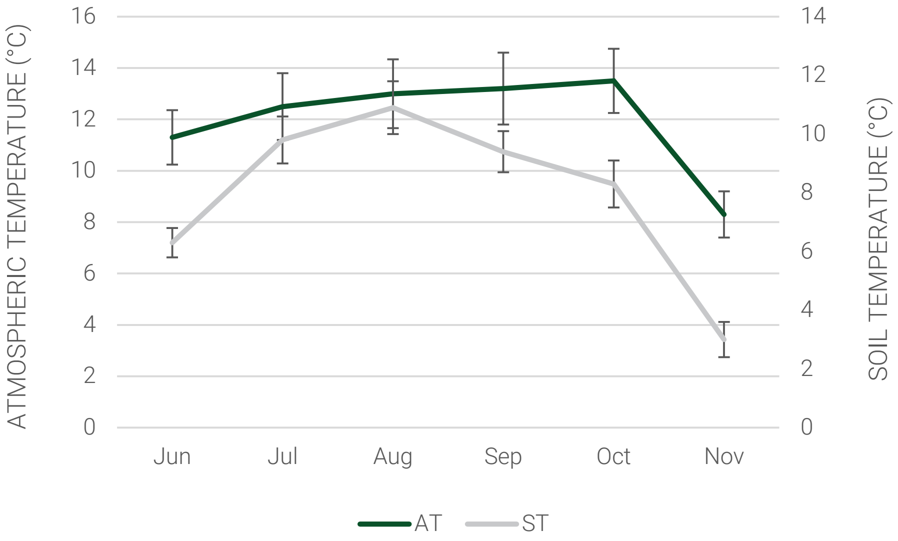


Figure 10.2: Air and soil temperature across the study period in ***B. utilis*** forest stands

Source: IHTRP, Singh and Negi 2018

HOW MOIST IS THE SOIL AT THE TUNGNATH TREELINE?

Compared to mid and low altitude areas, soil at the Tungnath treeline is significantly moist (Figure 10.3). This comparative data supports the view of Körner (2012) that treelines are not associated with water stress. The mean value presented in Figure 10.3 is based on several sites and seasons, and so they represent the two systems fairly well.

Figure 10.3: A comparison between soil moisture of mid-elevation and treeline sites

However, Tungnath is relatively moist because of heavy monsoonal rain (>2000 mm on overage), but other treelines can be drier, particularly in the inner valleys. Moreover, because of rapid climatic warming, water release from snow melt might have increased, thus reducing the pre-monsoon drought. Soil moisture increases further in alpine meadows possibly because of more snow deposits at higher elevations and relatively lower transpiration losses.

LEAF PHENOLOGY

There are several tree characteristics which change along the elevational gradient (Box. 10.1). However, since studies are scarce, patterns of change are difficult to generalize. In general, leaves become thicker, and trees stunted with elevation.

BOX 10.1

Changes in trees with elevation (a compilation)

- Leaf longevity does not change with elevation
- Stomatal density is not related to CO_2, partial pressure or temperature; it is related to solar radiation.
- Specific leaf area (SLA) across species declines (e.g. 133 to 76 cm^2 g^{-1} from 600 to 2500 masl, Western China, 29°N; Tang and Oshawa 1999)
- Low SLA, 37 cm^2 g^{-1} in *Picea abies*, 49 cm^2 g^{-1} *Pinus cembra* in the Alps and 44 cm^2 g^{-1} in *Abies georgei* in eastern Tibet
- Compactness of canopy increases, with more branching and inward growth
- Tapering in stems increases considerably
- Seed production per unit area generally declines with elevation, but seed limitation is unlikely to be a common cause of treeline formation. A good seed year in a century is enough to balance tree mortality, or even for upslope advancement of treeline.
- Seed mass does not decline with elevation
- Maximum leaf diffusion conductance for water vapour (stomatal conductance) increases with elevation

Treeline species generally put forth new leaves in May as soon as temperatures begin to rise. However, the birch starts leafing out in mid-April and the krummholz species, *R. campanulatum* is the last to leaf out (early June). Of the total leaf population, on average 69.9% are formed in the first month (Figure 10.4). *R. campanulatum* is an exception here, with 93.3% leaves emerging in the very first month. Being close to the ground, the twigs of this krummholz species get the advantage of warm temperatures and less wind exposure. The large leaves of *R. campanulatum* also expand more rapidly than that of the other treeline species. Leaf expansion rate in treeline species (average 0.73 cm²/day) was less than that of mid-elevation tree species (0.91 cm²/day), but overlap between the groups was quite wide (Figure 10.5a and 10.5b).

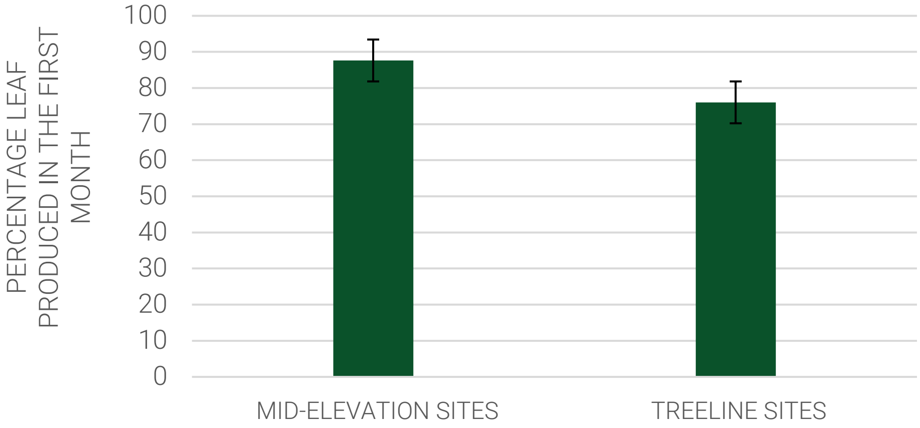


Figure 10.4: Comparison between mid-elevation sites and treeline sites (including ***R. campanulatum***) for percentage of leaves produced in the first month from leaf emergence.

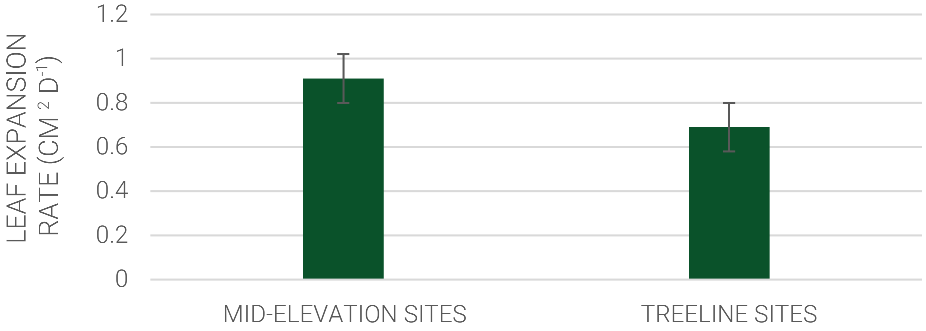


Figure 10.5a: A comparison between leaf expansion rates of species in mid-elevation sites and treeline sites (including ***R. campanulatum***)

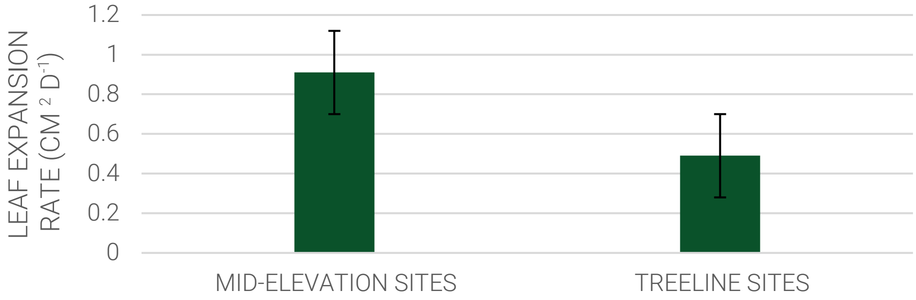


Figure 10.5b: A comparison between leaf expansion rates of species in mid-elevation sites and treeline sites (without ***R. campanulatum***).

In the treeline, small trees with branches close to ground had higher leaf expansion rates than tall trees with foliage away from the warm ground surface. Such a difference in leaf expansion rate (between short and tall trees) is not evident for mid-elevation tree species. Rapid leaf expansion is a necessity in treelines where the growing period is limited by low temperatures. This also includes species with thick leaves, such as rhododendrons, and *A. spectabilis*. In a cold and stressful environment, a leaf has to be sclerophyllous (evergreen with a tough, hard and stiff blade), as it protects it against mechanical injuries and conserves nutrients. At the treeline, soil nutrient availability is low because of cold conditions.

Small leaves can complete full expansion in a short period in treelines but large leaves with thicker boundary layers are likely to be better adapted to cold conditions. So there is a trade-off between the adaptation to complete leaf expansion rapidly and leaf size required to survive in a stressful environment.

The phase of leaf expansion was generally spread over 6-7 weeks, except in birch in which it was close to 8 weeks. It tended to increase with elevation, being about 44 days for *Q. semecarpifolia* and 55 days for *B. utilis* (Table 10.1). The average expansion period across the species was about 49.3 days for treeline species, compared to 43.1 days for mid-mountain tree species. Generally, leaf expansion time is shorter for deciduous species (e.g., 35 days for *Populus ciliata*) than evergreen species; the time taken by leaves to fully expand for the birch is long, possibly because it occurs at the highest elevation among the trees of Tungnath.

Table 10.1: Months when full leaf area, leaf mass and nitrogen mass are attained in treeline species of Tungnath, Uttarakhand (IHTRP, Singh and Negi 2018).

Species	Area	Dry mass	Nitrogen mass
Rhododendron campanulatum	September	October	October
R. arboreum	August	September	September
Quercus semecarpifolia	August	August	August
Betula utilis	September	September	September
Abies spectabilis	August	September	October

Treeline tree leaves begin to lose dry mass as they senesced generally from autumn, except in *R. campanulatum*. The leaf mass loss ranges from about 25% in *R. arboreum* to 42% in birch. These values are within the general ranges.

Soil nutrient availability in the treeline is limited because of cold conditions. As a result, leaf nitrogen concentrations are relatively lower in treeline species than mid-elevation species (1.71% and 2.5%, respectively). Keeping in view that treelines are nutrient scarce systems, we expected that the resorption of nutrients from senescing leaves should be on the higher side of the range across the tree species. However, contrary to it, nitrogen resorption was not high, and it ranged from 34% in *A. spectabilis* to 63% in *R. arboreum*. Here our assumption is that nutrient resorption is a nutrient conservation strategy. However, nutrient resorption requires sink or growth of tissues, which is limited in the harsh treeline environment. This situation is similar to that of carbon reserve, which gets accumulated because of growth limitation or lack of sink (Körner 2012).

While in mid-elevation forests, both leafing and leaf fall occur together during pre-monsoon months in most dominant evergreen species, treeline tree species begin to shed leaves soon after the growing season. In *A. spectabilis* leaf fall is a long process beginning from December and continuing for months up to the following summer. In contrast, in *B. utilis* leaves remain in a steady state only during July-August; before that they expand and accumulate mass, and during autumn they are shed. *Q. semecarpifolia* begins to shed leaves during winter (from November), but sheds most of its leaves following spring. In *R. arboreum* also leaf fall is a long process, occurring from August to winter end. The leaf fall in *R. campanulatum* is also long, and begins after November, and continues for 7-8 months until the following August-September.

In a nutshell, the Himalayan treeline is characterized by the presence of diverse growth forms: broadleaved deciduous, broadleaved evergreen, and multi-year evergreen conifers. The limited growth period is the key determiner of leaf phenology of treeline species. To maximize growth within a short period, leaf recruitment and leaf expansion are slow but with a considerable overlap in the ranges with mid-elevation tree species. Higher compactness of canopy, more taper in tree stems, and stuntedness differentiate treeline species from those of mid-elevation species.

CHAPTER 11

Relationship between tree-ring width and climate factors in the treeline

– P.S. Ranhotra, Bency David, Ayushi Singh, Utsa Singh, Mohit Phulara, Rajesh Joshi, and Amalava Bhattacharyya

Tree ring chronology at treelines can be used to depict changes in past climate (Figure 11.1). furthermore, tree ring data at population level can be used to indicate community dynamics under the influence of climate change and other factors.

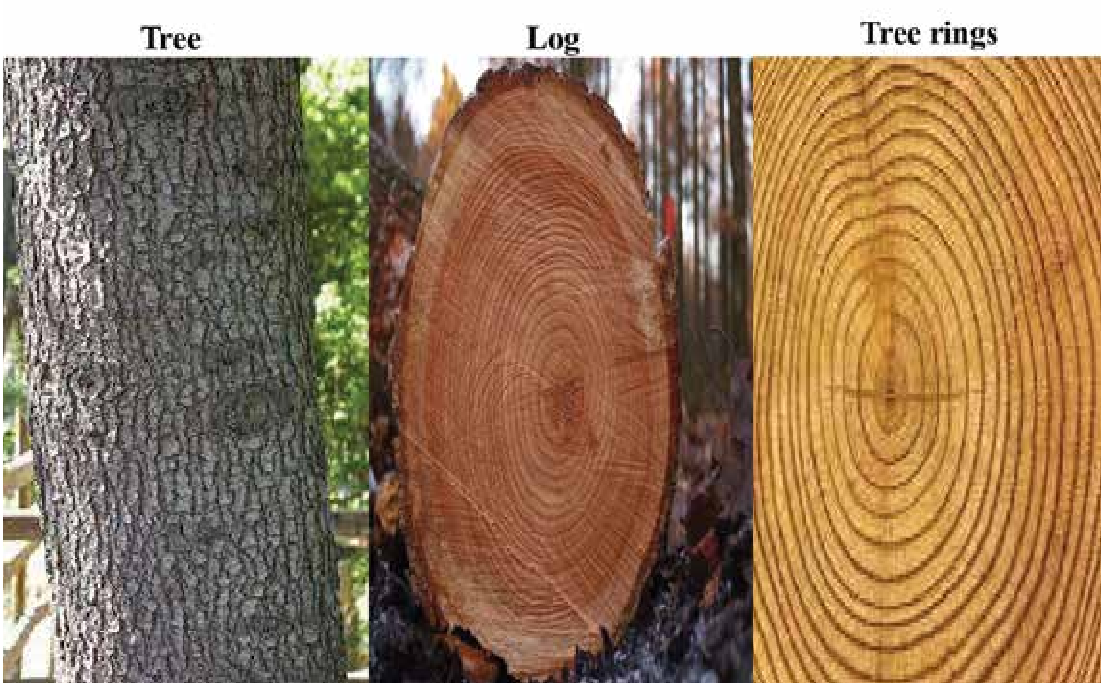


Figure 11.1: Tree ring width and climate relationship can be used to shed light on the impact of climate change on tree growth

SOIL MOISTURE AND CLIMATE

Remote sensing techniques are being increasingly used to monitor soil moisture both across years and seasonally, and linked with tree-ring width to understand climate and tree growth relationship.

Using remote sensing technique, Ranhotra and associates have shown persistent drying in treeline areas (IHTRP report 2019-20). Soil moisture has declined both in Kashmir and Uttarakhand during the last four decades (1979-2018, retrieved from

ERA-Interim). Tree-ring width corresponded with decreasing moisture over this period (Figure 11.2). The monthly soil moisture declined to the lowest level during pre-monsoon months, then rose sharply due to the monsoon rain. Subsequently, soil moisture declined rapidly during autumn and winter. However, both droughts (pre-monsoon and winter) were more intense in Tungnath than in Kashmir. So, despite much lower annual precipitation, soil water stress was milder in Kashmir because of evenly distributed precipitation.

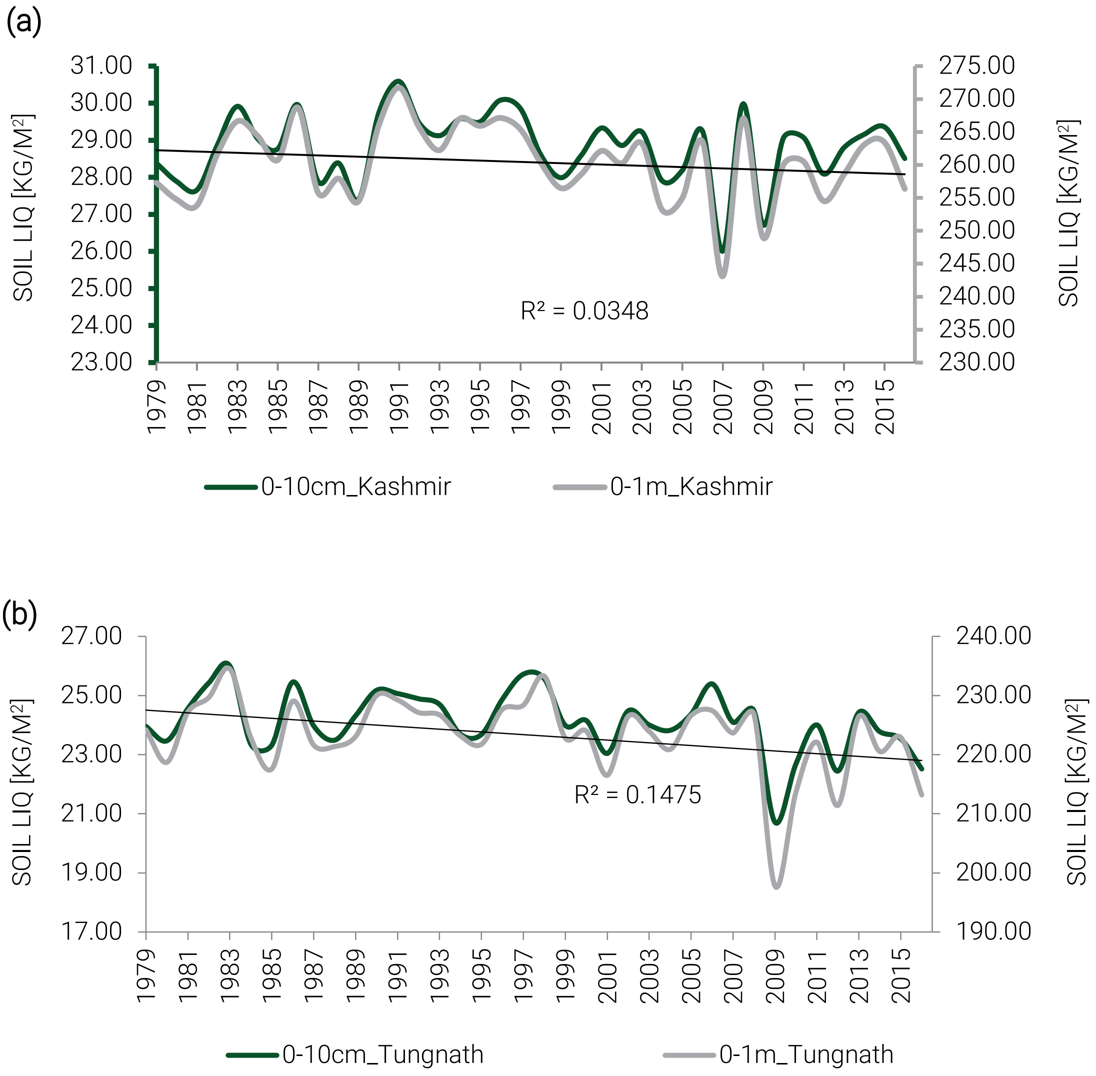


Figure 11.2: Trends in soil moisture at two depths (0-10 cm and 0-1 m) in (a) Kashmir, and (b) Tungnath (Uttarakhand) during 1979-2018

The winter in Kashmir was less dry than in Uttarakhand (Figure 11.3). The monthly soil moisture curve is similar to that of soil water potential in the central Himalayan region (Singh et al. 2006), except that pre-monsoon was relatively less dry at the treeline because of the availability of snowmelt water.

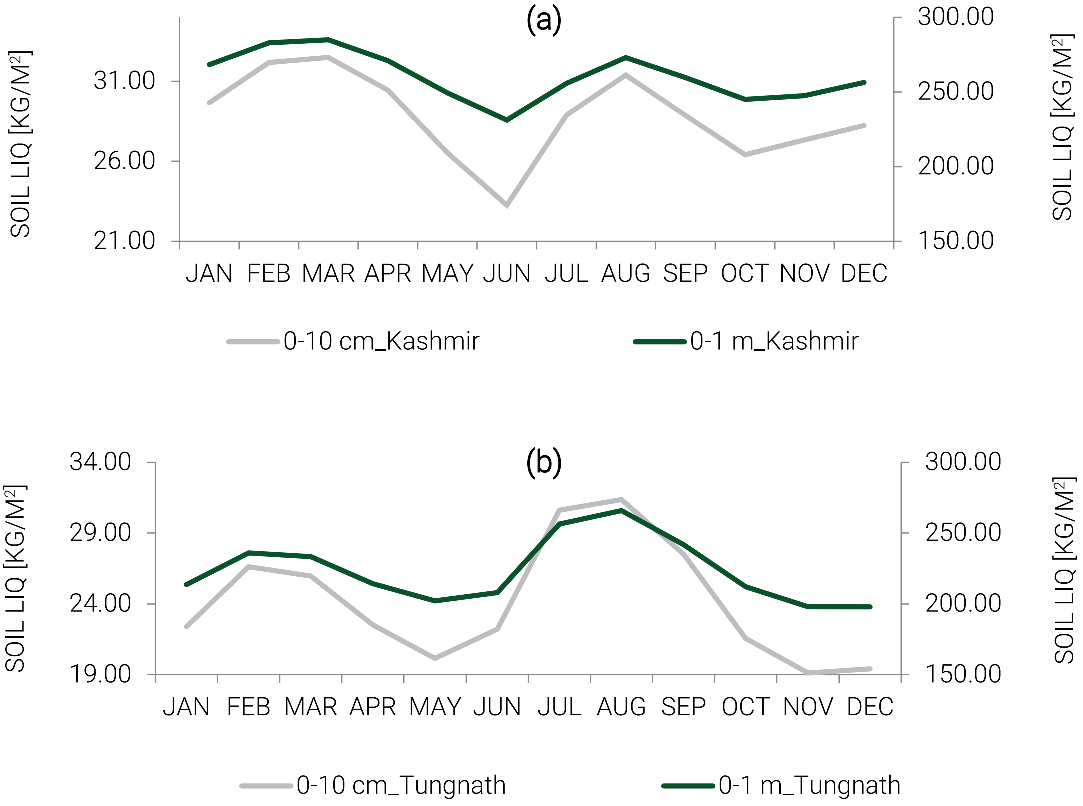


Figure 11.3: Monthly variations in soil moisture at two depths (0-10 cm and 0-1 m) in (a) Kashmir, and (b) Tungnath (Uttarakhand) during 1979-2018.

TREE RING GROWTH AND CLIMATE IN INDIAN HIMALAYA

In the IHTRP study, Ranhotra and his associates found that both in Kashmir and Uttarakhand the growth of silver fir was negatively affected by the monsoon precipitation and positively affected by pre-monsoon precipitation. The monsoon precipitation adversely affects tree growth possibly by reducing solar radiation and temperature. On the other hand, in the case of *Pinus wallichiana*, which occurs on the dry southern aspect, it was observed that monsoon precipitation increases growth while winter moisture decreases it. Winter precipitation is largely in the form of snowfall, which when accumulated in a large amount may delay growth initiation.

Tree growth-climate relationships based on ~260 years of *Cedrus deodara* chronology (Figure 11.4) showed prominent adverse effects of warmer pre-monsoon temperatures. Similarly, 300-year ring width chronology of *Abies spectabilis* indicates that the temperature of winter months, particularly February, have positive influence on the tree growth (IHTRP, Singh et al. 2018).

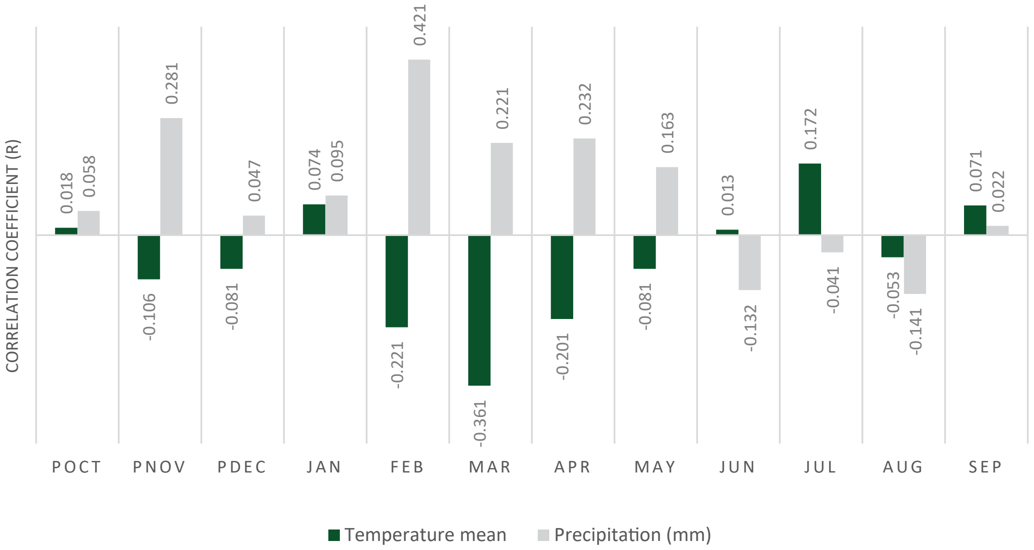


Figure 11.4: Tree growth-climate relationship of ***Cedrus deodara*** at Sangla (HP) on the basis of ~260 years chronology

The warmer pre-monsoon adversely affects tree-ring growth by intensifying droughts. However, a moist pre-monsoon favours tree-ring growth. The positive effect of the temperature increase accompanied by precipitation during monsoon can be seen also on *Abies*. The effect of pre-monsoon climate change is of critical importance in the Himalaya in several ways. It is the time when many dominant tree species put forth new leaves and shoots elongate, leading to simultaneous leaf litter fall, which provides ignition material for man-made fires. This is the time when birds build nests and raise their young, and tourist activities peak, causing disturbance to wildlife and stressing water sources.

Ranhotra and his associates show that the relationship between tree-ring growth and glacial mass can be used to predict future changes in glaciers (Figure 11.5). The years of more tree growth are also the years of more glacier melt or shrinkage (warmer temperatures), and tree ring growth is low when glacier mass is stable or is increasing (cold conditions).

Interestingly, at the Tungnath site, the effect of four decades of climate change is reflected in the trend of soil moisture decline as well as diminution in tree-ring width (Figure 11.5). Ranhotra and his associates also looked at the Tree Ring Width Index (TRWI) in relation to satellite-derived Normalized Differentiation Vegetation Index (NDVI) data for the Tungnath region. Interestingly, even treeline NDVI remained constantly high during monsoon as well as in October, the first autumn month which signals senescence in the temperate zone. This makes it clear that Himalayan forests have a considerable tropical element even at the treeline. The annual NDVI showed a considerable decline from 1988 to 2006 (Figure 11.6).

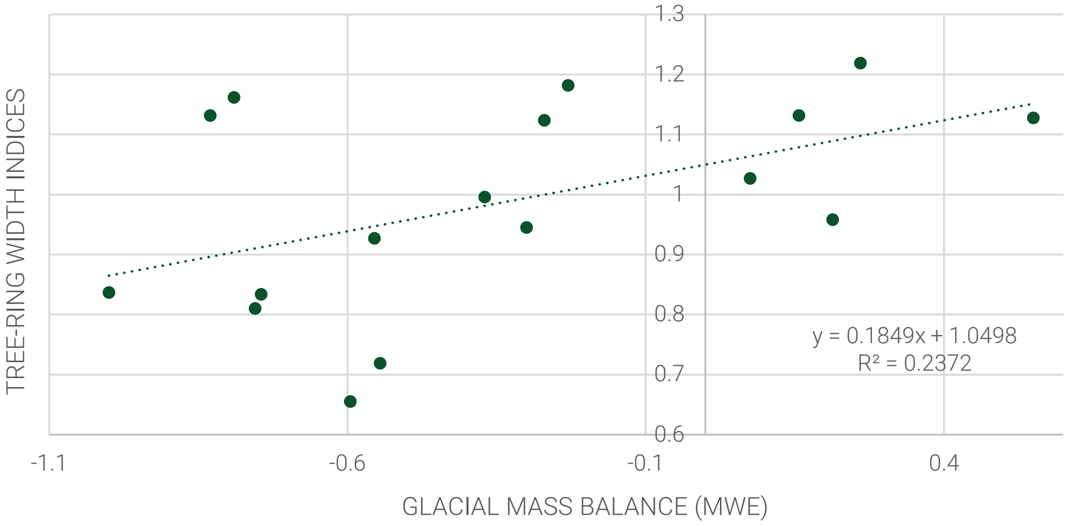


Figure 11.5: Relationship between glacial mass balance (mwe) and tree-ring width indices

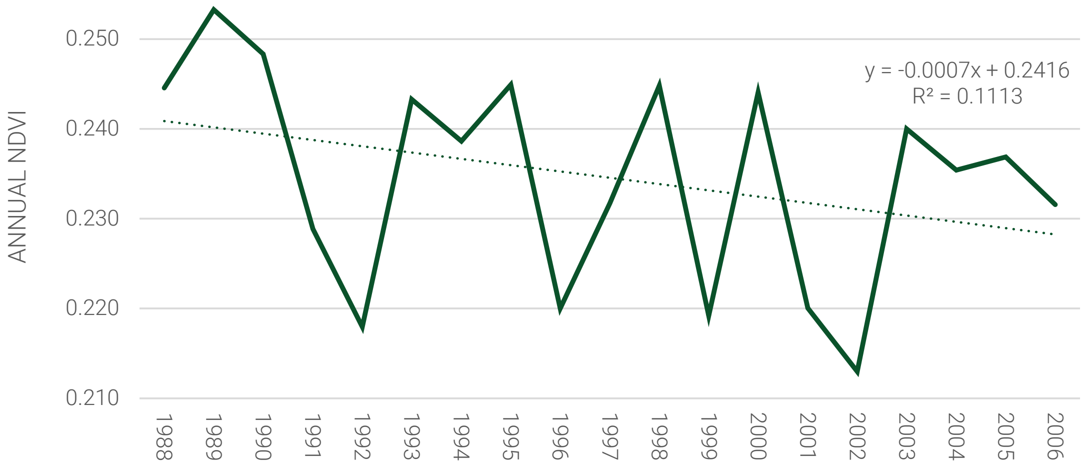


Figure 11.6: Trends of annual Normalized Differentiation Vegetation Index (NDVI) for Tungnath, Uttarakhand during 1988-2006

Reconstruction of NDVI since the 1700s indicates an initial decreasing trend from 1733 to 1794, a stable phase from 1774 to 1870, an increasing phase around 1914, a stable phase from 1945 to 1975, and finally an increasing phase. While the tree water potential data shows that treeline species are not water stressed, tree-ring growth analysis emphasizes that pre-monsoon drought often suppresses tree growth and treeline advancement. Data on tree age and elevational distribution of some treeline species are given in Appendix II (a summary table by Ranhotra and associates).

In a nutshell, contrary to the inference of tree water relation investigations that the treeline is not water stressed, tree-ring width studiesindicate that water stress during pre-monsoon is of critical importance in the treeline, and climatic warming is likely to intensify it. Analysis based on tree-ring counting sheds light on changes in populations over time. Studies on population structure and species regeneration can be used to shed light on the pattern of communities along the elevational gradient, and treeline shifts in a warming climate.

CHAPTER 12

Impact of climate change-induced early snow melt on herbaceous communities

– B.S. Adhikari and Rahul Kumar

Seasonal snow cover is a key feature of the treeline ecology. It influences soil temperatures, freezing depth, and various ecosystem processes such as shoot growth and nutrient cycling. Snow cover protects plants from cold air, and snow is a vital source of water for plants as it melts in spring when temperatures rise. Climate warming can thaw frozen soil, which is expected to enhance nutrient cycling and increase plant productivity. In alpine ecosystems, warming may induce water stress because of the depletion of snow mass and increased evapotranspiration (Penuelas et al. 2007; Wu et al. 2011).

Herbaceous communities of sub-alpine and alpine belts are directly affected by change in snow cover. In IHTRP (Adhikari et al. 2018) we examined the effect of snow depletion and early snowmelt due to climate warming on herbaceous plants in two ways. In the first (A), we compared two portions of a mountain slope differing in the timing of snowmelt (Figure 12.1). The portion in which snow melt occurred earlier had thinner snow deposits than the one in which snow melt occurred later. Hereafter, it would be referred to as study of early snowmelt impact. In the second (B), we raised the temperature with the help of an open top chamber (OTC) and then manipulated the snow inside it; in one set, snow was removed and in the other it was added. Hereafter, it is referred to as snow manipulation effect in OTC. In the first investigation (A), we compared the natural herbaceous stands differing in the time of snowmelt because of the snow depth, topographical difference, and exposure to sun. To an extent, the sites also differed in other features than the time of snowmelt, which we could not avoid. In the second investigation (B), based on artificial warming and snow manipulation, the other site conditions remained the same; they differed only because of the snow alteration.

Figure 12.1: View of study area (Tungnath, Uttarakhand) as on 19-02-2017 (top), early snowmelt (left, with more plant cover) and late snowmelt (right, still with bare soil surfaces) microsites as on 27-05-2017 (IHTRP, Adhikari et al. 2018).

The study was conducted in the timberline ecotone of Tungnath, Uttarakhand, which forms a part of the Kedarnath Wildlife Sanctuary and lies in the upper catchment of the Alaknanda and Mandakini rivers, two major tributaries of the Ganges. The timberline species were *Abies spectabilis*, *Rhododendron campanulatum* and *Quercus semecarpifolia*. The snow cover here lasts for about 4–5 months and melts away in May. This marks the beginning of the growth period lasting for about 6–7 months (up to September-end).

The snow manipulation OTC experiment (study B) was carried out in a small meadow on a south-facing slope. It was selected because of low human disturbances. Two mixed forb communities referred to as *Potentilla lineata* and *Fragaria spp*. were investigated. They were named *Potentilla*-mixed herbaceous and *Fragaria*-mixed herbaceous communities, because of their dominance in the initial stage of growing season.

For warming treatment, a modified design of hexagonal open-top chamber (OTC) with sloping sides was constructed. It was made of fiberglass with high transmittance of visible wavelengths (86%) and low transmittance of infrared (<5%; Molau and Molgaard 1996). Open-top chambers were installed in each of the mixed herb communities (*Potentilla* and *Fragaria*). One $OTC_{(SS)}$ was kept snow-free by frequent snow removal, and in the other the snow removed from the first OTC was added to $OTC_{(SA)}$. Apart from the main OTC chambers, snow manipulation was conducted in normal plots. All the treatments were carried out in both mixed herb communities.

- Control plot (with no treatment): 1x1 m marked and left without any snow investigation.
- OTC with added snow (OTC_{Add}): 2x2 m area was marked permanently and OTC was fixed to a depth of 10 cm within the plot. A gully was made on the outer perimeter to minimize the inflow of drain out water. The removed snow from snow-free OTC was added on the ground surface.
- OTC_{Free} as above, except that it was made snow-free by frequently removing snow from inside the chamber
- Normal plot (no heating) with snow addition (P_{SA}): 1x1 m plot was marked and the snow removed from the snow-free plot was added.
- Normal, snow free plot (P_{SS}): 1x1 m plot marked in both communities and kept free of snow by frequent removal. An area of 1.5x1.5 m was cleared every time to keep disturbance in the marked plots to a minimum.

In OTCs the temperature at 30 cm height was 1.49° C(± 0.37°) higher than in the control. For plant density, Tukey's pairwise test showed a significant difference between control and other snow regimes ($p<0.005$) except P_{SA} which was non-significant.

Our main findings are as follows:

(A) Impact of early snow melt on herb community based on comparison between early snowmelt (ESM) and late snowmelt (LSM) microsite plots: The micro-sites where snow melted earlier (ESM) were richer in species and more productive. This shows that climate warming would lead to an enhanced species richness and plant cover by causing early snow melt and prolonging the growth period. However, in the long run, as snow becomes scarce, the situation may be different. The depletion of snow is likely to intensify pre-monsoon drought and expose plants to cold air. Possibly because of snow melt water, the soils in alpine meadows are moister than mid-elevation forest sites (an average >30% soil moisture vs ~13% in forest sites) (Figures 12.2 - 12.4).

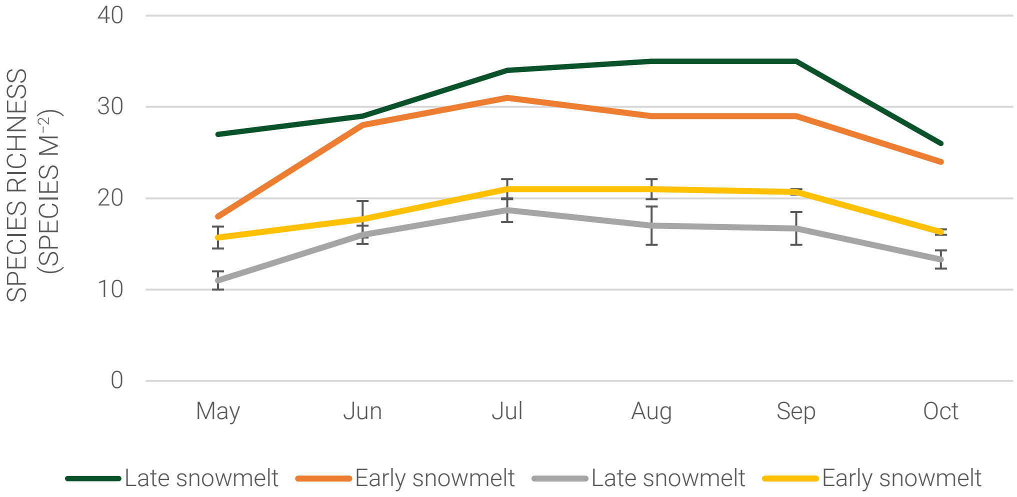


Figure 12.2: Herb species richness across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath, Uttarakhand (IHTRP, Adhikari et al. 2018). The upper two lines indicate total species number at study site and lower lines are average species richness per m^2.

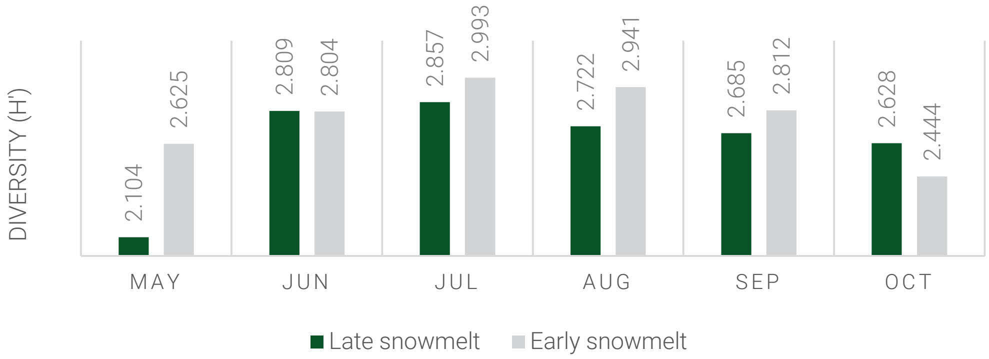


Figure 12.3: Pattern of species diversity (Shannon-Weiner Index) across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath, Uttarakhand (IHTRP, Adhikari et al. 2018)

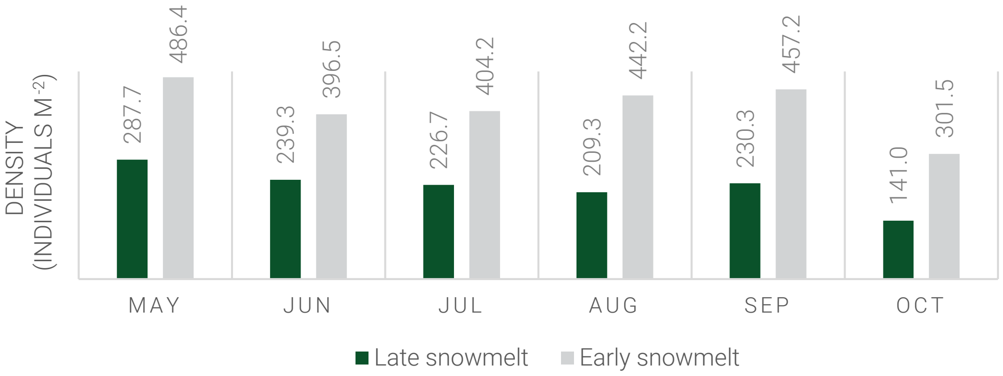


Figure 12.4: Plant density (individual m^{-2}) at different sites across months in early snowmelt (ESM) and late snowmelt (LSM) microsites in Tungnath, Uttarakhand

IHTRP, Adhikari et al. 2018.

(B) Warming and snow treatment:

(i) Warming (OTC experiment) enhanced both plant density and species richness (Figure 12.5), but the longterm effect cannot be predicted from the experiment. Since species richness and plant densities were similar both in snow-free and snow-added OTCs, we can infer that snow removal does not affect herbs adversely when conditions are warm. In other words, snow protection is not required when warming is at least by ~1.5°.

Figure 12.5: Plant density (individuals per m^2) and species richness (species per m^2) in different snow treatments in two herb communities of Tungnath. OTC – Open top chamber; Normal – No chamber; Add – Snow added; Free – made free by removing snow frequently

Source: IHTRP, Adhikari and Kumar unpubl.

(ii) Snow-free and snow-addition treatments without warming adversely affected both plant density and species richness. The worst affected were snowfree plots without warming, possibly because of water scarcity and exposure to cold temperatures without snow cover protection.

(iii) A comparison between snow-free and snow addition treatments without warming indicates that the snow addition by protecting plants from cold temperature and by providing subsequently snowmelt water enabled more plant species to grow and in higher densities. However, with regard to both plant performance (species number and plant density) snow treatments without warming yielded lower values than control (Figure 12.4). Warming seems to have increased species richness within a season possibly by promoting survival of marginal species stressed by low temperatures and competition.

In a nutshell, early snow melt due to climate warming would lead to more species richness and productivity in alpine meadows, but in the long run the effect may be different, as snow cover is needed to protect plants from severely cold air and as a source of soil moisture. The warming (OTC) treatment emphasizes that the snow cover protects plants from cold air. Because of the warm air temperature in OTCs, plants performed well with or without snow cover. However, long-term effects of snow reduction cannot be predicted from our experiments as in the long run pre-monsoon droughts may intensify with persistent decrease in snow. Our experiments simply provide some clues, and longer-term and more sophisticated experiments would be required to critically assess the climate change impacts.

CHAPTER 13

Anthropogenic pressures on Himalayan timberlines and experiences with livelihood interventions

– Pankaj Tewari, Ripu Daman Singh, Surabhi Gumber, Krishna Kumar Tamta, and Harshita Joshi

Within the Indian Himalayan Region, people in high altitude areas (i.e., above 2000 masl) still depend heavily on forests, including those in the timberline ecotones, for firewood, fodder, and litter (for fertilizing crop fields). Further, the widely recognized aesthetic, cultural and spiritual attributes of these high mountain areas have historically made them attractive to people, resulting in additional pressures from the continuous growth of religious, spiritual, and adventure tourism.

BIOMASS EXTRACTION IN TREELINE VILLAGES

Most households in Uttarakhand still grow agricultural crops on terraces carved out of the slopes, but the yields are not enough for household food sufficiency. A study carried out three decades ago estimated that each energy unit generated from crop fields entailed the use of 8-10 energy units from forests in the form of firewood, fodder and litter across much of Uttarakhand, Nepal, and Himachal Pradesh (Singh and Singh 1992). Because of lifestyle changes, some access to cooking gas, and reduction in livestock numbers, forest dependence has decreased in many parts, but in villages near treelines, biomass extraction continues unabated. Since agricultural produce is inadequate to meet the needs of households, many villagers are engaged in other jobs, such as running restaurants, shops, lodges, and tourist camps during the summer tourist season. A study by IHTRP (Singh et al. 2018b) in some villages just below Tungnath treeline revealed that summer tourism accounted for 47.3% of the total income generated at household level. The other income sources were shops (33.8%), physical labour (12.8%), government jobs (3.2%), and cash from horticultural (2.6%) and agricultural crops (0.16%).

Studies conducted in the mid-Himalayan region show that forest degradation, not deforestation, is the key problem (Singh 1999; Baland and Mookherjee 2013; Singh et al. 2014). The nature of degradation in the Himalayas is different when compared to degradation in other regions of the world (Singh 1998). In several parts of the Himalayas, whole tree cutting is uncommon, and trees are mostly lopped for firewood and fodder to feed livestock. Litter collection from the forest floor for fertilizing crop fields is still widely practised.

In order to meet the day-to-day demands of fuelwood and fodder, people in the Himalayan regions remove small and invisible fractions of biomass at a given time, generally as headloads of firewood, fodder, and leaf litter (Figure 13.1).

Figure 13.1: A girl carrying a load of firewood in Sari village, Rudraprayag

Photo: Surabhi Gumber

Rural inhabitants of the Himalaya have been exploiting forest resources for their livelihood for generations. Forest degradation due to this everyday extraction to support subsistence needs is widespread. The excessive and uncontrolled use of firewood for domestic and commercial purposes has led to severe deforestation. In India, the fuelwood demand ranges from 96 to 157 million tons/annum, including a rural demand of 80–128 million tons, or 148–242 kg per capita (Bhattacharya and Nanda 1992). However, the per capita annual consumption of dry wood in various parts of the Himalaya is reported to be even higher, ranging between 500 and 1200 kg (Campbell and Bhattarai 1983; Singh 1989; Metz 1991).

Figure 13.2: Fuelwood used by dhaba owners for cooking

Photo: Surabhi Gumber

Figure 13.3: Grazing of goats and sheep in a treeline ecotone of Uttarakhand. Grazing restricts the upslope movement of trees. Since livestock populations are declining, treelines may advance even without the warming effect

Photo: Pradeep Singh

Figure 13.4: Branches of banj-oak (*Q. leucotrichophora*) being lopped for fodder

Photo: Surabhi Gumber

The influx of tourists has increased in many parts of the Himalaya, resulting in an increase in the number of newly constructed dhabas, restaurants (shops and lodges), and biomass extraction for other purposes from forests. Singh et al. (2010) reported that about 14 temporary dhabas (small shops) are established every year at Chopta, Tungnath lasting about 5-6 months during tourist season (May to October). Due to the tourist season and low temperatures the use of fuelwood was appreciably high (10–14 ton fuelwood per year) compared to regular household consumption (7-10 ton fuelwood per year) in the villages (IHTRP, Singh et al. 2018b) (Figure 13.2).

Livestock rearing is an integral component of mountain farming systems, and it depends heavily on the use of forests up to the treeline. The cattle, buffaloes, sheep and goats freely graze in pastures and forests (Figure 13.3). The lopping of broad-leaved trees in the forests for fodder has been practised for centuries. Over 90% of firewood and 62% of leaf fodder were extracted from the nearby forests. In community-based interviews, 91% of respondents felt that the village forest stock is depleting and 30% emphasized that “drastic” forest degradation has occurred over the past 25 years (Baland et al. 2010) (Figure 13.4). According to the villagers, there are seasonal variations in fodder availability and fodder is generally lopped in the summer and winter seasons when grasses are scarce. The shift from ‘canopy fodder’ to ‘ground fodder’ has not materialized. Only some sporadic efforts have been made to grow grasses to feed livestock.

Local communities around treelines are highly diverse, demanding varied training and skill development streams. In a study by IHTRP, Singh et al. (2018b), some livelihood interventions were managed in two villages (viz., Makkumath and Sari) of Chopta (Tungnath region), which dealt with off-season vegetable production, mushroom cultivation, floriculture, vermi composting, and rainwater harvesting. Among them, off-season vegetable cultivation in polyhouses was most favoured (adopted by 120 families), followed by mushroom cultivation. As a direct result of these efforts, there are now a number of households which have adopted such technologies and enhanced their income significantly. Under the IHTRP, ~750 community members were trained in diverse fields, such as mushroom cultivation, bird watching, carbon sequestration measurement, bamboo craft, and poly house construction.

Figure 13.5: Kirha jarhi (***Ophiocordyceps sinensis***)

Photo: Jitendra Raj Bajracharya (ICIMOD)

OPHIOCORDYCEPS COLLECTION AND ECONOMY

The collection of *Ophiocordyceps sinensis* in the Himalaya has emerged as a major seasonal activity. Because of the huge economic benefits, 52 to 98% of households in the villages of Himni, Ghes, Wan, Kanol, Suto and Tolma in Chamoli district were involved in the seasonal collection of *O. sinensis* (Kuniyal and Sundriyal 2013). It is commonly referred to as the caterpillar fungus or yartsa gunbu (Tibetan for “winter worm, summer grass”) and known as kirha jarhi, meaning insect herb, in Uttarakhand. It is an entomopathogenic fungus (a fungus that grows on insects) in the Ophiocordycipitaceae family. It is mainly found in meadows above 3,500 masl on the Tibetan Plateau in Southwest China and the Himalayan regions of Bhutan, India, Myanmar and Nepal (Figure 13.5). It is highly valued in the traditional medicinal systems of China, Nepal, and India.

In 1994, one kilogram of yartsa gunbu sold at US $700 in China (Steinkraus and Whitfield 1994), but at present it fetches more than US $2000 per kg. Some villagers taking part in this short seasonal activity informed us that the stock of *O. sinensis* is declining. Now they are able to collect only 10-12 pieces in a day, compared to 100 pieces a day 5-6 years ago (Kuniyal and Sundriyal 2013).

Environmental changes may also be a reason for poor availability of the caterpillar fungus. According to a field survey conducted by CHEA in Chipla Kedar, Pithoragarh, India ~1200 villagers (20% female) were engaged for 7-8 hrs a day in the collection of caterpillar fungus during May-June (for about 60 days). According to the villagers, the quality of the caterpillar fungus is also declining and specimens with a golden hue are rare to find (Figure 13.6). This collection also results in soil disturbance at the timberline, affecting 20% of the sites (Figure 13.7).

Figure 13.6: A sample of caterpillar fungus showing the colour quality

Photo: Jitendra Raj Bajracharya

Figure 13.7: Digging to harvest the sporocarp of the caterpillar fungus can generate a large amount of loose soil, which is lost because of rains that follow

Photo: Jitendra Raj Bajracharya

TOURISM AND ENVIRONMENTAL STRESSES

Tourism is a rapidly growing sector worldwide. Consistent with its high rate of economic growth, Indian tourism has been experiencing considerable growth over the last few years. According to a report of World Travel and Tourism Council (WTTC 2017) about 8 million international tourists visited India in 2015 and the numbers increased to 8.80 million in 2016, generating an income of approx. US $220 billion in 2016 (WTTC 2017), which is 9.6% of the nation’s GDP. The number of tourists visiting Uttarakhand increased from 19.45 million in 2006 to 31.78 million in 2016 (Uttarakhand Tourism Development Board) (Figure 13.8). This number is 2.5 times the native population of the state.

The growth of tourism has led to the unregulated expansion of mountain towns, leading to serious problems of water and waste management. The impacts have also spread to biodiversity rich and ecologically fragile areas. There is evidence to suggest that several wild mammals have shifted to higher areas, including the treeline, not because of climate warming but as a response to anthropogenic stresses around tourism sites in lower areas. The transport network is also causing disturbance, disrupting corridors, impacting wildlife movement, and causing roadkill mortality (Sathyakumar et al. 2016; Bhattacharya et al. 2020).

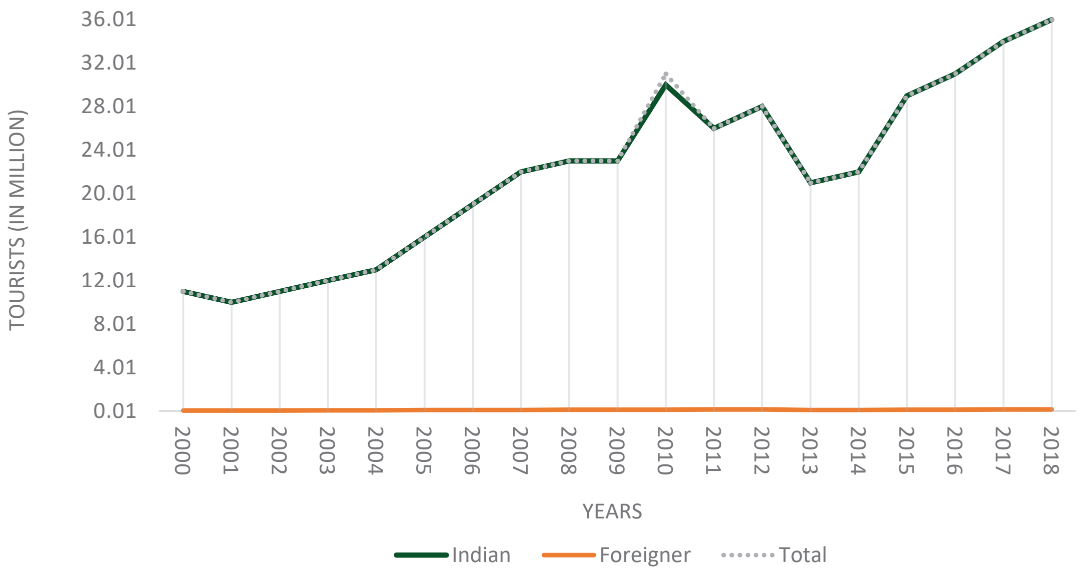


Figure 13.8: Number of Indian, foreign and total tourists (in millions) in Uttarakhand prior to the COVID-19 crisis (Source:Uttarakhand Tourism Department)

The fact that people are still living in poverty and migrating in search of opportunities despite a 10- to 20-fold increase in tourist arrivals in many parts of Himalaya raises doubts about tourism as an effective economic strategy for the people of Uttarakhand.

WILDLIFE MOVING UP COULD BE DUE TO ANTHROPOGENIC STRESS RATHER THAN CLIMATIC WARMING: A COVID-19 LOCKDOWN REVELATION

By drastically reducing anthropogenic activities and disturbance, the COVID-19 lockdown enabled nature to express itself in several ways. Following the three-month lockdown from March to May, June 16-19 2020 we studied an elevation transect of 2000-3500 masl at Tungnath, Uttarakhand, which was a part of our treeline research during 2016-2019 (referred to as non-COVID years; study by Pradeep Mehta, guided by GCS Negi and SP Singh). We observed that in the COVID-19 year (2020), wild animals such as tahr (*Hemitragus jemlahicus*) and blue sheep (*Pseudois nayaur*) were sighted at lower elevations (below 2800 masl) and in larger numbers than during non-COVID years (at 2800-3500 masl) (Figure 13.9). We argue that by eliminating anthropogenic stress, the COVID-19 lockdown presented an opportunity for wild animals to freely occupy elevational ranges of their choice, and they preferred lower elevation ranges (below 2800 masl) than they occupied in non-COVID years (Table 13.1). This indicates that these wild animals occupied higher elevations during the non-COVID years not because of climate warming but to escape from persistent anthropogenic stressors. In the Himalaya, the anthropogenic stressors includes day-to-day collection of biomass, man-made fires, pastoralism, widespread tourism activities, and associated infrastructure development. While day-to-day biomass collection is declining with increasing income, tourism is rapidly increasing (56-fold increase in tourists in Uttarakhand over the last five decades). Roads and traffic impact wildlife populations by increased mortality, reduced connectivity and habitat degradation (Teixeira et al. 2020). In another valley of Uttarakhand (Upper catchment of Gori river, Johar valley between 80° to 81°5'E longitudes, and 29°5' to 30°N latitudes), blue sheep have been pushed to the rugged mountains with sub-optimal habitat because of pastoralism (Bhattacharya et al. 2020). There is a need to conduct research and design interventions to reconcile tourism, pastoralism, and wildlife conservation at lower elevations so that wild animals are not forced to shift to sub-optimal conditions at higher elevations (above 2800 masl).

Table 13.1: A comparison of wildlife occurrence along the Tungnath Timberline Transect (TTT), Uttarakhand in COVID-19 year (2020) and normal years (2017-2019). Values for normal years are an average of three years.

Wildlife and others	Normal years		COVID-19 year		Remarks
	Elevation of sighting (masl)	Number of observed individuals	Elevation of sighting (masl)	Number of observed individuals	
Himalayan blue sheep (bharal) *Pseudois nayaur*	3500-3600	10-15	3000-3200	30	In normal years, individuals are confined to higher elevations and in fewer numbers
Monal (*Lophophorus impejanus*)	3300-3600	3-5	3100-3400	8	Records of monal at lower elevations uncommon in normal years
Himalayan pika (*Ochotona himalayana*)	3200-3600	2-3	3000	6	-
Rhesus macaque (*Macaca mulatta*)	3000-3500	50-60	-	0	No restaurants and tourists, so no food for monkeys
Himalayan pit viper (*Gloydius himalayanus*) (on SW aspect)	2900-3300	1-2	3000	5	Normally found hidden among tall grasses, it was found in open fields in the COVID-19 year

Groups of shepherds	3000-3500	7-10	3000	3	They were also confined to one or two places in the COVID-19 year
Livestock (sheep/ goats)	3000-3500	1400-1600	3000	250/300	-
Seedlings/ saplings of five dominant treeline tree species* (no./ha)	3000-3500	Negligible or absent	3000-3500	1975/1766	Seedlings were recruited in the preceding year but their higher number in the COVID-19 year was because of the absence of anthropogenic pressure

Source: Pradeep Mehta and GCS Negi

Abies spectabilis* **(367/158), *Betula utilis* **(83/217)**, *Quercus semecarpifolia* **(50/08)**, *Rhododendron arboreum* **(358/483)**, *R. campanulatum* **(1117/900). Figures in parentheses indicate numbers of seedlings and saplings, e.g., for** *A. spectabilis* **there were 367 seedlings and 158 saplings.**

Figure 13.9: A herd of Himalayan blue sheep (***Pseudois nayaur***) and a pit viper (***Gloydius himalayanus***) along the Tungnath Treeline Transect (TTT) in COVID-19 year (2020). The elevations at which they were sighted were lower than in normal years.

Source: Pradeep Mehta, GBPNIHESD. April 2020

CHAPTER 14

Policy issues and research questions

Global climate change is the greatest concern of our time. Among the various regions in the Indian subcontinent, the Himalaya and coastal zones are most vulnerable to the impacts of climate change. Within the Himalaya, climate change studies have largely focused on glaciers and the hydrological changes that are likely to result from changes to the cryosphere. Somehow, the treelines which are adjacent to the snowfields of the Himalaya have remained sidelined in the climate change discourse and programmes.

While the relationship between climate change and glaciers is largely driven by physical factors, treelines being biotic systems store varied information that can help us understand climate change dynamics over time. Biotic systems could, in turn, also influence the course of climate change at a landscape level. Tree population dynamics and tree-ring growth reveal considerable information about the pattern of climate change. Furthermore, changes in growth form and plant cover can influence the course of climate change because of their impact on albedo and carbon storage. For example, the replacement of snow fields with vegetation is likely to result in reduced albedo, which, in turn may further increase warming. On the other hand, increase in the woody component of vegetation cover may help sequester carbon in aboveground components of vegetation.

Treelines along with biotic belts of nival plants, meadow species and timberline biota make up a highly complex system with variously interconnected components, which includes some of the most attractive but threatened mammals like the snow leopard as well as rare lower plant groups like lichens and mosses. Here, the plant species and physiognomic groups are under constant flux because of climate change. The treeline ecotone complex is a dynamic system, and understanding its intricacies and complex interactions will require taxonomists of various disciplines, ecologists who can work in remote areas, and researchers and practitioners who can address various issues ranging from the rapid growth of tourism to glacier retreat and the thawing of permafrost.

This study was a small initiative to understand treeline dynamics and draw the attention of policy makers, decision making bodies, academia, and other stakeholders and to establish Himalayan treelines as a separate and principal unit of conservation and management in a changing world.

- Treeline as a separate entity: There is a need to recognize treelines as a separate and principal entity of conservation and management in view of the following: (i) treelines are present and apparent throughout the Himalaya, with an extraordinary length and variability in geographical position, (ii) treelines vary a lot in their response to climate change, and (iii) have high corridor and habitat values for all forms of organisms, particularly wild animals. In a warming climate, a species can migrate from lower to higher elevation as well as laterally along the Himalayan Arc. For example, *Betula utilis* may shift towards the eastern Himalaya in a drying climate.
- Independent treeline authority: An independent authority for treeline conservation, management and regulation (ATCMR) may be established. This system should be developed for the entire Indian Himalaya high enough to have treelines, such as in Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh.
- While developing the ATCMR, it is important to involved army personnel and establishments as partners and collaborators, given their presence and capacities. Researchers and local communities could be other partners in management.
- Treeline ecotone should be expanded to include adjoining biotic and abiotic zones: The management of treelines should be considered along with connected biotic zones such as alpine meadows and nival/subnival belts, and abiotic components such as permanent snow/glaciers and permafrost, which provide water to biotic systems. In other words, for all management purposes the treeline should be considered as a continuum consisting of forests, timberline, treeline and communities of short statured plants and barren snow and ice areas, all under a state of flux due to climate change. In this continuum, physiognomic dimensions and growth forms vary a lot. However, a closer look will show that the different forms constitute a complex mosaic of small pieces of vegetation. Wild and domestic animals should also be included in this continuum. Here, for all purposes, it is also important to recognize the specific features of two types of treeline viz. island type treeline (ITL), and continuous type treeline (CTL).

CLIMATE CHANGE AND VEGETATION BEYOND EXISTING ELEVATIONAL BOUNDARIES

The Himalayan treeline is the highest in the world (close to 5000 masl), but above it there occur varied forms of plants, which are moving upslope. Alpine meadows occur above treelines, but there are other species with different functional characters that occur above that. As high mountain snow cover depletes, fresh

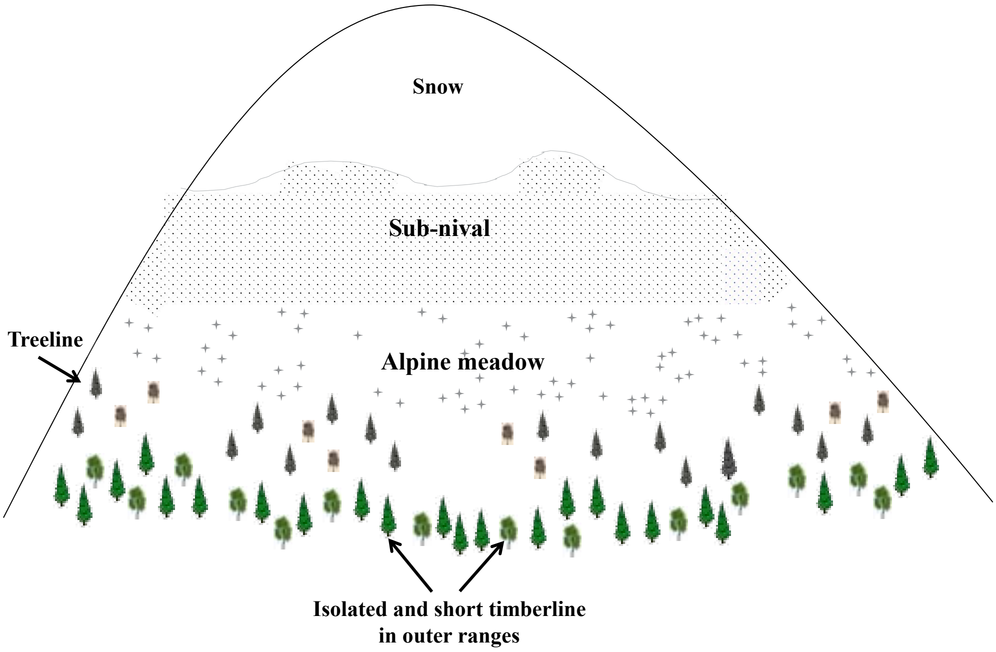


Figure 14.1: Subnival species can grow up to 6000 masl

Source: Akhani et al. 2013

surfaces are created for plant colonization by subnival species. A study in the Himalaya has shown that subnival species, which occur even above 6000 masl, differ in several ways from alpine meadow plants (Figure 14.1). In comparison, subnival species are on average 21% shorter, grow 25% slower, have 48% lower biomass, and have about 37% less rooting depth. However, subnival plants have 7% more nitrogen in their leaves and 30.6% more nitrogen in their roots (Dolezal et al. 2016). In a way, the treeline marks the beginning of decline of trees, and increase in relative domination of herbs, including minute ones, appressed to the ground surface. These plants have always existed here, climate change has simply made them more prominent. A dedicated treeline entity could promote research on subnival plant based ecosystems. While a sal forest is at the base of the series of forest types in Himalaya, treelines lie at the base of a series of short, cold-adapted plant communities. In India, we have not even begun to study them. We need to better understand these tiny plants, conceived by open sky and freezing ground surfaces. Treelines provide a base for such an effort.

- There is a need to develop training material on treeline management and conservation for stakeholders at different levels, such as forest department personnel, biodiversity management committees, NGOs, and army and para-military personnel.
- Develop short courses on treelines and climate change for schools and college level students

- Treeline-based tourism should be carefully developed and monitored.

BUILDING ON INFRASTRUCTURE ALREADY DEVELOPED, RESEARCH AREAS

i. Building upon the infrastructure that IHTRP has created: A policy provision is required to build upon the research infrastructure that a project like IHTRP has created. Here research infrastructure is a broad term, which includes data collection which can be continued following the methods already in place with some adjustments, instruments placed in the field, and a research scholar familiar with the sites and research methods. From our present project, LONG-TERM data collection can be managed with about Rs. 50 to 60 lakh per year. The services of the project coordinator could also be availed.

ii. Temperature lapse rate: Long-term data from several representative sites would be required to understand how climate change is affecting elevation-dependent warming and temperature lapse rate (TLR). The other related questions for both basic understanding and management are: How are seasonal differences in TLR likely to affect biotic components? How is TLR itself modified by climate change? The other question relates to how widespread pollution in the big cities of adjacent plains are affecting these processes. A macro-ecological approach which gives a coherent picture of various interconnected systems might serve the purpose of managing high landscapes in the Himalaya.

iii. Two types of Himalayan timberlines: Following our IHTRP study, there is a need to recognize two distinct types of treelines in the Himalaya: the island type treelines (ITL) in the outer ranges, and the continuous treelines (CTL) in the inner /main Himalayan ranges. They differ in length, climatic conditions and responses to climate change, and are exposed to different forms of disturbances. Both livestock grazing and tourist activities are more in the ITL than CTL. Further, ITL is more vulnerable to climate change than CTL, so would require closer monitoring and regulation.

iv. Plant species dynamics around mountain summits: Treelines and mountain summits are likely to experience changes in species composition, species accumulation, migration and extinction due to climate change impacts. We need to mark and maintain permanent plots to monitor species flux around summits on a long-term basis. While doing so, sites should be chosen to appropriately represent outer ranges as well as inner valleys, which differ in treeline elevation, climatic conditions, and treeline dimensions. As our remote sensed data indicates, mountain summits in the outer ranges are expected to be more vulnerable to climate change. Treelines go higher in a dry climate, hence they are higher on south-facing slopes than on north-facing slopes. The difference is related to the warmer temperatures of south-facing slopes when sky is clear; temperatures are higher because of more solar radiation. An annual precipitation of 250 mm is enough for treeline formation (Miehe et al. 2008). Trees also grow on mountain slopes with lower precipitation when trees get upslope runoff. Scree-type loose surfaces keep evaporation losses low. Sites with such surfaces and underlying sand or volcanic ash store moisture, as there is no capillary connection to the surface.

v. Transboundary cooperation and expanded team science: Greater research networking is required to capture Himalaya-level variability in treeline dynamics and climate change impacts. This would require greater research cooperation and alignment of research purposes and approaches across borders. Team research should be expanded to include research for several Himalayan countries and shared transboundary landscapes and measures should be taken to build team science culture. A few research scholars/field assistants could be trained to collect comparable data in the different countries.

vi. Resolving difficult questions about tree water relations in Himalayan treelines: Globally, tree water relation studies in treelines are scanty partly because treelines are not considered to be water stressed (Körner 2012b). Evaporation at low temperatures is low. However, this needs to be analysed more deeply as treelines vary a lot, with inner valleys being far drier than outer ranges. High leaf water conductance, particularly in inner dry treelines, and high daily change in tree water potential during monsoon are some observations which are difficult to explain based on existing data. Studies on more sites and over a longer period are required to ascertain the water status of treeline species. Studies on tree ring growth in relation to precipitation and drought, particularly pre-monsoon drought, indicate that the upward shift of treelines is partly restricted because of the intensification of pre-monsoon droughts. In the inner valleys of Sikkim, for example, rainfall rapidly declines with elevation. So, at least at higher elevations, water stress could be a limiting factor in relative terms. Several studies on the relationship between tree-ring width and climate indicate that pre-monsoon temperature and tree-ring growth are negatively correlated and pre-monsoon precipitation and annual tree-ring width are positively correlated. Evidently, water stress is a factor in treeline ecology, which we are not able to capture adequately through our tree water relations investigations.

It is clear that we need to better understand tree water relations of treeline species in the Himalaya and consider treelines of both moist outer ranges and dry inner valleys. Methodologically, the research should consider both water potential and selected parameters as well as dendrochronogical studies with focus on climate relationships.

RESEARCH QUESTIONS GENERATED FROM THE IHTRP STUDY

i. What are the implications for Himalayan timberlines that are the highest yet substantially depressed in elevation? A timberline that is unable to go upslope in a warming climate (can be called an arrested timberline) would get too warm to retain some basic timberline characteristics, including species composition. How would long and segmented timberlines (CTL) and short strip island type timberlines (ITL) differ in their responses to climate change and anthropogenic factors? Remote sensed data shows that ITLs are likely to go up more than CTLs. What would be the fate of alpine meadows and species near the mountain summits? Perhaps, livestock grazing would be needed to reduce the depletion of alpine meadows in selected sites? What kind of incentives could be given to local people to sustain livestock grazing?

ii. Between broadleaved and conifer species, which are going to be favoured in treeline areas in a warming climate? Past records indicate that a warming climate phase has favoured broadleaved trees. However, if water stress increases with warming, the conditions are likely to favour conifers. Conifers with narrow tracheids are likely to be more resistant to cavitation caused by dry conditions.

iii. What would be the role of livestock grazing in maintaining the diversity, structure and function of alpine meadows? How do we manage competition for resources between livestock and wildlife?

iv. What would be the asylum value of the timberline ecotone for threatened species? Do we need to develop a science of assisted migration to save critically threatened species? How do we create topographical refugia for species threatened by climate change?

v. Are timberline areas going to be more important for tourism in a warmer world? How would species conservation be impacted by tourism?

vi. What are the likely ecosystem services of timberlines in a warming world and how are they likely to be impacted?

In a nutshell, treelines should be declared a separate unit of conservation and management. Research should be carried out to monitor changes that are occurring in the treeline continuum consisting of forests, alpine meadows and nival communities, apart from studies of treelines to capture inter-community exchanges, and responses across communities to climate change impacts. Transboundary cooperation and research collaboration will be crucial for developing a Himalayan perspective on treelines in a changing world.

Appendix I

List of research scholars involved in Indian Himalayan Timberline Research Project

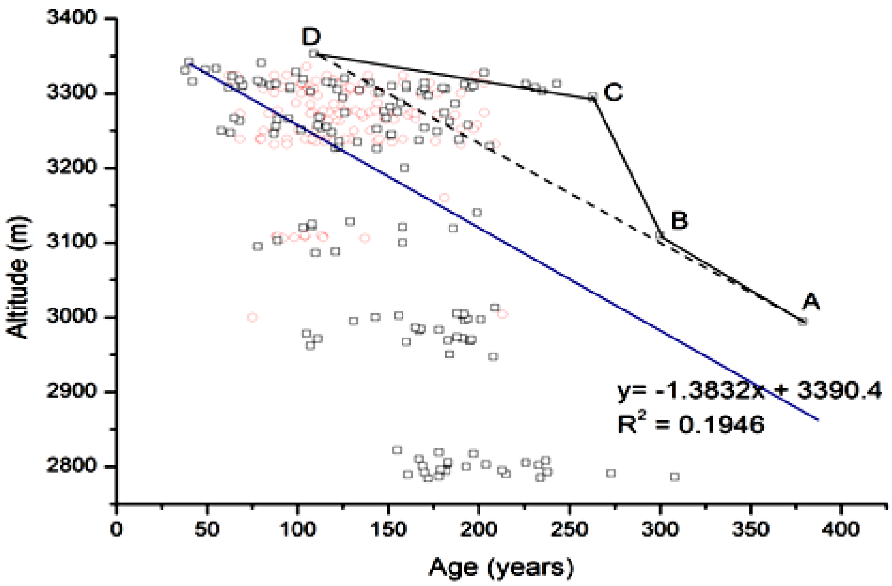
- Amit Mittal
- Ashish Pandey
- Avantika Latwal
- Ayushi Singh
- Balam Singh Bisht
- Bency David
- Chetna Mehra
- Disha Upreti
- Harshita Joshi
- Ishfaq Mir
- Krishna Kumar Tamta
- Kumar Sambhav
- Kunchok Namgyal Bhutia
- Mohit Fulara
- Mukesh Kumar
- Nandan Singh
- Ninchhen Dolma Tamang
- Pradeep Singh
- Pratap Dhaila
- Priyanka Sah
- Rahul Kumar
- Renu Rawal
- Ripu Daman Singh
- Safzar Nanda
- Sahil Joshi
- Sandhya Rai
- Shruti Sah
- Sorav Tamang
- Sunil Chandra Joshi
- Surabhi Gumber
- Utsa Singh
- Vijay Arya

Appendix II

A summary table of age and altitude data based on tree ring study (some data on tree age and elevation from Ranhotra and his associates, IHTRP and other studies)

TUNGNATH- STUDY I (JUNE 2019- ABIES SPECTABILIS):

- Oldest tree recorded was ~379 yrs old at 2994 masl
- Youngest tree was ~38 yrs old at ~3331 masl
- Recruitment of fir at the upper ecotone limit (~3350 masl) by early 20th Century AD with the shift rate of ~13 m per decade.
- The highest advancement rate of ~39 m per decade occurred during 18th Century AD.



TUNGNATH- STUDY II (AFTER JUNE 2019- ABIES SPECTABILIS):

- Oldest tree of ~462 yrs at ~3280 masl in fir patch
- Oldest 462 yr tree at 3280 masl and 110 yr tree at ~3360 masl
- Age of *Rhododendron campanulatum* ranged from 24 yrs to 74 yrs growing between ~3270 and ~3290 masl.

Field measurements at Tungnath timberline site, Uttarakhand

Measuring circumference at breast height of fir tree

Measuring bark thickness of a rhododendron (*Rhododendron barbatum*)

Recording air temperature

Measuring twig thickness of *Betula utilis*

From left to right – Prof. Zafar Reshi (4th), Prof. S. P. Singh (5th), Dr. P. P. Dhyani (7th), Dr. Subrat Sharma (9th), and the late Dr. R. S. Rawal (10th), pictured with researchers from Kashmir University.

Himalayan timberlines, despite being the highest in the world and being highly vulnerable to a warming climate, have remained poorly investigated. Even basic information on the subject is not readily available. In view of this, our team coordinator, Dr. S. P. Singh, conceptualized a research project on the Himalayan timberline.

Our study has involved over 30 researchers, dispersed across six institutions located in geographically unconnected areas, both in the Himalaya and in the Indian plains. It is an exception in the sense that it possibly covers more aspects of the Himalayan timberline than any other single paper on the subject has done so far.

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