International Journal of Ecology and Environmental Sciences 50: 11-31, 2024
ISSN: 2320-5199 (Online); https://doi.org/10.55863/ijees.2024.3250

Review article

A Leaf Based Classification for Himalayan Forests

SURENDRA P. SINGH[1] AND RAJESH THADANI[2]*
[1]*Centre for Himalayan Studies, Graphic Era Deemed to be University, Dehradun, 248006, Uttarakhand, India*
[2]*Centre for Ecology, Development and Research (CEDAR), A-17 Mayfair Gardens, New Delhi,110016, India*
E-mail: surps@yahoo.com; spsecology@gmail.com, rajesh@cedarhimalaya.org
ORCID ID: 0000-0003-3139-9301 (SPS), 0000-0001-5713-8367 (RT)
***Corresponding author**

ABSTRACT
The topographic heterogeneity of the Himalayas leads to a mosaic of growing conditions which limit the utility of traditional systems of forest classification. A leaf phenology based classification is suggested as an alternate to help understand patterns of Himalayan forests. Leaf traits such as longevity, time of new flush and shedding and type of leaf, are linked with ecosystem processes and show more consistent patterns across Himalayan landscapes. While low temperatures and a short growing season limit growth at extremely high altitudes and near the timberline, drought stress is the variable that most influences forest structure in the majority of Himalayan forests. Precipitation occurs through two major weather systems: the monsoon which is the dominant climate system for much of the Himalayas, and the westerlies, which are active in the Western part and northern fringes of the Himalayas. The pre-monsoon dry season is the most important in determining forest type and leaf phenology. Based on these differing weather systems and rainfall deficits, the Himalayas can be broadly divided into five categories based on type of leaf and when it is shed. Trees which leaf out in the pre-monsoon period, with approximately one year leaf life span and almost simultaneous leaf fall (e1 type), can best benefit from the monsoonal climate. This type lies on a continuum between pre-monsoon deciduous (dp) and evergreen species with multiple leaf flush (e2). At higher altitudes and dryer sites conifers (e3 type) dominate while winter deciduous (dw) are most abundant near the treeline. The Himalayas lie at the confluence of the Palearctic and Indo-malayan biogeographic zones and the influence of these different vegetation types is evident. Despite the presence of a floristic base and diversity of deciduous species Himalayan forests are largely evergreen as climatic conditions favour this evergreen strategy.

Key words: Phenology, Evergreen, Deciduous, Pre-monsoon, Biogeography

INTRODUCTION

In 1968, Champion and Seth classified the forests of India in their landmark book 'Forest types of India'. In this revision of an earlier publication by Champion (1936), Champion and Seth (1968) divided the forests of India into six major groups based on climatic factors. While the bulk of India's forests, were divided into the first two groups, viz. Moist Tropical Forests, and Dry Tropical forests, the remaining four groups were devoted to forests that occurred in mountainous locations and especially the Himalayas. They were groups III (Montane Subtropical forests), IV (Montane Temperate forests), V (Sub-Alpine forests) and VI (Alpine forests). The six major groups were further subdivided into 16 Forest types based on Moisture regimes and physiognomy, and here again 9 of these types pertain to montane environments. The preponderance of categories of montane forests, which make up the majority of forest divisions of India, reflected the variability of Himalayan forests when such climatic factors were used for classification.

Champion and Seth's classification was excellent for the country as a whole, and its popularity is such that it has been adopted by several neighbouring countries such as Pakistan and Nepal (Stainton 1972) to describe Himalayan forests. While the classification is well accepted for lowland tropical forests, there are some drawbacks with regards to montane forests. The disproportionately large number of types and sub-types allocated to montane forests is perhaps a reflection of the issues Champion and Seth faced in trying to fit all mountainous forests into a classification system based on temperature and moisture regimes.

The Himalayas, more than any other region in Asia, shows extreme variability of temperature and moisture over short distances. Over just 100 km, ecosystems can change from Tropical to Sub-alpine with the intermediate sub-tropical and montane temperate encompassed within. Similarly, from the south ranges of the Himalayas exposed to the full fury of the monsoon winds, to the rain shadow areas of the inner ranges, precipitation amounts can vary an order of magnitude. Given this high variability which leads to a mosaic of vegetation types, we propose here some alternate conceptual frameworks to help enhance an understanding of Himalayan forest systems.

Heterogenous landforms: variations in Elevation and Precipitation

Elevational gradients have the most pronounced impacts on vegetation. Temperatures decrease as one moves up in elevation. On average, the drop in mean annual temperature is around 0.6°C per 100m increase in altitude, though there is considerable variation with seasons and also across the Himalayan arc (Kattel et al. 2013, Joshi and Tamang 2021). The impact of this temperature decline with elevation can be seen in various ways, such as increase in frost and freezing which inhibits several species, and a decrease in growing period, which changes species composition.

Moisture also plays an important role in determining species. While the quantum of rainfall is the main determinant of vegetation type, periodicity and distribution also matter. The vast extent of the east-west arc of the Himalayas, that covers over twenty degrees of longitude (74°E-95°E) encompasses differing precipitation regimes, From the west-to-east, conditions are increasingly moist and humid because of increasing precipitation and the shift of climate from continental type to marine type (Sakai and Malla 1981, Singh et al. 2021). The higher precipitation and shorter dry season in the Eastern Himalayas have important consequences for forest vegetation and it is in the Indian Eastern Himalayas (IEH) where most of the wet forest types can be found (Champion and Seth 1968).

While the Himalayas are known as an east-west range, the latitudinal variations are also considerable. Latitude increases rapidly towards the western end of the Himalayan arc. Consequently, seasonal variations in day length and temperature are far more in Gilgit (35.92°N), than in Gangtok (23.36°N) as an example. The effect of this difference is apparent in vegetation. For example, the percentage of deciduous tree species declines from West to East along the Himalayan arc from Jammu & Kashmir (71.4%) and Himachal (69.6%) to Sikkim (46.6%) and Arunachal Pradesh (43.4%) (Bhatt et al. 2020).

In addition, north-south transects at a given latitude also show significant differences based on their proximity to the outer ranges (that face the monsoon as it progresses up from the indo-gangetic plains. The outer (southern) front of the Himalayas receives the full force of the monsoon and are considerably more moist than valleys deeper in Inner Himalayan ranges that are shielded from the monsoon winds and are in the rain-shadow (Ohsawa 1987, Bookhagen and Burbank 2010). Some forest types such as deodar (*Cedrus deodara*), blue pine (*Pinus wallichiana*) and spruce (*Picea smithiana*) tend to be associated with dry inner valleys (Champion and Seth 1968, Miehe et al. 2015) which receive a significant part of their precipitation from the Westerlies (largely snowfall during winters) (Miehe 2015). Other forest types such as *Quercus lanata, Quercus leucotrichophora* and *Pinus roxburghii* flourish best in the outer (southern) ranges that are most impacted by the monsoon.

Altitude and rainfall interact to produce varying moisture environments. As temperatures decline evapotranspiration losses decrease. Thus, for the same amount of precipitation higher elevation sites are more mesic than lower (warmer) elevations. Transeau (1905) recognised the dependence of vegetation on this interaction and gave a climate ratio, which is the ratio of precipitation to evaporation from a free water surface (Prescott 1946). This Transeau ratio helps describe the effectiveness of rainfall. A few studies on soil moisture indicate that it increases with elevation (Wangda and Ohsawa 2006, Chen et al. 2017) and this is evidenced in some forests of the outer Himalayan ranges. These moist mid-elevational forests, with a high Transeau ratio (often above 3) have been referred to as cloud forests (Miehe 2015), *Quercus lamellosa, Lithocarpus* *pachyphylla,* and *Tsuga dumosa* dominated forests are some examples. Inner ranges in contrast are dryer and forests have lower Transeau ratio's (Table 1).

It needs to also be highlighted that the use of the term 'Temperate' for mid-elevational Himalayan forests is problematic as these forests have numerous unique features that distinguish them from other temperate forests (Zobel and Singh 1997). While altitude does bring with it temperature regimes that are similar to Temperate forests, the sub-tropical latitudes lead to longer growing seasons and relatively long and warm days with high productivity even in the winter. The higher solar insolation and the protective effect of the northern physical barrier of the Himalayas protect the Himalayan 'temperate' forests from extreme low temperatures. These features, along with the monsoonal precipitation regime, lead to an unusually high proportion of evergreen trees, high litter decomposition and nutrient turnover rates which are closer to tropical then temperate forests. We encourage use of the terms Montane temperate forests, a term also used by Champion and Seth (1968).

Added to the temperature-moisture variations is topographical heterogeneity and varied landforms. The Himalayan ranges are varied entities in terms of their formation and folding, Varied rock strata and dip and scarp slopes create myriad combination of soil depths and soil types. The numerous parallel ranges, such as the Shivaliks and the lesser Himalayas reflect the differences in orogeny and lead to differences in soils composition, depth and drainage which influence vegetation. Position on a slope also plays an important role (Tyagi et al. 2023).

Superimposed on these natural variations are human impacts. The Himalayas have been populated and used by humans for millennia and the impact of humans can be seen in forests in every part of the Himalayas (Singh and Singh 1992, Schmidt-Vogt and Miehe 2015). Human impact extends to the treelines and most Himalayan treelines are anthropogenically depressed (Schickhoff et al. 2015). The population density in Himalayas is higher than in the other mountains of the planet and grew by 250% from under 20 million to almost 55 million between 1961-2011 (Apollo 2017). Even as remote a region as the Tibetan plateau shows human habitations over 30,000 years old (Zhang et al. 2018). However, livelihood opportunities are limited and subsistence agricultural activities still dominate. Transhumance and pastoralism have been an integral part of the western Himalayas since time immemorial, while shifting cultivation has been practiced in the eastern regions for centuries. Burning of forests, lopping and pollarding of trees, and whole tree cutting for fuel and construction work, transformed Himalayan forests long before commercial forestry. As human populations have grown, the degradation, fragmentation and reduction in area of forests have occurred (Singh and Singh 1992, Reddy et al. 2018). In many areas it is difficult to ascertain what the original vegetation would have been. Champion and Seth (1968) also recognized the presence of degradation stages in their classification. Moreover, the scale of deforestation varied. While much of it was local, in many cases there were regional impacts. For example, the spread of railways in the 19th century led to large scale cutting of sal in India (Tucker 1983) and in Nepal agriculture expanded widely in *Schima-Castanopsis* forest area (Stainton 1972).

Thus, in the Himalayas, forest vegetation follows multiple and complex gradients, resulting in varying degrees of species dominance. The varied topography

Table 1. Transeau ratio for forest types in the inner and outer Himalayas (derived from Miehe et al. 2015)

Location	**Aspect**	**Lowest Transeau Ratio**		**No. of forest types**	**Average TR lowest**
		Average	**Range**		
Inner ranges	All exposures	1.3	1.3	1	1.27±0.26
	Northern	1.46±0.34	0.48-2.01	4	
	Southern	1.10±0.47	0.19-2.84	5	
Outer ranges	All exposures	1.86±0.25	1.38-2.36	4	1.74±0.20
	Northern	2.70±0.57	1.71-4.0	5	
	Southern	1.28±0.13	0.72-1.89	9	

leads to a patchwork of altitudinal and moisture combinations which makes characterising regional patterns more difficult.

Influence of biogeography and its interactions with climate

The Himalayas are at the confluence of the Palearctic and Indo-Malayan biogeographic reams and the influence of these two realms on vegetation needs to be considered while describing Himalayan forests. The Palearctic brings species that are familiar to Europe and North Africa and that have evolved with stronger seasonality common in more temperate climes. The influence of this biogeographic region is strongest in the northern and western parts of the Himalayas and is characterized by genera such as *Pinus*, *Quercus*, *Betula* and *Cornus*. The Indo-Malayan in contrast is characterized by a tropical and subtropical climate, and a high level of biodiversity with higher endemism. *Shorea*, which dominates across the lower foothills is representative of this realm. At higher elevations species such as *Schima wallichii* and *Duabanga sonneratioides* are common examples. The forests in the south and east of the Himalayas are characterized by their Indo-Malayan affinities.

As per Udvardy (1975), the northern and western part of the Himalayas (The 'Himalayan Highlands' biogeographic province (2.38.12) as well as the Hindu Kush Highlands (2.37.12) form part of the Palearctic realm, whereas southern flanks of the Himalayas – 'south of the temperate-Palearctic Himalayas' are part of the Indo-Malayan biogeographical realm (Bengalian rainforest (4.3.1) and Indo Ganges Monsoon forest (4.8.4)). Holt et al. (2013) use phylogenetic considerations to draw a global map of zoogeographic regions and show a similar meeting of regions in the Himalayas though they name the regions Oriental (along the southern slopes of the Himalayas and in the east), Sino Japanese (along the northern flanks of the Eastern Himalayas) and Palearctic and Saharo-Arabian meeting around the Hindu-Kush Himalayas. Situated at the meeting point of these biogeographic zones lies the Himalayas with vegetation that shows affinities to these different biogeographic regions and has also evolved distinctly under conditions of differing moisture and temperature regimes which leads to high levels of endemism.

Influence of rainfall patterns

The Himalayas are subject to two major pluviometric regimes. The dominating one is the South Asian summer monsoon which sweeps in from the southeastern Himalayas and leads to heavy precipitation typically from June - September. The second is the extra-tropical upper westerlies which supply smaller, but significant moisture inputs to the high mountain ranges, especially in the northwestern Himalayas where they may be the dominant source of precipitation. Winter precipitation is often caused by these Westerlies. While forests that are dependent on the monsoons tend to be wetter, the seasonality of rainfall is equally important in determining forest type.

Based on these affinities and moving from Southeast to Northwest across the Himalayas the vegetation can be divided into the following broad ecological divisions (Fig. 1):

Type I: Submontane zone of broadleaved evergreen tropical and subtropical forests, largely eastern Himalayan as well as the southern flank of the Himalayas consisting of wet/moist forests with high tree diversity and strong Indo-Malayan affinities.

They are best found in Northeast India, Bhutan and Eastern Nepal. Dipterocarps such as *Shorea* characterise the lower reaches, and as altitudes increase Ericaceae (eg *Rhododendron*) and Theaceae (eg *Schima*) become more common. While families, such as the Fagaceae, are well represented across the Himalayas, in these eastern forests they often tend to occur in mixed species stands where no one species dominates. For example, in the Buk oak (*Quercus lamellosa*) forests, which are named for a single species, (Type IV; Group 11B, Ci-1b as per Champion and Seth 1968), the Buk oak only forms 12.5% of the forest. *Castanopsis* and *Schima* are common genera of some of these forests, and the Ericaceae, especially various Rhododendron species often find great abundance. Several sub-tropical and lower temperate species, including Bauhinia's and species such as *Duabanga grandiflora, Lithocarpus elegans, Engelhardtia spicata, Toona ciliata, Magnolia hodgsonii, Acrocarpus fraxinifolius, Michelia cathcartii, Bischofia javanica, Careya arborea are commonly found in these forests.*

Type II: Montane forests of the central and western Himalayas, and higher elevation forests**:** These are forests with stronger Palearctic and Tibetan affinities.

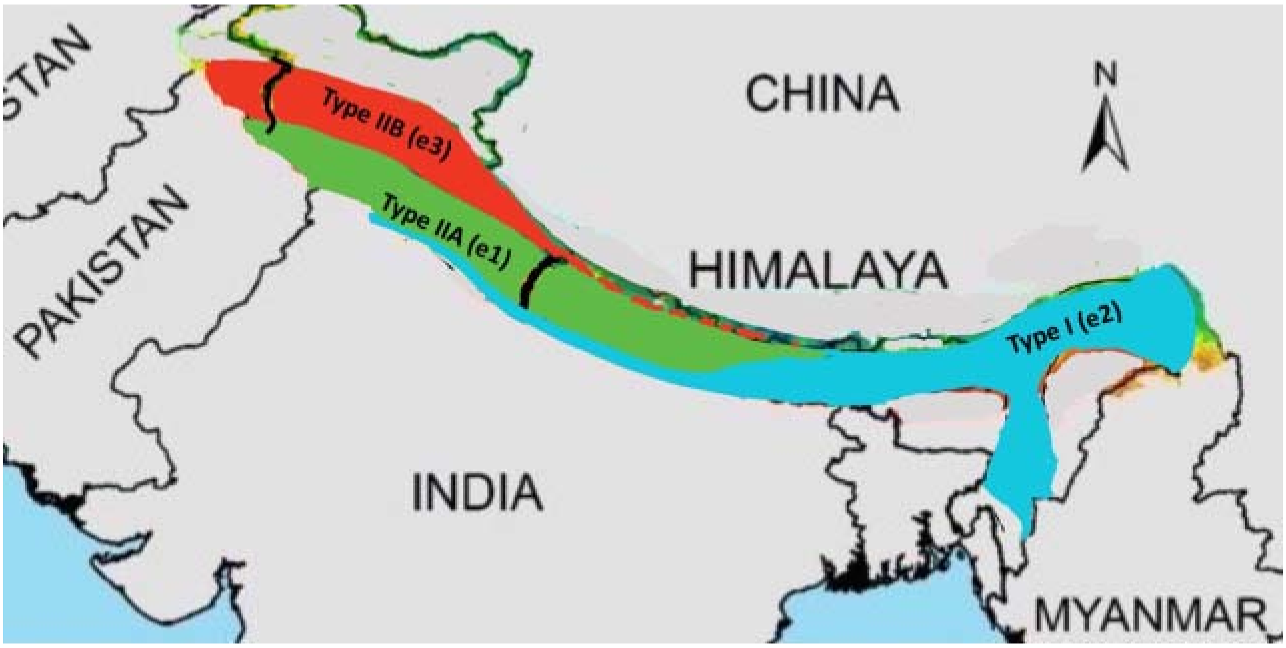

Figure 1. Different forest and leaf types across the Himalaya (boundaries of forest type are representative and indicative)

They are simpler in structure, with lower tree diversity, often forming monodominant stands. They occur across the central and western Himalayas and along the northern ranges and inner valleys across the Himalayan arc. These type II forests are what best represent the Himalayan forests. Not only is their geographical extent significantly greater, but they represent species that have evolved and better adapted to the montane conditions of the Himalayas. While sensitive to moisture, they are better adapted to varying edaphic factors and these species can often dominate across a greater variation in soil types and parent materials. Soil depth and soil moisture is typically more important than the nature of the parent rock and many of these soils are immature, lacking a well-developed profile.

They can be further subdivided into:

II-A: *Forests of the Outer Himalayan ranges* which are exposed to the direct monsoon thrust. These include broadleaved oaks, alder, laurels, some winter deciduous forests, as well as some conifers: a Diploxylon pine (*Pinus roxburghii*) and a fir (*Abies spectabilis*). Evergreen species which shed their leaves annually and simultaneously leaf out dominate this eco-division.

II-B: *Forests of the Inner Himalayan ranges*. These are the dryer ranges, often in the rain-shadow areas, and at higher altitudes, shielded from the direct monsoon thrust. These forests have trees with a lower Transeau ratio than trees of the outer ranges (Table 1). The impact of the westerlies is high on this vegetation which is rich in conifers: such as deodar (*Cedrus deodara*), spruce (*Picea*), Haploxylon pines, larch and juniper forests, and some firs (*Abies pindrow*) winter deciduous forest types. It includes largely conifers with multi-year leaves differing in form and length. However, the type also includes small areas of deciduous forests, both of broadleaved (birch and willows) and conifer (larch). Some of the most attractive forest types consisting of tall (up to 60 m or more) stately trees of deodar, spruce, and firs occur in this division (Champion and Seth 1968).

Abundance of monodominant forests

When it comes to classifying vegetation, we heavily depend on identifying dominant species, which becomes difficult when species richness is high, as is the case in the more moist forests of the eastern Himalayas (termed above as Type I Himalayan forests).

In the western and central parts of the Himalayas (Type II forests) monodominant stands abound. Interestingly, every elevational zone in the Himalayas has species which can form large contiguous monodominant stands. In the foothills (upto 1000m), Sal (*Shorea robusta*) is known for its extreme gregariousness typically allowing few other species to get associated (Stainton 1972), in the frequently burned chir pine (*P. roxburghii*) forest (1000-1800m) most other woody species are suppressed; at warm temperate altitudes (1500-2100m) banj oak (*Q. leucotrichophora*) can form almost continuous stands in the central Himalayas, above which kharsu oak (*Q. semecarpifolia*) is highly successful in dominating from about 2500-3200m. In the Western and central Himalayas *Betula utilis* dominates the treeline, while firs namely *Abies pindrow*, *A. spectabilis* and *A. densa* can dominate in stands at/near treelines in the western, central and eastern Himalayas, respectively (Troup 1921, Stainton 1972). Some of these forest types, such as *Pinus roxburghii* and *Cedrus deodara*, can attain valley-level dominance over hundreds of kilometres regardless of local variabilities. The monodominance may be related with particular edaphic factors and disturbances. *Cupressus torulosa* (Cypress), as an example in the Nainital region owes its monodominance to steep south facing slope with limestone rocks, prone to gravitational fall. Such a habitat is inhospitable to most other species, and cypress is often able to form pure stands in the absence of competition with them. Alder (*Alnus nepalensis*) colonizes landslides and forms monospecific stands in areas varying in annual precipitation from 1000-5000 mm both in the eastern and western regions of the Himalayas. *Dalbergia sissoo* and *Acacia catechu* colonize freshly formed substratum along rivers (Champion and Seth 1968).

Thus, dominant tree species that belong to very different families, and can be either angiosperms or gymnosperms are a very visible and important component of most Himalayan forests across a range of altitudinal and moisture regimes.

Using a leaf-based classification and dominant leaf type to categorise Himalayan forests

Leaf characters, such as leaf life span, size, extent of sclerophylly, periodicity of leafing and leaf drop have been used to classify vegetation (Webb 1959, Wu 1980, 1987, Medina et al. 1990, Ashton 2014, Ashton and Zhu 2020). Division of forests into evergreen and deciduous types, or broadleaved and conifers, has been practiced since the beginning of vegetation classification. Raunkiers' (1934) categories of leaf size (leptophylls to megaphylls) have been widely used in vegetation classification. Leaf size is known to influence several aspects of tree function, such as rate of transpiration and photosynthesis (Malhado et al. 2009) and is thought to increase along the gradient of increasing precipitation (Givnish 1987). Leaf size and wood density often show inverse correlation, trees with lower wood density have larger leaves (Wright et al. 2007). Smaller leaves may suffer less herbivory during leaf expansion (Moles and Westoby 2000). Leaf characters directly and indirectly influence community composition and adaptational features and are predominantly associated with physiognomy of vegetation. Leaf traits are known to determine plant and stand characters (Reich et al. 1992). Leaf life span influences photosynthesis and defensive traits (Matsuki and Koike 2006), leaf traits vary in response to variation in resource availability (Zhang et al. 2020), and leaf life span and photosynthesis parameters are linked (Vasfilov 2016). There are evidences to indicate that competition between conifers and angiosperm trees is affected by leaf characters (Brodribb et al. 2012), and adaptive significance of evergreen vs deciduous leaves (Givnish 2002) is related to several other plant traits and habitat condition. Leaf traits are associated with several ecosystem characters (Luo et al. 2005). As an example, needle leaves are known to retain more water, are less damaged by snow, and are more energy saving than broadleaved (Norris 2018). Conifer leaves have more carbon concentration than leaves of broadleaved species (Ma et al. 2018).

Plant phenology is strongly interlinked with ecosystem processes and biodiversity (Gray and Ewers 2021). In view of the widespread relevance of leaf characters, we use leaf traits of canopy species to classify Himalayan forests.

Furthermore, the focus on leaf characters for forest classification enables us to characterize the Himalayan forests at a regional scale and distinguish them from the forests of other regions. We considered leaf life span and phenology and manner of leafing and leaf drop, form of leaves (e.g., broadleaf and needle-like leaf) and extent of sclerophylly of dominant trees species. Instead of treating conifers' leaves as one category, we divided them keeping in

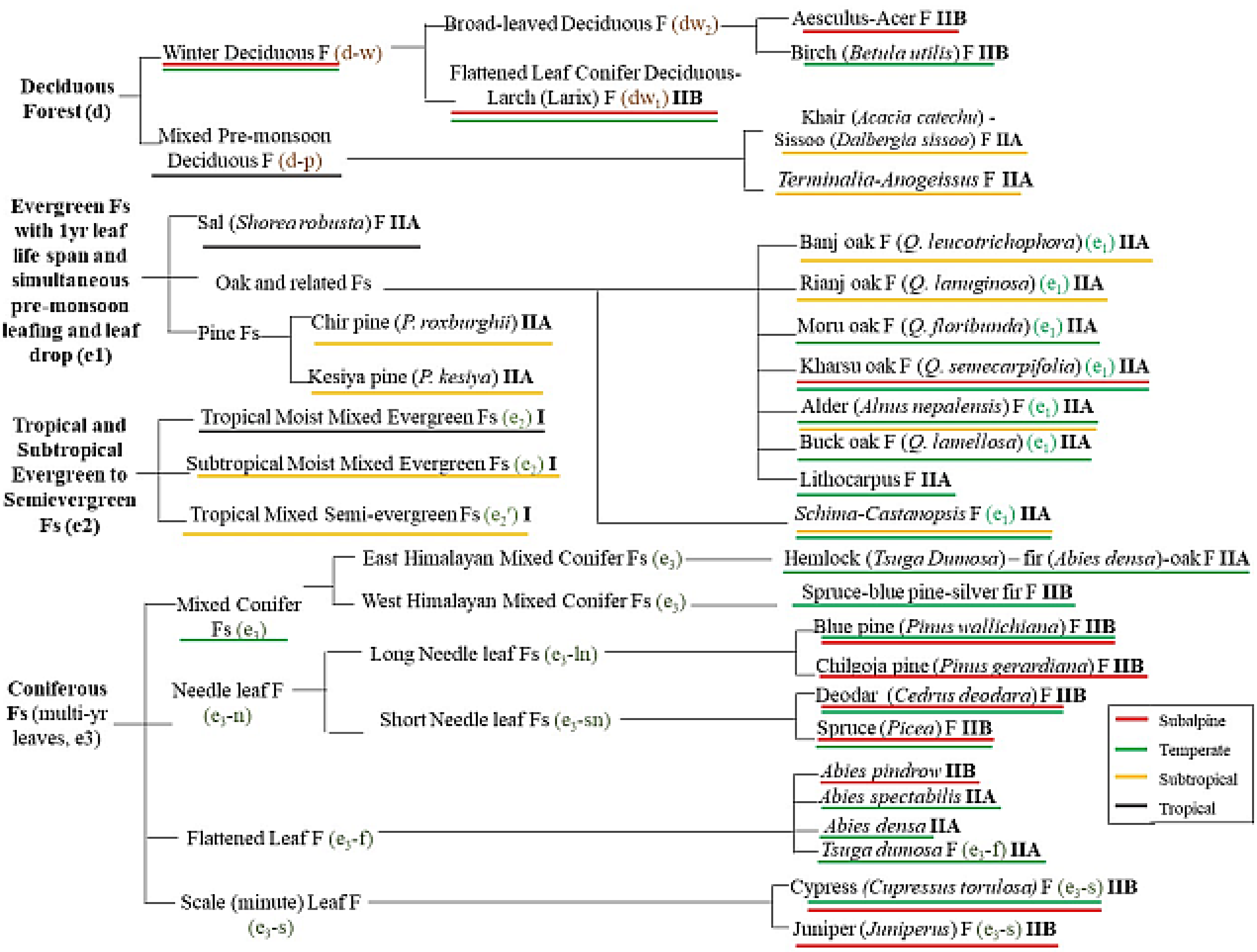

Figure 2. Leaf based classification of Himalayan Forests - a schematic representation.
The Himalayan forests are divided into five main types with regard to leaf, viz. deciduous (d) represented by (i) winter deciduous and (ii) drought (pre-monsoon) deciduous; (iii) evergreen with about one year leaf life span and simultaneous leafing, and leaf drop during pre-monsoon (e_1); (iv) tropical evergreen with mixed leaf life span, size and other leaf characters (e2); and (v) coniferous type, generally with leaves of several years longevity (3-6 years) (e3). Each of these large groups can further divided. Winter deciduous is divided into broadleaf deciduous and flattened leaf conifer deciduous which includes larch. The e_1 type is a heterogenous group, consisting of mesophyllous sal, scelerophyllous oaks and long needle leaved pines. The classification emphasizes that conifers also vary considerably in leaf form, and species with different leaf forms vary in adaptation to environment and photosynthetic rate. Coniferous forests (e3) type can be divided into conifers with needle like leaf, flattened leaf and scale like leaf and so on. The colour of underlines indicates altitudinal belts corresponding to tropical, subtropical, temperate and subalpine areas. When a forest occurs in more than one belt, it is underlined with more than one colour. F is for forest.

view the adaptational significance. The forest groups recognized based on leaves are given in Figure 2 and described below.

We limit ourselves to trees – the dominant life form of the forest. Herbs and shrubs may form patterns that are very different. Herb diversity for example can be richest in forest types where tree diversity is low. Furthermore, the effect of human disturbances (through activities such as grazing, litter removal, fodder extraction or surface fires) can in short time scales very significantly impact herb and shrub flora. Given the high impact of humans across the Himalayan landscape, it becomes more difficult to use these lifeforms for forest classification. Within trees also, the focus is on overstory trees. It needs to be emphasised that not all trees in the forest follow the dominant pattern and understory trees in particular, which are subject to different limiting variables may often show variance in strategies.

We divide the Himalayan forests into five main types with regard to leaf types, viz. (i) evergreen with about one year leaf life span and simultaneous leafing and leaf drop during pre-monsoon (e1); (ii) sub-tropical and tropical evergreen with mixed leaf life span (e2); (iii) coniferous type, with leaves of greater than 1-year longevity (e3) and deciduous (d) – forests where the dominant trees lose their leaves in response to unfavourable conditions for part of the year which are further divided into (iv) winter deciduous (dw) and (iv) Pre-monsoon deciduous (dp).

These leaf characters associated with phenology are important also because they emphasize adaptational commonalities across different groups. Thus, the e1 type includes disparate taxonomic and altitudinal groups from tropical dipterocarps to temperate oaks and even conifers.

The e1 species are central to Himalayan forests

The Himalayan forests are best exemplified by evergreen species with concentrated leaf drop and simultaneous leafing during the pre-monsoon (March-May, dry and warm season). In the western and central Himalayas these dominate, but are commonly found in the eastern Himalayas as well. Referred to as e1 type these includes varied growth forms, mostly broadleaved species, but also some conifers. They range from sclerophyllous oaks (e.g., *Quercus leucotrichophora*, *Q. floribunda*), mesophyllous dipterocarps (*Shorea robusta*), an evergreen maple (*Acer oblongum*) and even sub-tropical needle leaved pines (*Pinus roxburghii, Pinus kesiya)*. While globally pines are associated with leaf (needle) life spans of 2-40 years (Richardson 1998), in the Himalayas these subtropical pines have a leaf life span of about one year and follow the e1 strategy. Variation in specific leaf mass (g m^{-2}) of these species vary widely: 112 for *Shorea robusta*, 137-200 for the oaks and over 300 for *Pinus roxburghii*. (Singh et al. 1994).

While the dominant leaf flush occurs in the pre-monsoon, some species have secondary leaf production during or after monsoon to take advantage of favourable growth periods with fresh leaves. However, unlike evergreen tropical rainforests which have leaf fall through the year (Reich 1998), leaf fall is episodic in e1 forests. In many species, including *Pinus roxburghii* and *Shorea robusta*, which are among the most common Himalayan species (FSI 2021) there is a period when the tree has a sparse leaf cover during the pre-monsoon months and in this respect they resemble pre-monsoon deciduous trees. The shedding of old leaves and thinning of the canopy during pre-monsoon drought allows these trees to replenish tree water status enough to initiate the growth of young leaves (Zobel et al. 2001). These occur over a wide range of elevation from foothills (*Shorea robusta*) to treelines (*Quercus semecarpifolia*) but are much more pronounced in outer Himalayan ranges that are directly exposed to the monsoon thrust (Type II A forests).

This particular leaf trait (evergreen with leaf life span of about one year, showing simultaneous leaf drop and leafing during pre-monsoon) significantly contributes to separating the Himalayan forests from other regions of the world. The reason why such species prevail, and often dominate in Himalayas, have been discussed by Singh et al. (1994). The monsoon pattern of rainfall, characterized by three to four months of concentrated rains, followed by long rainless spells during winters and early summer is a major climatic factor that greatly influences the selection of plant functional types and species. The autumn (post-monsoon season) is highly favourable for plant growth with sunny and long days (for e.g., >11 hour daylength through October in Nainital, Central Himalaya), high relative humidity and soil moisture, and night time temperatures that remain above freezing up to a considerably high elevation. This enables e1 type species to attain peak photosynthetic rate during the fall season (Thadani 1999, Tyagi et al. 2023).

This is the time when broad-leaved trees in most temperate regions start senescing and decreasing their physiological activities because of cold temperatures and short-day lengths. These Himalayan species in contrast are able to maintain a high fraction of photosynthetic capacity of mature leaves (Luo et al. 2017). *Q. leucotrichophora* has been observed to conduct photosynthesis until the last days of its leaf life span (SPS personal observation). A forest dominated by e1 type of canopy species may have undercanopy species with leaf life span that clearly exceed one year. For example, the leaf life span of *Rhododendron arboreum* shows ranges between 18-23 months (Singh and Negi 2018). This long leaf life span of such species could be related to a low concentration of nutrients in its leaf tissues (Singh and Singh 1992). In Himalayan conditions characterized by mild winters with relatively long day length, and high relative humidity during much of the year, the species which produce new leaves just before the favourable season for photosynthesis and retain them round the year (e1-leaf type) have a competitive advantage over other species. These evergreen species (e1) dominate over deciduous species as they can assimilate carbon throughout the year, including the mild winters. By overhauling the entire foliage mass in the pre-monsoon, they have fresh leaves to maximize the photosynthesis by the time rains arrive. Multi-year evergreen species in contrast have many old leaves with reduced photosynthetic capacities. Tree species with these other strategies also co-exist in each forest type. For example in the e1 forests of the central Himalaya, genera such as *Rhododendrons, Machilus, Ilex*, which have differing strategies may commonly co-exist.

The e2 type (Evergreen to Semi-evergreen and tropical to sub-tropical)

In the lower elevation forests of the Eastern Himalaya, trees remain evergreen and show multiple flushes through the year. These species are classified as e2 species and the common feature is multiple leaf flushes. Leaf life span is often less than one year (Devi and Garkoti 2013; Devi et al. 2014) though some authors have reported longer leaf life spans of upto 20 months (Boojh and Ramakrishnan 1981). Some species show almost continuous leaf flush through much of the year, while others have only 2-3 flushes at fixed times often in the pre-monsoon (March -April) and then again in the late monsoon (August-September). Peak leaf fall occurred in the dryer, i.e. pre-monsoon months (January-February) (Kikim and Yadava 2001). Common trees include *Schima wallichii, Duabanga sonneratioides, Dillenia pentagyna*, *Artocarpus chaplasa, Tetrameles nudiflora* and severeal species of *Lithocarpus* and *Castanopsis.* At higher elevations Rhododendrons increasingly dominate.

Typically, e2 tree species are not sclerophyllous, have leaves generally of mesophyll size, and at the stand level the evergreen character is maintained, though some forests show a slight thinning during pre-monsoon or late winter. The presence of a significant number of deciduous species is reported especially at tropical altitudes (Kikim and Yadava 2001) though deciduous species are usually not dominant and the general character of the forest remains evergreen. One convenient criterion to classify is the percentage of tree species having mesophylls and megaphylls. Though a highly plastic leaf trait, leaf size is significantly associated with environmental variables like moisture, irradiance and elevation (Malhado et al. 2009). In lowland rainforests the percentage of species with mesophyll is estimated at 75% by Turner (2001), and 73.6% for Amazonia by Malhado et al. (2009). In a tropical wet evergreen forest of Assam (Devi and Garkoti 2013) in a sample of 19 tree species 84.2% had mesophyllous leaves which is similar to that of tropical rain forests of Amazonia, and other rainforests region.

Evergreen conifers with multiple year leaf life spans (e3 type)

While some pines, and notably chir pine can have a one-year leaf life span with simultaneous leaf production and leaf fall (e1 type), the majority of conifers follow a distinct patterns with leaves that persist for multiple years (often 3-6 years). These are categorised as e3 type and include the majority of conifer species such as the firs, spruce, and cedar. While they are found across the Himalayas, the e3 type conifers dominate in the inner (more northernly) ranges at altitudes above 2000m. They also dominate in much larger areas in the Western Himalayas.

On the basis of leaf morphological characters, e3 type conifers are divisible into three main types: (i) needle like leaves, (ii) flattened leaves (dorsiventrally asymmetric) and (iii) scale like leaves. Among the Himalayan conifers, *Pinus, Cedrus,* and *Picea* have needle like leaves, *Abies, Tsuga, Larix* and *Taxus* have flattened leaf type, and *Cupressus* and *Juniperus* (family Cupressaceae) appressed imbricate scale leaves (Fig. 2). The mean leaf width to thickness ratio (WTR) of the cross section is less than 2 in needle like leaves and more than 2 in flattened type (Du et al. 2020).

In the pine family needle like leaves show a higher photosynthetic rate than flattened leaves (Brobribb et al. 2007, Brodribb and Feild 2007). The needle like leaves are suited to sunny and dry environments, whereas flattened and broader leaves are better adapted to shady and humid conditions. Members of the *Cupressaceae,* with scale like leaves, are through a combination of morphological and physiological means adapted to some of the driest areas of the Himalayas. Their appressed small and imbricated leaves accompanied by reduced xylem specific conductivity (Brobribb et al. 2007, Pittermann et al. 2012) reduce transpiration losses. Physiologically, the Cupressaceae are most efficient among conifers to be able to survive among the lowest water potentials without cavitations and embolisms that damage leaves of other conifers (Brodribb et al. 2014). Consistent with these attributes, several *Juniperus* species and *Cupressus torulosa* occupy some of the driest sites in Himalayas and are generally associated with dry inner valleys. Junipers are the only evergreen species which occur in the cold deserts of Ladakh with about 100 mm annual precipitation.

Conifers with flattened leaves, can occur in a range of moisture regimes. Mention may be made of the two fir species, *A. pindrow* associated with both dry inner and moist outer ranges and *A. spectabilis,* a fir that can form extensive stands in the moist outer ranges along much of the Himalayan arc. *A. pindrow* is the main fir of Kashmir valley, a region shielded from the monsoon by Pir Panjal ranges though it can also be found in more monsoonal climes. It occupies lower elevations than *A. spectabilis*, and generally these do not form mixed stands. *Abies spectabilis* (silver fir) along with other conifers with flattened leaves, such as and *Tsuga dumosa* (hemlock), generally occur in the outer (southern) ranges and can even occur among the most mesic forests, such as the cloud forest zone of the Himalayas (Miehe et al. 2015)

Conifers with short needles, such as *Picea* and *Cedrus* largely occur in dry areas, particularly in dry inner valleys, as in moist outer ranges they are unable to compete with conifers like silver fir with flattened leaves and broadleaved oaks (Champion and Seth 1968).

In this leaf-based classification, the diploxylon pines (*Pinus roxburghii, P. kesiya* and *P. merkusii*) go with oaks and sal (e1 type) as they share similar phenology: evergreen and yearly leaf drop and simultaneous leafing during the pre-monsoon. Presumably, morphologically distinct species having similar phenologies come together under the influence of monsoon force. *P. wallichiana* is unique among Himalayan conifers, though centred in high and dry inner Himalayan ranges, this haploxylon pine is follows an e1 like leaf phenology.

The conifers do also mix with broadleaved trees. In the Eastern Himalayas, mixed coniferous forest consists of *Tsuga dumosa* and *Abies densa* in canopy, and *Quercus pachyphylla, Q. lineata, Acer campbelli, Magnolia campbelli, Taxus baccata* and rhododendron in the undercanopy. In the Western Himalayas, mixed coniferous forest consist of spruce, silver fur, blue pine and deodar and varying mixtures of oaks and deciduous broadleaved species, in particular oaks.

Deciduous (d) type

Deciduous forests are divided into two distinct groups, (1) winter deciduous trees where leaves are shed in the late fall as a result of colder temperatures, and (2) pre-monsoon deciduous (March-May) where leaf loss is a response to droughty conditions.

The number of deciduous species in the Himalayas are considerable. In the Indian Himalayas there are 727 evergreen tree species and 574 deciduous species, which is 44% of total tree species (Bhatt et al. 2020). The western Himalayan forests are richer in deciduous species than evergreen trees and even in the eastern forests for example Shukla and Ramakrishnan (1982) report 54 deciduous species out of 122 tree species in a subtropical humid seasonal forest. However, deciduous species form far fewer forest types, and much smaller forests areas, than do the evergreen species. Above 2000 m elevation, Miehe et al. (2015) recognized only three deciduous (winter deciduous) forest types, namely birch (*Betula utilis*) forest, *Aesculus-Acer* forest, and larch, a conifer deciduous forest. Champion and Seth (1968) recognized only two of them, namely birch and larch forest. With the exception of upper elevation birch forests, a characteristic feature of the Himalayas is the absence of large areas under deciduous species in spite of their being a floristic base.

Winter deciduous forests:

Winter deciduous forests are further divided into broadleaf deciduous species, such as *Betula utilis (Himalayan birch),* and into flattened leaf deciduous conifers which includes larch (*Larix griffithii*) which belongs to the Pinaceae family. These shed their leaves in response to the changing photoperiod and decreasing temperature as winter approaches. They are typically influenced by seasonal changes in light and temperature, which signal the approaching winter. The decrease in day length and temperatures prompt hormonal changes that lead to leaf fall. These trees typically enter a dormant state during winter and physiological activity is very low. While these forests are best seen at higher elevations and close to the timber line where *Betula* dominates extensively in treeline areas of inner valleys in the western and central Himalayas, several deciduous species form smaller patches at temperate altitudes. Examples include *Aesculus indica* (Himalayan horse chestnut*)*, *Acer caesium* (Himalayan maple), and *Carpinus viminea* (Hornbeam).

Drought deciduous forests:

Pre-monsoon or Drought deciduous trees on the other hand shed their leaves in response to prolonged dry period and drought conditions. Water scarcity triggers the abscission process to help the trees survive dry periods. The lack of soil moisture is usually the trigger to initiate abscission and hence many of these trees, if grown in mesic environments will not completely lose their leaves during the dry period.

Pre-monsoon deciduous forests are most common in the foothills. Examples include *Dalbergia sissoo*, *Acacia catechu* and *Bauhinia variegata* as well as species of *Terminalia*, and *Anogeissus*. The pre-monsoon deciduous and the e1 type evergreen species show a continuum, with several e1 type species (including major species such as *Shorea robusta* and even *Pinus roxburghii*) having a phase with distinctly reduced leaves and an almost deciduous character in some sites. While sal has been described as a deciduous species by some authors, in our opinion it can be considered evergreen, as sal trees typically do not become leafless and remain physiologically active during the period of leaf thinning. Sal has a greater degree of canopy thinning than other e1 species. However, its canopy thinning is on a continuum with chir pine and most oaks, which are regarded as evergreen by all.

Thus winter and pre-monsoon deciduous differ fundamentally. Winter deciduous species show a period of physiological dormancy which is not seen in the drought deciduous. The drought deciduous are also more responsive to the limiting variable (moisture) for leaf shedding. The specific leaf area of pre-monsoon deciduous species is lower (9.46 m^2/kg) than that of winter deciduous species (15.2 m^2/kg) (Zobel and Singh 1997).

In the mid-elevations the canopy is usually evergreen. At least in the Western Himalayas deciduous species are often confined to small pockets along water courses, like streams and in hollows and depression. Deciduous species form occasional stands amidst evergreen forests also by colonizing landslide deposits eroded sites (Suri 1933). The winter deciduous forest, *Aesculus-Acer* frequently occurs as patches along the water courses on shady slopes, often with boulder fields in the western part (69°30'-82°30' E), generally beyond the full thrust of monsoon.

In some areas, especially in the dry inner valleys, evergreen and deciduous species occur in mixed patches. Common deciduous species include *Aesculus indica, Acer caesium* and *A. cappadocicum, Ulmus wallichiana, Cornus macrophylla, Populus ciliata, Carpinus viminea*, *Fraxinus micrantha* and *Sapium insigne* in the western Himalayas. We refer to these as western Himalayan mixed deciduous forest. At higher elevations birch may occur mixed with oaks such as *Q. floribunda* and *Q. semecarpifolia*. In the eastern Himalayas deciduous species include *Magnolia campbellii, M. globose, Osmanthus suavis, Corylus ferox, Acer caudatum, A. hookeri, A. pectinatum, A sikkimensis, Prunus rufa, Sorbus thomsonii* (Stainton 1972). Distributional patterns of these species in these Eastern Himalayan mixed winter deciduous forest and their contributions to forest communities need to be better investigated as data is limited.

Deciduous strategy has limitations in the Himalayas

The deciduous habit has been referred to as acquisitive leaf strategy and evergreen habit as conservationist strategy (Donovan et al. 2011, Bai et al. 2015). Where resources are not strongly limited, deciduous species have a competitive advantage over evergreen as they are able to acquire higher carbon amounts at a lower leaf dry mass cost (Reich et al. 1992, van Ommen Kloeke et al. 2012). In the Himalayas, high rates of soil erosion in the monsoon-drenched outer ranges, may be limiting to nutrients. While photosynthetic capacity per unit dry weight of leaf is typically lower in evergreen species than in deciduous (Reich et al. 1991, Wright et al. 2005), the advantage which is associated with the longer leaf life span of evergreen species is their higher nutrient retention potential, which gives them a competitive edge in infertile habitats (Pornon et al. 2011).

In the moist outer ranges of Himalayas deciduous species are outcompeted by evergreen species with e1 leaf habit, which much like a deciduous species produce much of their new leaves annually just before the most favourable periods for photosynthesis (moist and warm days). As winters are relatively warm and sunny, these e1 species are able to fix carbon throughout the winter which compensates for the higher cost of the evergreen, often sclerophyllous, leaves. Thus, e1 species, by combining traits of deciduous and evergreen habits are able to dominate.

In the dry and cold inner ranges, conifers and broadleaf species with multi-year leaves with low nutrient concentration outcompete deciduous species from dry and infertile habitats. In such resource-poor habitats, leaves of longer leaf life span may outcompete deciduous species with their inherently resource conservation traits.

Even at the limits of tree growth, at the treeline, species such as *Abies spectabilis* and various rhododendrons dominate especially when moisture is adequate. Only at the extreme limits of cold and dry climates near the timberline, birch (*Betula utilis*) and some species of *Sorbus* are able to develop communities over large stretches. This is especially in the Western Himalayas where the climate is more continental, winter temperatures are lower and impact of the monsoons is less (Bobrowski et al. 2017). These more inhospitable conditions (the treeline is over 500 metres lower in the Western Himalayas compared to the Eastern Himalayas, and winter temperatures far colder), and the presence of higher winter snowfall due to the westerlies, allow birch to outcompete the evergreen species (Schickhoff et al. 2015, Bobrowski et al. 2017).

While the outer, moister ranges of the Himalayas are associated with e1 type forests, the inner ranges seem to be associated with multiple year leaves of conifers. Among the important broadleaved species, only *B. utilis* and some deciduous species of *Acer* and *Aesculus indica* occur in inner ranges. How strong is this association between e1 forests of the outer ranges, and e3 conifers (conifers with multi-year leaf spans) needs further investigation and study. While predicting the impact of climate change on Himalayan forests, this split in forest type into dry inner ranges (where e3 type dominate) and moist outer ranges (where e1 type dominate) has never been analysed. The two regions may respond differently to climate change, as the relative impacts of monsoon and westerlies vary.

Advantages of a leaf based classification system

Townshend et al. (1991) argue that future systems of vegetation classification should be remote sensing driven, so as to be able to provide a realistic measure of existing landcover. Using consistent, remote sensing based measurement regimes would also eliminate the ambiguities currently extant in vegetation maps derived from varying methodologies and definitions (Running et al. 1995).

Classification of vegetation is today increasingly based on remote sensing methods, where identifying forest types becomes increasingly difficult as ground truthing is often inadequate or even lacking. In the Himalayas due to the steeply undulating topography, rainfall, patterns and temperatures, forests can vary dramatically over short distances of only a few kilometres, and the inhospitable terrain makes ground truthing these difficult.

Our classification system is based on leaf type and phenology. As such it meets the suggestions of Running et al (1995) that classification systems be (a) based on simple, observable, unambiguous characteristics of vegetation structure that are important to ecosystem biogeochemistry and could be measured in the field for validation, b) remotely sensible so that repeatable reclassifications of existing vegetation will be possible, and c) directly translates into the biophysical parameters of interest to climate and biogeochemical models.

Important to this logic is the explicit separation of climate from the vegetation classification, to allow

Table 2. Differentiating between forest types based on leaf cover in different seasons

Forest type	Nomenclature	Winter (December)	Pre-monsoon (March)	Post monsoon (October)
Evergreen -Tropical and Subtropical	e2	++	++	++
Evergreen – 1 yr leaf life span and simultaneous leafing and leaf drop	e1	++	+	++
Deciduous (Winter)	dw	-	+	++
Deciduous (Pre-monsoon)	dp	++	-	++
Coniferous (Multi year life span)	e3	++	++	++

(++ full leaf cover; + sparse leaves; - leafless)
The months suggested are relatively cloudless months when clear satellite images can typically be obtained. Variations in leaf drop and leaf flush lead to varying canopy cover which can be used to distinguish these forest types.

the classification to be based purely on observable remotely sensed vegetation properties. Temperate, tropical, boreal, and other such designations can later be added with specific ranges of temperature and precipitation. Leaf longevity, sometimes simply termed evergreen versus deciduous canopy, is an extremely critical variable in carbon cycle dynamics of vegetation, and is important for seasonal albedo and energy transfer characteristics of the land surface. Thus, leaf longevity class defines whether a plant must completely regrow its canopy each year, or merely a portion of it, with direct consequences to ecosystem carbon partitioning, leaf litterfall dynamics, and soil carbon pools (Running et al. 1995). Using this classification it should be possible through simple seasonal measurements (and largely cloud free seasons are chosen for measurement) based on remote sensing methods to differentiate between these various Himalayan forest types (Table 2).

A continuum based on moisture

In the majority of Himalayan forests, upto the temperate altitudes, the lack of moisture during the dry season is most often limiting to growth. These include the forests categorised as e1, e2 and d-p. For these forests, the pre-monsoon dry period is phenologically the most important phase (Shukla and Ramakrishnan 1982, Singh and Singh 1987, Kikim and Yadava 2001). The pre-monsoon season is one of limiting moisture. In forests in the tropics, sub-tropics and lower temperate regions of the Himalaya, trees typically drop their leaves between November and April. This is not a response to low temperature, but rather low moisture availability. This is a period when rainfall is sparse and trees conserve moisture through low photosynthetic rates and leaf senescence. However, this is also a common period for leaf renewal so as to take advantage of the abundant moisture that the subsequent monsoons rains bring. Photosynthetic rates appear to be high through the monsoon, and often peak in the post monsoon season when light is abundant and moisture not limiting. The most common, and seemingly efficient response, is exemplified by the e1 species, in which nutrient retranslocation occurs during the pre-monsoon, and leaf fall and new flush occur almost simultaneously. During this period photosynthesis rates are low, and moisture loss is also low so as to conserve water which is better available for the new flush (Zobel et al. 2001). The timing of the new flush allows the trees to make best use of the favourable conditions that occur in the monsoon.

The d-p group of trees, which are deciduous in response to the pre-monsoon drought usually drop their leaves earlier, between October and January. These are often found in areas of higher moisture stress (eg at lower altitudes where heat is greater). Leaves are lost 1-3 months before new leaf flush so as to tide over this period of water stress.

In more mesic environments, such as in the eastern Himalayas (the e2 forests), the maximum leaf fall is again between January and March (Shukla and Ramakrishnan 1982, Kikim and Yadava 2001) the period of the pre-monsoon drought. Leaf flush occurs at multiple times of the year reflecting the more

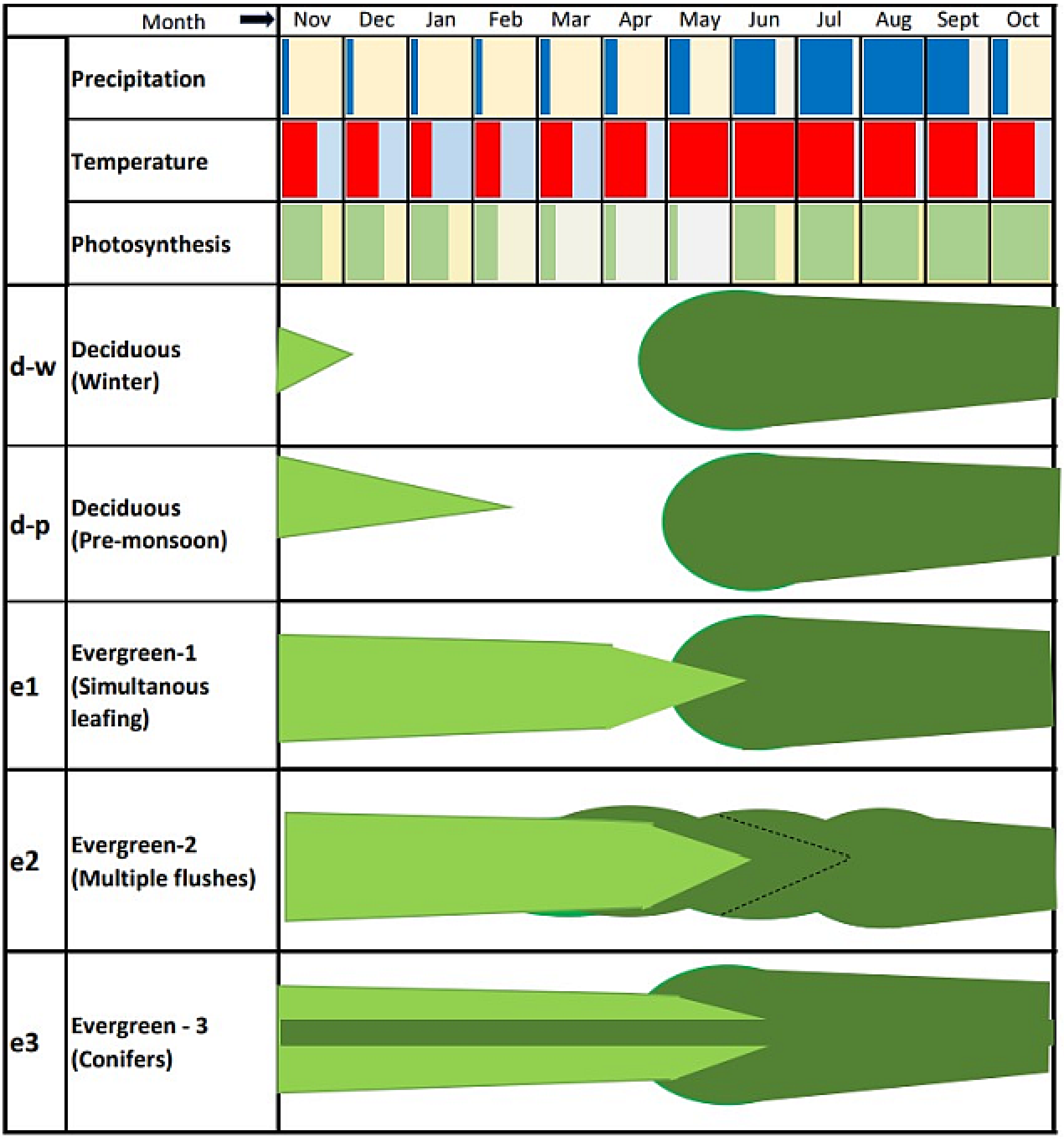

Figure 3. Leaf drop and new flush among broadleaved species: a continuum seen from d-p, e1 and e2 species. Figure showing changing precipitation, temperature and max photosynthesis patterns in a monsoonal forest. Time of leaf drop and leaf flush is shown for species with different strategies

spread out periods of favourable photosynthetic gain. While much like e1 species, these too produce a leaf flush in the pre-monsoon, but so as to take advantage of the favourable post monsoon conditions, additional flushes of leaves are put out by e2 species (Ralhan and Singh 1987, Kikim and Yadava 2001). Figure 3 shows this continuum between these strategies, viz. dp, e1 and e2. Some common examples of these various leaf types are shown in Figure 4.

Varying moisture conditions can impact leaf fall within a species. For example, in dryer areas *Schima wallichii* has been reported to be deciduous (Boojh and Ramakrishnan 1981) whereas across much of

Figure 4. Leaves of some Himalayan trees representing different forest types

Figure 4. Leaves of some Himalayan trees representing different forest types

Figure 4. Leaves of some Himalayan trees representing different forest types

the bhabhar or dry south facing slopes, the tree may be for some time deciduous while retaining a more evergreen nature in moisture areas in the terai or on cooler slopes.

This Himalayan strategy contrasts strongly with trees from most other temperate and alpine zones where changing day length rather than unfavourable conditions (cooling temperatures) trigger leaf fall. For example, introduced horticulture crops such as apples lose their leaves late summer when conditions for photosynthesis are still quite favourable.

CONCLUSIONS

Classifications of Himalayan forests has traditionally been based on temperature and precipitation regimes. While this mode of dividing forests works well regionally, the special characteristics of the Himalaya call for exploring differing systems to categorise these forests. The topographic heterogeneity of the Himalaya creates variation of altitude and moisture regimes over short distances which leads to a patchwork of forest types which do not convey a regional sense of forest change. Furthermore, the Himalaya occur in the confluence of multiple biogeographic regions which also needs to be recognized in any attempt to classify forests. At elevations below about 2500m in the Himalaya the latter part of the spring (pre-monsoon) is when conditions are unfavourable due to water scarcity. The monsoons which start mid-summer, lead to a period of plentiful moisture. Given lower temperatures and low evapotranspiration rates, the adequacy of soil moisture persists well into the fall and Himalayan trees are adapted to take advantage of this season as well as of a mild winter with plentiful light. The majority of Himalayan forests are adapted to these unique conditions. Tree leaves, in terms of form and phenology, help explain some of the variability in ecological strategies found across the Himalaya. We proposed the introduction of a leaf based system of classification to draw attention to the functional traits of Himalayan forests that follow regional trends and help better explain the gradients across the Himalayas. A leaf phenology based classification will also potentially allow for easy differentiation of forest canopies based on remote sensing. It needs to be emphasized that the system proposed based on leaf phenology needs further refinement and improvement. As our understanding of Himalayan trees and their phylogeny improves refinements can be made in this system of classification.

ACKNOWLEDGEMENTS

Authors acknowledge the photographs from Soham Kacker (*Aesculus, Acer, Abies pindrow*), Dr. Pradeep Singh (*Betula*), Bhatt et al. (2020) (*Bauhinia, Engelhardtia, Picea, Abies spectabilis, Taxus*), Surabhi Gumber (*Shorea, Pinus*), Dr. S.K. Tripathi (*Alstonia, Mesua*). Ripu Daman Singh and Surabhi Gumber, researchers of Appropriate Technology India (AT India), Dehradun helped immensely in developing the manuscript.

Authors' contributions: Both the authors contributed equally

Conflict of interest: Authors declare no conflict of interest

REFERENCES

Apollo, M. 2017. The population of Himalayan regions–by the numbers: Past, present and future. Pp. 145-160. In: Efe, R. and Ozturk, M. (Eds.). Contemporary Studies in Environment and Tourism, Cambridge Scholars Publishing, UK..

Ashton, P.S. 2014. On the Forests of Tropical Asia, Lest the Memory Fade. Royal Botanical Gardens, Kew and the Arnold Arboretum, Harvard University. 670 pages.

Ashton, P.S. and Zhu, H. 2020. The tropical-subtropical evergreen forest transition in East Asia: An exploration. Plant Diversity, 42, 255-280. https://doi.org/10.1016/j.pld.2020.04.001

Bai, K., He, C., Wan, X. and Jiang, D. 2015. Leaf economics of evergreen and deciduous tree species along an elevational gradient in a subtropical mountain. AoB Plants, 7, plv064. https://doi.org/10.1093/aobpla/plv064

Bhatt, D., Sekar, K.C. and Kumar, K. 2020. Tree Diversity of Indian Himalayan Region. GB Pant National Institute of Himalayan Environment, Almora, Uttarakhand, India. 178 pages. https://www.gbpihed.gov.in/PDF/Publication/tree_div_IHR.pdf

Bobrowski, M., Gerlitz, L. and Schickhoff, U. 2017. Modelling the potential distribution of *Betula utilis* in the Himalaya. Global Ecology and Conservation, 11, 69-83. http://doi.org/10.1016/j.gecco.2017.04.003

Boojh, R. and Ramakrishnan, P.S. 1981. Temperature responses to seed germination in two closely related tree species of *Schima*, Reinw. Current Science, 50(9), 416-418. https://currentscience.ac.in/Volumes/50/09/0416.pdf

Bookhagen, B. and Burbank, D.W. 2010. Toward a complete Himalayan hydrological budget: Spatiotemporal distribution of snowmelt and rainfall and their impact on river discharge. Journal of Geophycal Research, 115, F03019. https://doi.org/10.1029/2009JF001426

Brodribb, T.J. and Field, T.S. 2007. Evolutionary significance of a flat-leaved Pinus in Vietnamese rainforest. New Phytologist, 178, 201–209. https://doi.org/10.1111/j.1469-8137.2007.02338.x

Brodribb, T.J., Field, T.S. and Jordan, G.J. 2007. Leaf maximum photosynthetic rate and venation are linked by hydraulics. Plant Physiology, 144, 1890–1898. https://doi.org/10.1104/pp.107.101352

Brodribb, T.J., McAdam, S.A., Jordan, G.J. and Martins, S.C. 2014. Conifer species adapt to low-rainfall climates by following one of two divergent pathways. Proceedings of the National Academy of Sciences USA, 111(40), 14489-14493. https://doi.org/10.1073/pnas.1407930111

Brodribb, T.J., Pittermann, J. and Coomes, D.A. 2012. Elegance versus speed: examining the competition between conifer and angiosperm trees. International Journal of Plant Sciences, 173(6), 673-694. https://doi.org/10.1086/666005

Champion, H.G. 1936. A preliminary survey of forest types of India and Burma. Indian Forestry Record (NS) Silviculture, 1(1), 286 pages.

Champion, H.G. and Seth, S.K. 1968. A Revised Survey of Forest Types of India. Govt. of India Press, New Delhi. 404 pages.

Chen, Z., Wang, G. and Jia, Y. 2017. Foliar ä 13C showed no altitudinal trend in an arid region and atmospheric pressure exerted a negative effect on plant _13C. Frontiers in Plant Science, 8, 1070. https://doi.org/10.3389/fpls.2017.01070

Devi, A.F. and Garkoti, S.C. 2013. Variation in evergreen and deciduous species leaf phenology in Assam, India. Trees, 27, 985-997. https://doi.org/10.1007/s00468-013-0850-8

Devi, A.F., Garkoti, S.C. and Borah, N. 2014. Periodicity of leaf growth and leaf dry mass changes in the evergreen and deciduous species of Southern Assam, India. Ecological Research, 29, 153-165. https://doi.org/10.1007/s11284-013-1105-2

Donovan, L.A., Maherali, H., Caruso, C.M., Huber, H. and de Kroon, H. 2011. The evolution of the worldwide leaf economics spectrum. Trends in Ecology & Evolution, 26(2), 88-95. https://doi.org/10.1016/j.tree.2010.11.011

Du, H., Ran, J.H., Feng, Y.Y. and Wang, X.Q. 2020. The flattened and needlelike leaves of the pine family (Pinaceae) share a conserved genetic network for adaxial-abaxial polarity but have diverged for photosynthetic adaptation. BMC Evolutionary Biology, 20(1), 1-12. https://doi.org/10.1186/s12862-020-01694-5

FSI. 2021. Indian State of Forest Report. Forest Survey of India, Dehradun, India. https://www.fsi.nic.in/forest-report-2021-details/

Givnish, T.J. 1987. Comparative studies of leaf form: assessing the relative roles of selective pressures and phylogenetic constraints. New phytologist, 106, 131-160. https://doi.org/10.1111/j.1469-8137.1987.tb04687.x

Givnish, T.J. 2002. Adaptive significance of evergreen vs. deciduous leaves: solving the triple paradox. Silva Fennica, 36(3), 703–743. https://doi.org/10.14214/sf.535

Gray, R.E. and Ewers, R.M. 2021. Monitoring forest phenology in a changing world. Forests, 12(3), 297. https://doi.org/10.3390/f12030297

Holt, B.G., Lessard, J.P., Borregaard, M.K., Fritz, S.A., Araújo, M.B., Dimitrov, D., Fabre, P.H., Graham, C.H., Graves, G.R., Jonsson, K.A., Nogues-Bravo, D., Wang, Z., Whittaker, R.J., Fjeldsa, J. and Rahbek, C. 2013. An update of Wallace's zoogeographic regions of the world. Science, 339(6115), 74-78. https://doi.org/10.1126%2Fscience.1228282

Joshi, R. and Tamang, N.D. 2021. Temperature Lapse rate in the Himalaya. Pp. 59-63. In: Singh, S.P., Singh, R.D. and Gumber, S. (Eds.) Interpreting Mountain Treelines in a Changing World. Central Himalayan Environment Association and International Centre for Integrated Mountain Development, Nepal.

Kattel, D.B., Yao, T., Yang, K., Tian, L., Yang, G. and Joswiak, D. 2013. Temperature lapse rate in complex mountain terrain on the southern slope of the central Himalayas. Theoretical and Applied Climatology, 113, 671-682. https://doi.org/10.1007/s00704-012-0816-6

Kikim, A. and Yadava, P.S. 2001. Phenology of tree species in subtropical forests of Manipur in north eastern India. Tropical Ecology, 42(2), 269-276. https://tropecol.org/pdf/open/PDF_42_2/42212.pdf

Luo, T., Luo, J. and Pan, Y. 2005. Leaf traits and associated ecosystem characteristics across subtropical and timberline forests in the Gongga Mountains, Eastern Tibetan Plateau. Oecologia, 142, 261-273. https://doi.org/10.1007/s00442-004-1729-6

Luo, Z., Guan, H., Zhang, X. and Liu, N. 2017. Photosynthetic capacity of senescent leaves for a subtropical broadleaf deciduous tree species *Liquidambar formosana* Hance. Scientific Reports, 7, 6323. https://doi.org/10.1038/s41598-017-06629-7

Turner, I.M. 2001. The Ecology of Trees in the Tropical Rain Forest. Cambridge University Press, Cambridge. 290 pages. https://doi.org/10.1017/CBO9780511542206

Ma, S., He, F., Tian, D., Zou, D., Yan, Z., Yang, Y., Zhou, T., Huang, K., Shen, H. and Fang, J. 2018. Variations and determinants of carbon content in plants: a global synthesis. Biogeosciences, 15, 693–702. https://doi.org/10.5194/bg-15-693-2018

Malhado, A.C.M., Whittaker, R.J., Malhi, Y., Ladle, R.J., Ter Steege, H., Butt, N., aragao, L.E.O.C., Quesada, C.A., Murakami-Araujo, A., Phillips, O.L., Peacock, J., Lopez-Gonzalez, G., Baker, T.R., Anderson, L.O., Arroyo, L., Almeida, S., Higuchi, N., Killeen, T.J., Monteagudo, A., Neill, D.A., Pitman, N.C.A., Prieto, A., Salomao, R.P,., Vasquea-M, R., Laurance, W.F. and Ramírez, A.H. 2009. Spatial distribution and functional significance of leaf lamina shape in Amazonian forest trees. Biogeosciences, 6(8), 1577-1590. https://doi.org/10.5194/bg-6-1577-2009

Matsuki, S. and Koike, T. 2006. Comparison of leaf life span, photosynthesis and defensive traits across seven species of deciduous broad-leaf tree seedlings. Annals of Botany, 97(5), 813-817. https://doi.org/10.1093/aob/mcl041

Medina, E., Garcia, V. and Cuevas, E. 1990. Sclerophyllly and oligotrophic environments: Relationships between leaf structure, mineral nutrient content, and drought resistance in tropical rain forests of the Upper Rio Negro Region. Biotropica, 22(1), 51–64. https://doi.org/10.2307/2388719

Miehe, G. 2015. Landscapes of Nepal. Pp. 7-15. In: Miehe, G., Pendry, C.A. and Chaudhary, R.P. (Eds.). Nepal: An Introduction to the Natural History, Ecology and Human Environment of the Himalayas. Edinburgh: Royal Botanic Garden, Edinburgh.

Miehe, G., Miehe, S., Bohner, J., Baumler, et al. 2015. Vegetation ecology. Pp. 385-472. In: Miehe, G., Pendry, C.A. and Chaudhary, R.P. (Eds.). Nepal: An Introduction to the Natural History, Ecology and Human Environment of the Himalayas. Edinburgh: Royal Botanic Garden, Edinburgh.

Moles, A.T. and Westoby, M. 2000. Do small leaves expand faster than large leaves, and do shorter expansion times reduce herbivore damage? Oikos, 90(3), 517-524. https://doi.org/10.1034/j.1600-0706.2000.900310.x

Norris, L. 2018. The functions of needle leaves. Home Guides, Garden, Soil Care. SFGATE. Newsletter. 06 December, 2018. https://homeguides.sfgate.com/functions-needle-leaves-82695.html

Ohsawa, M. (Ed.) 1987. Life Zone Ecology of the Bhutan Himalaya. Chiba University, Chiba, Japan. 79 pages

Oohata, S. 1992. Leaf life spans in genus *Pinus*. Bulletin of the Kyoto University Forests (Japan), 64, 15-26.

Pittermann, J., Stuart, S.A., Dawson, T.E. and Moreau, A. 2012. Cenozoic climate change shaped the evolutionary ecophysiology of the Cupressaceae conifers. Proceedings of National Academy of Sciences, U S A, 109, 9647–9652.

Pornon, A., Marty, C., Winterton, P. and Lamaze, T. 2011. The intriguing paradox of leaf lifespan responses to nitrogen availability. Functional Ecology, 25(4), 796-801. https://doi.org/10.1111/j.1365-2435.2011.01849.x

Prescott, J.A. 1946. A climatic index. Nature, 157(3991), 555.

Ralhan, P.K. and Singh, S.P. 1987. Dynamics of nutrients and leaf mass in central Himalayan forest trees and shrubs. Ecology, 68(6), 1974-1983. https://doi.org/10.2307/1939888

Raunkiaer, C. 1934. The Life Forms of Plants and Statistical Plant Geography. Oxford University Press, London. 721 pages. https://ia904703.us.archive.org/34/items/in.ernet.dli.2015.271790/2015.271790.The-Life.pdf

Reddy, C.S., Saranya, K.R.L., Pasha, S.V., Satish, K.V., Jha, C.S., Diwakar, P.G., Dadhwal, V.K., Rao, P.V.N. and Murthy, Y.K. 2018. Assessment and monitoring of deforestation and forest fragmentation in South Asia since the 1930s. Global and Planetary Change, 161,132-148. https://doi.org/10.1016/j.gloplacha.2017.10.007

Reich, P.B. 1988. Variation among plant species in leaf turnover rates and associated traits: implications for growth at all life stages. Pp. 467-487. In: Lambers, H., Poorter, H. and Van Vauren, M.M.I. (Eds.). Inherent Variations in Plant Growth: Physiological Mechanisms and Ecological Consequences, Buckhuys, Leiden.

Reich, P.B., Uhl, C., Walters, M.B. and Ellsworth, D.S. 1991. Leaf lifespan as a determinant of leaf structure and function among 23 Amazonian tree species. Oecologia, 86, 16-24. https://doi.org/10.1007/BF00317383

Reich, P.B., Walters, M.B. and Ellsworth, D.S. 1992. Leaf life span in relation to leaf, plant, and stand characteristics among diverse ecosystems. Ecological Monographs, 62(3), 365-392. https://doi.org/10.2307/2937116

Richardson, D.M. (Ed.). 1998. Ecology and Biogeography of *Pinus*. Cambridge University Press. 548 pages

Running, S.W., Loveland, T.R., Pierce, L.L., Nemani, R.R. and Hunt Jr, E.R. 1995. A remote sensing based vegetation classification logic for global land cover analysis. Remote sensing of Environment, 51(1), 39-48. https://doi.org/10.1016/0034-4257(94)00063-S

Sakai, A. and Malla, S.B. 1981. Winter hardiness of tree species at high altitudes in the East Himalaya, Nepal. Ecology, 62(5), 1288-1298. https://doi.org/10.2307/1937293

Schickhoff, U., Bobrowski, M., Böhner, J., Bürzle, B., Chaudhary, R.P., Gerlitz, L., Heyken, H. Lange, J., Muller, M., Scholten, T., Schwab, N. and Wedegartner, R. 2015. Do Himalayan treelines respond to recent climate change? An evaluation of sensitivity indicators. Earth System Dynamics, 6, 1, 245-265. https://doi.org/10.5194/esdd-5-1407-2014

Schmidt-Vogt, D. and Miehe, G. 2015. Land use. Pp. 287-310. In: Miehe, G., Pendry, C.A. and Chaudhary, R.P. (Eds.). Nepal: An Introduction to the Natural History, Ecology and Human Environment of the Himalayas. Edinburgh: Royal Botanic Garden, Edinburgh.

Shukla, R.P. and Ramakrishnan, P.S. 1982. Phenology of trees in a sub-tropical humid forest in north-eastern India. Vegetatio, 49(2), 103-109. https://doi.org/10.1007/BF00052764

Singh, J.S. and Singh, S.P. 1987. Forest vegetation of the Himalaya. The Botanical Review, 53, 80-192. https://doi.org/10.1007/BF02858183

Singh, P. and Negi, G.C.S. 2018. Treeline species phenology: shoot growth, leaf characteristics and nutrient dynamics. Tropical Ecology, 59(2), 297-311. https://tropecol.org/pdf/open/PDF_59_2/11%20Singh%20&%20Negi.pdf

Singh, S.P. and Singh, J.S. 1992. Forests of the Himalayas: Structure, Function and Impact of Man. Gyanodaya Prakashan, Nainital. 294 pages.

Singh, S.P., Adhikari, B.S. and Zobel, D.B. 1994. Biomass, productivity, leaf longevity, and forest structure in the central Himalaya. Ecological Monographs, 64(4), 401-421. https://doi.org/10.2307/2937143

Singh, S.P., Singh, R.D. and Gumber, S. 2021. Interpreting MountainTtreelines in a Changing World. Central Himalayan Environment Association and International Centre for Integrated Mountain Development, Nepal. https://doi.org/10.53055/ICIMOD.787

Stainton, J.D.A. 1972. Forests of Nepal. John Murray, London. 181 pages.

Suri, P.N. 1933. A study in the ecology and silviculture of the

Himalayan Spruce and silver fir with special reference to works in progress in Kulu. In: Proceedings Punjab Forest Conference.

Thadani, R. 1999. Disturbance, Microclimate and Competitive Dynamics of Tree Seedlings in Banj Oak (*Quercus leucotrichophora*) in Forest of Central Himalayas India. A dissertation presented to faculty of graduate school of Yale University in candidacy for the Degree of Philosophy.

Townshend, J., Justice, C., Li, W., Gurney, C. and McManus, J. 1991. Global land cover classification by remote sensing: present capabilities and future possibilities. Remote Sensing of Environment, 35(2-3), 243-255. https://doi.org/10.1016/0034-4257(91)90016-Y

Transeau, E.N. 1905. Forest centers of eastern America. The American Naturalist, 39(468), 875-889. https://www.jstor.org/stable/2455267

Troup, R.S. 1921. The Silviculture of Indian Trees. Clarendon Press, London.

Tucker, R.P. 1983. The British Colonial System and the Forests of the Western Himalayas. Pp. 146-166. In: Tucker, R.P. and Richards, J.F. (Eds.). Global Deforestation and the Nineteenth Century World Economy. Duke University Press, Durham, USA.

Tyagi, V., Singh, S.P., Singh, R.D. and Gumber, S. 2023. Chir pine and banj oak responses to pre-monsoon drought across slope aspects and positions in Central Himalaya. Environmental Monitoring and Assessment, 195(2), 258. https://doi.org/10.1007/s10661-022-10860-9

Udvardy, M.D.F. 1975. A Classification of the Biogeographical Provinces of the World. IUCN Occasional Paper no. 18. IUCN, Morges, Switzerland. 50 pages

van Ommen Kloeke, A.E.E., Douma, J.C., Ordonez, J.C., Reich, P.B. and Van Bodegom, P.M. 2012. Global quantification of contrasting leaf life span strategies for deciduous and evergreen species in response to environmental conditions. Global Ecology and Biogeography, 21(2), 224-235. https://doi.org/10.1111/j.1466-8238.2011.00667.x

Vasfilov, S.P. 2016. The effect of photosynthesis parameters on leaf lifespan. Biology Bulletin Reviews, 6, 96-112. https://doi.org/10.1134/S2079086416010084

Wangda, P. and Ohsawa, M. 2006. Gradational forest change along the climatically dry valley slopes of Bhutan in the midst of humid eastern Himalaya. Plant Ecology, 186, 109–128. https://doi.org/10.1007/s11258-006-9116-5

Webb, L.J. 1959. A physiognomic classification of Australian rain forest. Journal of Ecology, 47(3), 551-570. https://doi.org/10.2307/2257290

Wright, I.J., Ackerly, D.D., Bongers, F.J.J.M., Harms, K.E., Ibarra-Manriquez, G., Martinez-Ramos, M., Mazer, S.J., Muller-Landau, H.C., Paz, H., Pitman, N.C.A., Poorter, L., Silman, M.R., Vriesendorp, C.F., Webb, C.O., Westoby, M. and Wright, S.J. 2007. Relationships among ecologically important dimensions of plant trait variation in seven neotropical forests. Annals of Botany, 99(5), 1003-1015. https://doi.org/10.1093/aob/mcl066 Wright, I.J., Ackerly, D.D., Bongers, F., Harms, K.E., Ibarra-Manriquez, G., Martinez-Ramos, M., Mazer, S.J., Muller-Landau, H.C., Paz, H., Pitman, N.C., Poorter, L., Silman, M.R., Vriesendorp, C.F., Webb, C.O., Westoby, M. and Wright, S.J. 2006. Relationships among ecologically important dimensions of plant trait variation in seven neotropical forests. Annals of Botany, 99(5), 1003-1015. https://doi.org/10.1093/aob/mcl066

Wright, I.J., Reich, P.B., Cornelissen, J.H., Falster, D.S., Groom, P.K., Hikosaka, K., Lee, W., Lusk, C.H., Niinemets, U. Oleksyn, J., Osada, N., Poorter, H., Warton, D.I. and Westoby, M. 2005. Modulation of leaf economic traits and trait relationships by climate. Global ecology and biogeography, 14(5), 411-421. https://doi.org/10.1111/j.1466-822x.2005.00172.x

Wu, Z.Y. 1980. The Vegetation of China. Science Press, Beijing (in Chinese, with maps).

Wu, Z.Y. 1987. The Vegetation of Yunnan. Science Press, Beijing (in Chinese, with maps).

Zhang, X.L., Ha, B.B., Wang, S.J., Chen, Z.J., Ge, J.Y., Long, H., He, W., Da, W., Nian, X.M., Yi, M.J. and Zhou, X.Y. 2018. The earliest human occupation of the high-altitude Tibetan Plateau 40 thousand to 30 thousand years ago. Science, 362(6418), 1049-1051. https://doi.org/ 10.1126/science.aat8824

Zhang, Y.L., Moser, B., Li, M.H., Wohlgemuth, T., Lei, J.P. and Bachofen, C. 2020. Contrasting leaf trait responses of conifer and broadleaved seedlings to altered resource availability are linked to resource strategies. Plants, 9(5), 621. https://doi.org/10.3390/plants9050621

Zobel, D.B. and Singh, S.P. 1997. Himalayan forests and ecological generalizations. BioScience, 47(11), 735-745. https://doi.org/10.2307/1313096

Zobel, D.B., Garkoti, S.C., Singh, S.P., Tewari, A. and Negi, C.M.S. 2001. Patterns of water potential among forest types of the central Himalaya. Current Science, 80, 774-779. https://www.jstor.org/stable/24105664

Received:10th September 2023
Accepted: 7th November 2023