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Cedrus deodara, A Himalayan Cedar: Distribution, Community Structure and Climate Change Responses

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ABSTRACT
Cedrus deodara (deodar), a true cedar, is a key conifer of the western Himalaya with considerable potential as a plantation species. This preliminary synthesis integrates published literature and repeated field observations to examine the distribution, ecology, phenology, biomass allocation, and growth dynamics of *C. deodara. The species* is predominantly gregarious, forming extensive pure stands, although mixed forests are also common. It is found in both outer ranges exposed to the monsoon and inner dry ranges shielded from monsoonal influence. In dry areas, *P. wallichiana* is a frequent associate, while in outer moist ranges, *Quercus floribunda* commonly co-occurs. Radial growth rates are significantly higher in the outer Himalayan ranges compared to the inner ranges. *C. deodara* exhibits pronounced shoot dimorphism, with needles borne on both short and elongated shoots. Soil nutrient availability and organic carbon content increase with forest age. Gender expression is highly variable, ranging from monoecious to dioecious individuals. New shoots emerge during the pre-monsoon period (April–May), followed by gradual leaf shedding. Seeds germinate in the pre-monsoon but rapidly lose viability due to high oil content; seed production may begin at approximately 28 years in plantations. Biomass allocation studies indicate a high proportion of bole biomass (approximately 91%) compared to *P. roxburghii* (approximately 76%). Due to distinct annual rings, long life spans, and other characteristics, *C. deodara* is frequently utilized in climate change research. Tree-ring analyses indicate that growth is primarily controlled by pre-monsoon moisture at lower elevations and by temperature at higher, colder sites.

Key words: *C. deodara*, Distribution, Himalaya, Monsoon shadow, Phenology, Precipitation

INTRODUCTION

Spread over nearly 2,500 km across South Asia (74°–95°E longitude, 27°–37°N latitude), the Himalayas, along with the Hindu Kush, are one of the greatest geo-ecological features of the planet. The region is not only known for some of the tallest summits of the world, but also for its range of climatic and rich biodiversity. The outer ranges consist of the Shiwaliks and the Lesser Himalaya. They are directly exposed to the monsoon and generally receive over 1500 mm of precipitation annually, with some pockets exceeding 4000 mm. The inner range (the greater or inner Himalaya) is shielded from the monsoon. It is dry, with annual precipitation generally less than 1000 mm. Both broadleaved and coniferous forests occur in each of these regions, but the extent of their dominance differs. In the outer ranges, broadleaved forests are widespread, while in the inner ranges, conifers prevail. *Cedrus deodara* is the Himalayan species of the genus *Cedrus* (real Cedar), which has four species. The other three species are associated with the Mediterranean region (Table 1). All four species are associated with mountains in distribution and have moderate wood density and high timber value. *C. deodara* is comparatively larger.

Cedar species are known for their majestic appearance, high-quality timber with aroma, and ornamental values. As an ornamental tree, there are few species in the world that can compare with the deodar. Being the most valuable timber species, deodar is widely planted in the Himalayas. Its religious association is obvious, as it is commonly planted near temples. It is a major horticultural tree species almost planted in all cities of the UK and HP, such as Nainital, Shimla and Almora.

The majestic trees are generally 30-40m tall, but can attain up to 60 m height (Gamble 1922). Like pines, cedars have long as well as dwarf shoots, but

Table 1. Certain background information about *C. deodara* and the three other *Cedrus* (Cedar) species

Species	Geographic distribution	Habitat and elevation range	Mean annual precipitation (mm)	Tree height (m)	Avg. DBH (cm)	Wood density (g cm^{-3})	Source
Himalayan Cedar							
C. deodara (Roxb.) G. Don	Western Nepal, Eastern Afghanistan, Northern Pakistan, India (J&K, HP, Uttarakhand)	Montane temperate forests; 1,500–3,200 inner & outer Himalaya	~900–1,500	40–60	150–250	0.52–0.56	Troup (1921); Gamble (1922); Champion and Seth (1968); Panshin and de Zeeuw (1980); Singh and Singh (1992); Qiao et al. (2007); Anonymous (2010); Miehe et al. (2015)
Mediterranean Cedar							
*C. libani*A. Rich.	Eastern Mediterranean: Turkey, Lebanon, Syria	Mountain slopes; 1,000–2,100 m; Mediterranean climate	~800–1,200	30–40	100-200	0.55–0.59	Davis (1965); Farjon (2001); Quézel and Médail (2003); Boydak (2004); Wagenführ (2007); Qiao et al. (2007)
C. atlantica (Endl.) Manetti ex Carrière	Atlas Mountains, Morocco & Algeria	Montane dry forests; 1,300–2,600 m	~600–1,000	30–35	80–180	0.53–0.57	Zobel and van Buijtenen (1989); Farjon (2001); Qiao et al. (2007); Linares et al. (2011)
C. brevifolia (Hook. f.) Henry	Cyprus (endemic)	High-elevation slopes; 900–1,400 m	~900–1,100	20–25	60–120	~0.54	Meikle (1977); Farjon (2001); Christou (2001); Qiao et al. (2007); Wagenführ (2007)

unlike the pines, in which needles are borne only on dwarf shoots, in cedars, needles are found both on dwarf and long shoots. Like pines, deodar is generally monoecious (with male and female cones in different branches), but dioecious trees also occur, and its gender distribution is rather complex (Khanduri et al. 2021). Deodar has been studied for pharmacology with a focus on therapeutics and tree ring studies (Kumar and Pandey 2024). However, knowledge about the deodar forest ecosystem is scanty. Research on tree ring growth in relation to climate has been carried out frequently at Birbal Sahni Institute (BSI), Lucknow, while studies on vegetation analysis have frequently been published by the Botanists of Pakistan and other parts of the Himalayas (Kumar and Pandey 2024). Research involving non-Himalayan collaboration has been scanty.

When both ecological and non-ecological studies are considered, we find that during the last century (1916-2024), 616 academic documents have been published, involving authors from 48 countries, of which India, China, Pakistan, the USA, Italy, Japan, and South Korea are major contributors. The common keywords, apart from *C. deodara*, and the names of other plants or plant groups, and regions were dendrochronology, tree rings, antioxidant, ethanol, biomass, adsorption, molecular docking, etc. (Kumar and Pandey 2024).

This article presents a preliminary account of the distribution and ecology of *C. deodara, synthesizing information from the literature and field observations conducted in* Uttarakhand, Himachal Pradesh, and the Kashmir valley of the Indian Himalayas. Although deodar is found throughout much of the Western Himalayas, including both moist outer and dry inner Himalayan areas, it is primarily a species of the inner Himalaya (Stainton 1972, Parker, 1952, Miehe et al. 2015), while also being common in the outer ranges. In the outer ranges, a significant proportion of deodar forests are the result of plantation efforts.

The main objective of this paper is to synthesise information on deodar distribution and ecology for further research on this important Himalayan species. We also list existing knowledge gaps and research issues. Our approach includes gathering fragmented information from literature and field visits, then assembling these in a meaningful way. Field visits to many deodar areas generated new information and allowed us to verify facts from the literature.

MATERIAL AND METHODS

Study area and species

Covering about 4.2 million km^2 area, the Himalayas (including the Hindu Kush Region) have the greatest aerial extent among the mountain areas of the world (Wester et al. 2019). These originate from it, ten river systems, such as the Gangetic system, Brahmaputra, Indus, Salween, Tarim, and Yangtse, supporting some 1.3 billion people. The region has four global biodiversity hotspots, and forests up to 5000 m elevation. Himalaya are young and rising mountain range, with an extraordinary range of precipitation and cultural variations. The topographical complexity is high and ever-changing spatially. In the region, glaciers and other cryosphere components together form the largest snow and ice reserves outside the two poles. However, they are being depleted rapidly under the global climate change impact. Himalayan ranges are warming rapidly, at rates clearly higher than the global average (Wester et al. 2019). The temperature rise is presumably more in higher elevations than in lower elevations (Joshi et al. 2021).

The Himalayan forests are divisible into two principal eco-geographical regimes: the outer moist ranges directly exposed to monsoon thrust, and the inner dry valleys, shielded from the monsoon thrust by the high mountain barriers. The temperate and subalpine areas of the outer ranges are dominated by broadleaved evergreen forests with an abundance of oaks and other genera of Fagaceae and Lauraceae in many areas. The common forest trees of the inner Himalayan region are largely coniferous, all of which are canopy-forming species in the temperate to subalpine zones. Though largely distributed in dry inner ranges, these conifer forests also occur in moist outer ranges. Annual temperature lapse rate increases with aridity, being 0.51°C/100 m in humid Sikkim and 0.67°C in semiarid Kashmir (Joshi et al. 2021).

Methods

This study adopts an integrative, mixed-method approach, combining field observations, literature synthesis, and analysis of existing dendrochronological and modelling studies to assess the distribution, ecology, and climate sensitivity of *C. deodara*. Information on the occurrence of *C. deodara* in both the outer and inner Himalaya was compiled through (i) field visits conducted in Uttarakhand, Himachal Pradesh, and Jammu & Kashmir to validate species distribution, forest types, and ecological associations; (ii) consultations with subject experts; and (iii) an extensive review of classical and contemporary literature, including forest working plans, monographs, research papers, and doctoral theses.

Growth responses were assessed through published tree-ring chronologies representing long-term radial growth patterns across elevational gradients. In addition, existing modelling and projection studies were reviewed to understand potential shifts in deodar distribution and growth under different climate change scenarios, with particular attention to elevational migration and habitat suitability. Ecological parameters such as species composition, forest stratification, biomass allocation, and phenology were synthesised from available literature. This integrative approach provides a preliminary understanding of the current status, ecological behaviour, and vulnerability of *C. deodara* in the Himalaya.

RESULTS

Origin, distribution and habitat

Evolution of Cedrus species

The genus *Cedrus* belongs to the family Pinaceae, and is known by only four species (Table 1). A study based on sequence analysis of seven cytoplasmic DNA fragments showed that among the *Cedrus* species, the Himalayan species, *C. deodara,* diverged first, followed by the N-African species *C. atlantica,* which separated from the common ancestor of *C. libani* and *C. brenifolia* (of eastern Mediterranean clade) at 23.49 to 18.8 M Yr age (Qiao et al. 2007). They suggest that *Cedrus* could have originated in the high-latitude area of Eurasia.

C. deodara (deodar) is a species of semi-humid to semi-arid areas in the Western Himalaya (69-83°E) between 1800 and 3000 m elevations (Fig. 1). In the areas where deodar occurs, the mean winter temperature ranges from 30 to 10°C at the uppermost

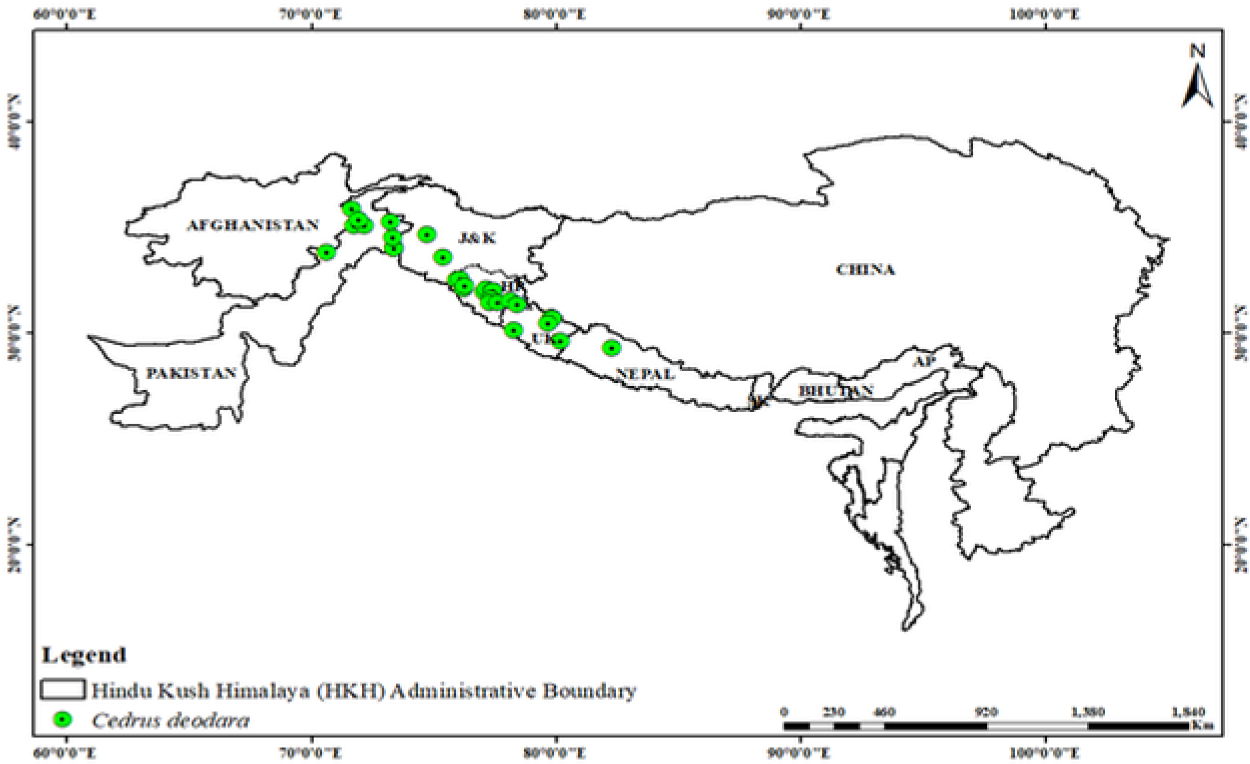

Figure 1. Distribution of *C. deodara* across the Hindu Kush Himalaya (HKH)

and lowermost elevation, respectively. Snowfall is common, and its contribution ranges from 25 to 75% of annual precipitation.

Optimum conditions of the distribution of deodar are only roughly known. It occurs widely from Safed Koh with 450 mm annual precipitation to areas with 1300 mm precipitation, sizeable with winter precipitation and long period of snow cover (Miehe et al. 2015). Low monsoon rainfall seems to favour deodar by reducing competition with oaks (*Q. floribunda* and *Q. semecarpifolia*), which are monsoonal in distribution (Champion and Seth 1968). At the easternmost site of its occurrence in Nepal, winter precipitation is about 25% and of the annual precipitation. In the valleys of Tila Khola, SW Jumla, Nepal, deodar grows intermittently on the valley slopes leading down to the river. In Kinnaur, *Populus ciliata* is common in deodar stands along the rivers. Canopy cover is generally 30-60%. Branches and foliage cover most of the stem. The canopy head may be chopped by snow and/or drought, often bifurcating or trifurcating the stem. Such deodar trees frequently occur in Malari, Uttarakhand.

Forest types and floristic associations

Among the conifer companions of deodar, blue pine (*P. wallichiana*) is common in drier sites and spruce in moist sites. At higher elevations, above 2500 m, *A. pindrow* (fir) is its common companion, while in low ranges (<2000 m), it occurs with *Cupressus torulosa* (cypress) and even *P. roxburghii* (chir pine). In the areas of inner valleys, such as Kinnaur (Himachal), it is found with *P. gerardiana* (chilgoza pine) and occasionally also with *Q. baloot*. Its common broadleaved associates in outer ranges include: *Pyrus pashia, Rhododendron arboreum, Prunus* sps*, Aesculus* sps*, Populus ciliata, Cornus macrophylla,* and *Juglans regia.*

In outer ranges, deodar forests have the flora similar to that of *Quercus floribunda* forests. However, in such forests, oaks are subordinated by conifers, as follows in the spruce-deodar belt, Sutlej Valley, HP.

A. Canopy

I. *C. deodara* and *Picea smithiana*

Undercanopy tree layer

I. *Q. floribunda*, *Q. leucotrichophora*, *Q. semecarpifolia*, *Acer acuminatum*, *Acer caesium*, *Acer pictum*, *Taxus baccata*, *Betula alnoides*

Shrub layer

(II a) *Arundinaria falcata - Drepanostachyum falcatum*

(III b) *Ribes nigrum, Viburnum erosum, Strobilanthes sp.*

Herb layer

(IV) *Fragaria* sps*, Viola* sps*, Pteridium* sps*,*

B. Canopy

I. *Cedrus deodara, A. pindrow*, *Picea smithiana*

II. *Q. semecarpifolia*, *Euonymus lacerus*, *Rhamnus* sps.

Cedrus deodara forests at 2500m showed the following composition.

C. Canopy

I. *Cedrus deodara, A. pindrow,* and *Picea smithiana* mixed forests (all multi-year leaf evergreen)

II. *Acer* spp.*, Juglans regia, Celtris* (all deciduous)

The mixed coniferous forest type appears to be climatic.

Climax (Champion and Seth 1968, Parker, 1942, Mohan and Puri 1955) based on Upper Satluj Valley (Bashhr), and Pure *Q. semecarpifolia* is regarded as a stable climatic climax (Champion and Seth 1968)

In Manoor Valley, Pakistan, Gillani et al. (2025) found deodar forming three major communities between 1581-2374 m elevations; they are as follows:

1. *Cedrus-Isodon-Cynadon* community
2. *Cedrus-Cynadon-Drypolus*
3. *Sorbus-Cedrus-Desmodium*– 129 plant species

The soil was sandy and loamy type, and 162 species of trees, shrubs and herbs were recorded across 23 stands.

Extent of monodominance and stand structure in the deodar forest

Deodar is a gregarious species, forming large and dense clusters of pure stands. However, mixed deodar forests are also common (Gamble 1922). A study on forest vegetation of Hindu Kush and Himalayan ranges of Pakistan (Ahmed et al. 2011) showed that of the 47 stands sampled, about 60% had either only deodar or deodar with very high (75%-99%) relative basal area, and 76.6% stands had >50% of its relative basal area (Fig. 2). The 12 stands in which only deodar was present occurred between 1650 and 2770 m, generally on steep slopes (12°-50°). Of the 35 mixed forest stands, 25 had *P. wallichiana. Q. baloot*,

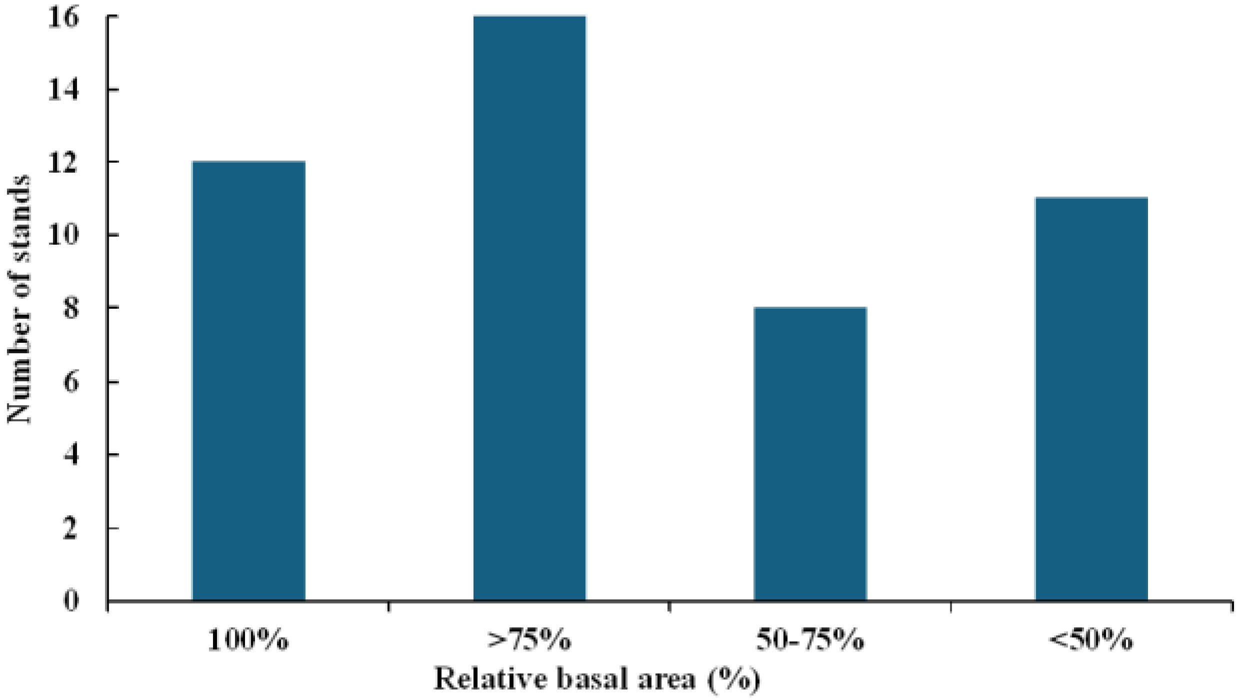

Figure 2. Distribution of deodar (*C. deodara*) containing stands (total of 47 stands) in relation to the extent of dominance of deodar (Relative Basal Area) in Hindu Kush and Himalayan ranges of Pakistan (derived from Ahmed et al. 2011)

the shrubby oak with spinose leaves, occurred along with *P. gerardiana* occasionally (4 stands) in stands with harsher environmental conditions. Co-occurrence of *Q. baloot* and *P. gerardiana* on drier slopes could also be seen in Kinnaur, HP. In exceptional casesthe absolute values of tree basal area exceed 100 m^2/ha, indicating that old-growth deodar stands can have a huge biomass. To conclude, depending upon topography and growth conditions, deodar forests vary considerably from absolute monodominance to mixed stands, monodominance being more prevalent in unfavourable growth conditions. When conditions are favourable, such as in outer ranges, oaks and other broad-leaved species mix up.

Growth in relation to outer and inner ranges

There is no study with the objective of comparing the growth of deodar between the outer and inner ranges. Here, we have used data on the number of tree rings in relation to the stem radius for the comparison. It shows that the radial growth of deodar is distinctly more in the outer ranges than in the inner ranges (derived from the data given in Gamble 1922). It is based on the years taken to reach 1.82 m girth of the stem.

· Outer ranges under the full influence of monsoon- 110 years
· Intermediate ranges and valleys- 110-140 years
· Inner ranges shielded from monsoon for >140 years.

Evidently, deodar's prevalence in the inner ranges is largely because of the lack of competition with oaks and other broad-leaved species. As for growth, it is adversely affected in the inner ranges.

The number of annual growth rings per unit radius is used to show girth increment; the fewer the rings, the faster the growth of the tree ring (rate are of natural trees).

· Number of rings per ~5 cm radius
· Giri valley near Shimla 8-18 rings
· Planted trees at Kullu, 6-10 rings, but 19 rings for natural forest trees.
· Kuram valley Afghanistan, 42 rings

Regeneration

The seed cones are barrel-shaped, measuring 6 - 12 cm long and 3 - 8 cm broad, initially green, maturing to gray-brown and disintegrate at maturity to release the winged seeds. Pollen cones are slender ovoid, 3 - 8 cm long, produced in late summer and shedding pollen in autumn. The seeds measure 10 - 15 mm long, with 20 - 30 mm long wings. The seeds have

2-3 resin blisters, containing an unpleasant-tasting resin, thought to be a defence against squirrel predation.

Jay and nutcrackers attack unripe cones from the beginning of September and continue to do so for two to three months. Bears, porcupines and monkeys are destructive. Bears lick the surface beneath the bark. Seeds lying on the ground during winter are devoured by pheasants. Seed germination is epigeous, with cotyledons being 9-11 in number. Seeds remain on the ground throughout the winter and germinate in March-April, which is earlier than other conifers. Seedlings are very vulnerable to drought during April-June and September-November; the monsoon rains of June-September enable seedlings to grow rapidly. However, where the monsoon is weak, the period of June-September can be a period of seedling mortality.

The influence of snow melt water on species regeneration is insufficiently known; it may be safely said that the moisture resulting from snow melt plays a key role to tide over the drought, particularly in the inner ranges. In inner ranges, natural regeneration of deodar is often profuse (Troup 1921). The absence of heavy undergrowth, combined with snow melt, plays a major role in the regeneration of deodar and its associated pine species. In the inner ranges, the thick raw humus layer of undecayed needles absorbs water readily but parts with it immediately, resulting in a dry substratum difficult to penetrate by roots. Grazing of sheep and goats, which is prevalent in several areas, particularly in Kashmir, is injurious to seedlings. Snowfall damages young deodar trees, bending poles and breaking branches and uprooting whole individuals.

Shoots and needles

Leaves in deodar show a pronounced shoot dimorphism, being borne on two distinct shoot types: dwarf (short) shoots and long (elongated) shoots (Fig. 3). On dwarf shoots, leaves are produced in dense clusters or rosettes, typically comprising 20–45 acicular needles, the number of needles per cluster increasing with shoot thickness and vigour. These clustered needles arise from a highly contracted axis, imparting the characteristic tufted appearance to deodar branches. Such an arrangement maximises photosynthetic surface area while maintaining a compact shoot structure, an adaptive feature in cool

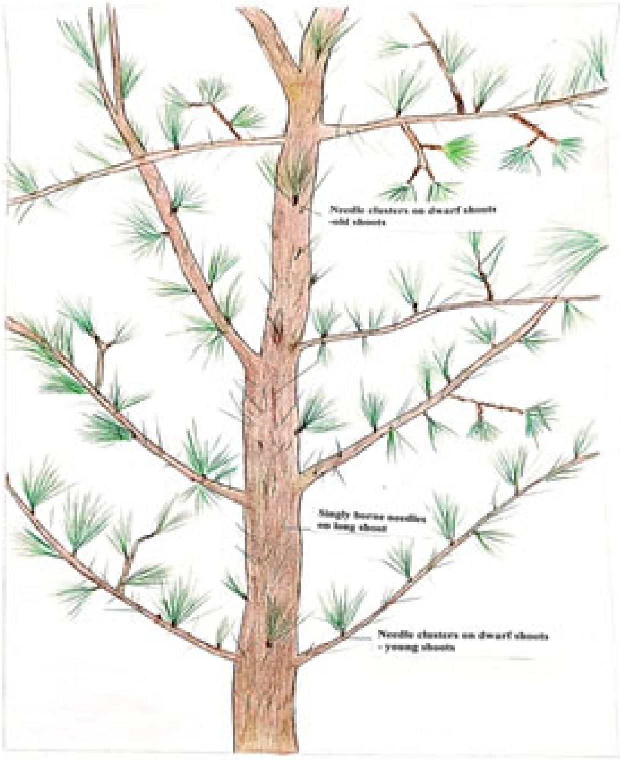

Figure 3. Branch and needle arrangement in *Cedrus deodara*, showing singly borne needles on long shoots and needle clusters on dwarf shoots (young and old)

temperate and montane environments. In contrast, on long shoots, the needles are borne singly, arranged spirally or irregularly, and are directly attached to the elongated axis. These solitary needles are more widely spaced and are primarily associated with shoot extension, branch elongation, and crown development. Typically, the leaves have 3-6 years longevity, measuring 8 - 60 mm long, arranged in an open spiral phyllotaxis on long shoots, and in dense spiral clusters of 15 to 45 together on short shoots; they vary from bright grass-green to dark green to strongly glaucous pale blue-green, depending on the thickness of the white wax layer which protects the leaves from desiccation.

Effect of the longevity of the deodar forest on soil properties

A study on soil properties in relation to the age of the deodar forest (from 134 to 480 yrs) showed that soil (0-15 cm depth) nutrient content and soil organic carbon improved with the age of the deodar forest. Values of soil organic carbon, total P and total N were higher in deodar old growth forest (5.97±0.11%, 1.42±0.08%, and 0.49±0.03%, respectively) than in young forests (1.89±0.15%, 0.657±0.056%, and 0.061±0.006%, respectively) (Vishwakarma et al. 2024).

Gender segregation

Deodar varies considerably in gender segregation in the tree crown. An in-depth study by Khanduri et al. (2021) based on 500 trees of deodar in Uttarakhand (outer Himalaya) shows a range of sex expressions from pure monoecious trees (both seed cone and pollen cone on the same tree individual) to pure dioecy (seed cones and pollen cones on different tree individuals) with some intermediate stages (subdioecy). They identified five sexual morphs (Table 2).

Out of the 327 monoecious trees, in 206 trees, seed cones were in the lower crown and the pollen cones in the upper crown. In the remaining 39 trees upper and lower crowns had pollen cones and the middle seed cones. Of the above 206 trees, 93 had predominantly seed cones, 26 had predominantly pollen cones, and 87 were mixed monoecious type. Location of seed cones and pollen cones varied: (i) The lower crown layer was seed-cone-bearing and the upper pollen-cone-bearing; (ii) The lower crown layer was pollen cone-bearing, and the upper seed cone-bearing; and (iii) Lower and upper pollen cone bearing and middle seed cone bearing.

Intermediate morphs could be referred to as representing subdioecy. Such a variation can occur from plasticity, often linked with plant size, age, or genetic factors (Charlesworth 1999). Monoecious trees have the advantage of being flexible in their sex allocation. The female and monoecious genders are frequently found in larger trees. The gender expression also changes due to light availability; in shade, more trees are seed cone-bearing, and in an open environment with intense light, more trees are pollen cone-bearing. The location of seed cones in the top canopy might decrease self-pollination. Khanduri et al. (2021) emphasise that in natural populations, deodar has a subdioecious gender expression (coexistence of pollen, seed and monoecious condition). The plasticity of gender gives an advantage for attaining gender stability by promoting outcrossing. There is a need to have long-term data collection across different sites, both from the outer and inner ranges.

Table 2. A distribution of dioecious and monoecious trees based on cone-bearing characteristics and crown position (values in parentheses are the percentages of total 500).

	Number of trees
Dioecious	173 (34.6%)
Bearing only seed cones	63 (12.4%)
Bearing only pollen cones	110 (22.2%)
Monoecious	327 (65.4%)
Mixed-monoecious bearing seed	68 (13.6%)
Predominantly seed cone bearing	125 (25%)
Predominantly pollen cone bearing	131 (26.2%)

Phenology and reproduction

New shoots appear during dry pre-monsoon months (April-May), which seems to lead to gradual leaf shedding during May onwards (not a full drop like that of oaks and chir pines). Female cones appear in August, hidden among the needles. Seeds remain covered under snow in higher elevations, which protects them from herbivory and desiccation. The seeds germinate during the next pre-monsoon as conditions become warm. Male cone (5 cm long and 1.5 cm in diameter) initiation occurs in mid-June, and the cones are born on short shoots, more or less erect. They start growth again in August-end after a period of dormancy, and pollen is formed in Sept-Oct. Female cones are born singly at the tip of dwarf shoots, almost erect. During late August-end seed cones are initiated. The number of cones produced per tree varies considerably from one year to another. In a deodar forest of Uttarakhand, the production of pollen cones per tree was 3563 in 2000 and 815 in 2001 (Khanduri and Sharma 2010).

The ripe female cones (Sept-Nov) are solitary and erect at the end of branchlets on the upper sides, usually farther than the cones of the previous year. Young female cones appear in August; they are pollinated from mid-Sept to mid-Oct; the female cones are inconspicuous at the time of pollination, hidden by needles. No growth in female cones occurs until the following spring, whereafter by May they become clearly visible, by June-July they are fully grown, pale-bluish green; they fully ripen by September-end to November-end, so the time taken is 12.5-13.5 months from the first appearance to the ripening of cones (7.5-11.25 cm length x 5-8.75 cm diameter). Numerous fan-shaped scales occur around the woody axis, and on each scale rest a pair of winged seeds. Cones break up on the tree. Scales fall on the ground, while the woody axis remains on the tree for 4-5 years. Sunny and dry conditions favour cone opening. Seeds with wings are 2.5-3.75 cm long, and triangular, wings with rounded corners measure 1.8-2.5 cm. Seeds alone are 0.8-1.5 cm broad with a mass of 125 mg per seed. Seeds are oily, so they soon lose viability. Trees could produce seeds at the age of 28 years in plantations. Good seed years occur once every 3 years. In a cone, the upper and lower portions have abortive seeds; only the middle seeds are healthy and fertile. For example, in a seed cone, Troup (1921) counted 190 scales, of which basal-53, and apical-20 scales had abortive seeds, and the middle 117 scales had 234 fertile seeds. Birds which destroy unripe seeds are Jays and nutcrackers, while pheasants devour ripe seeds during winter. Germination (epigeous) occurs during March-May. It has 9-11 cotyledons, and seedling needles are 1.5-3.2 cm long. Leaves may be shed in part during the second year in vigorous seedlings and wholly during the 3rd year. In some leaves may persist 4-5 yrs. Seedlings are very sensitive to drought. Wild animals- bear, porcupines, monkeys are most injurious, bears remove bark of young trees by teeth and claws, presumably to lick resins; porcupines damage bark by gnawing at the base of the trunk, and so do langurs. Fungus attack on seedlings is common. Germination occurs during March-April, but can occur even in February at warm places. Germinated seedlings are found even under snow. Seedling mortality due to drought, during April-June and Sept-Nov, is high. Good seed years come irregularly, roughly once in four or five years (Troup 1921, Gamble 1922). Deodar requires open forests to produce a good seed crop; in a closed forest stand seed are sparsely produced. A good seed bearer often occurs on a dry and sunny site. Within a seed cone, all portions are not the same with regard to seeds; the middle portion bears more healthy seeds than the lower and upper ones. On the edges of deodar forests, where blue pine also occurs with seed-bearers, the young populations of both come on in mixture. However, being faster in growth, the blue pine overtops the deodar and may outcompete it (Gamble 1922). In several forest stands of Malari (located in dry inner ranges), we found blue pine regenerating and growing more than deodar in the forest edges. To produce tall straight boles without branches, deodar should be grown closely, gradually thinning until it is sufficiently tall.

Vertical stratification of biomass

In deodar, the apical dominance is strong, even more than in the major Himalayan pine, *P. roxburghii.* The percentage of total aboveground biomass allocated to bole is 91% for deodar (at 55 years of age) and 76% *P. roxburghii* (at 60 years of age) (Singh and Singh 1992). With ageing from 16 to 55 years, the proportion of bole in the biomass of deodar increases from 62 to 91%, and that of foliage decreases from 19.5 to 5.1%. This level of strong dominance of bole is reported for the North American Subalpine conifers (Turner and Singh 1976). Deodar's canopy is deeper than that of *P. roxburghii;* however, it changes with age. The foliage mass is the highest in the lower stratum at 16-24 yrs of age, whereafter it tapers towards the top, while at 35-60 yrs of age, it is the highest in the middle canopy (12-18 m above ground). In deodar, branches are small, hence foliage mass is more than branch mass throughout the canopy depth.

Wood

The bark of the deodar is greyish-brown, with many vertical fissures running into each other, giving a reticulate appearance (Gamble 1922). Distinct annual rings and oily and scented wood characterise deodar. The wood is moderately hard (490-600 kg m^{-3}) with light sapwood and light yellowish-brown heartwood. The wood is without resin ducts, while heartwood cells contain oil. The natural oil gives long durability and resistance to decay and insects. That is why it is used for furniture, and in past for railway sleepers.

Mycorrhizal association

Ectomycorrhizae contribute to forest productivity by enhancing plant access to nutrients and water, and their role in the cycling of P and N (Agarwal and Sah 2009). Conifers are quite rich in ectomycorrhizae. From *P. wallichiana* and *C. deodara* forests of Kashmir (studied at five sites), 76 potential ectomycorrhizal species were recorded (Itoo and Reshi 2014). *C. deodara* was found to be associated with 44 species, of which 25 were shared with *P. wallichiana*, and 19 occurred only with it. The total species number associated with *P. wallichiana* was 57, of which 32 were associated with it alone (25 were common). The 76 ectomycorrhizal species belonged to 14 families and 24 genera. The common fungal families were *Russulaceae, Boletaceae, Amanitaceae*, and *Cortinariaceae*with 17, 11, 11 and 10 species, respectively. The important genera in terms of species number were *Amanita* (11 species), *Russula* (10 species), *Lactarius* (07 species), and *Suillus* (06 species). Of the 76 species, 74 were of Basidiomycete, and 02 were Ascomycete, and 68 were with epigeous and 08 hypogeous sporocarp. Of the 76 species, 34 were rare to very rare (Itoo and Reshi 2014). The common species associated with *C. deodara* were *Amanita vaginata, A. flavoconia, A. pantherina, Lactariusdeliciosus*, *Ramariafalva, Russuladecolorans, R. fragilis, R. brevipes, R. maculathus, Suillus brevipes, S. elegans.*

Growth responses of deodar to climate change

From the studies on the relationship between growth of deodar and climate, we summarise that the growth recorded in tree-ring width is primarily controlled by pre-monsoon (March-May) moisture (precipitation/drought stress) in several mid- and low-latitude monsoon-influenced sites, while at higher-elevation in colder sites, temperature (late winter/spring warmth) can become limiting. Under 21st-century warming, models and dendro-projections suggest growth declines for low–mid elevation/monsoon-dominated deodar sites (because higher temperatures increase evapotranspiration and produce drought stress), whereas high-elevation populations may show neutral or modest gains because warming relieves cold limitation (Bhattacharyya et al. 2023). Evidence in support of the above findings is as follows:

1. Strong hydroclimatic signal (precipitation/ drought): Multiple ring-width chronologies of deodar from the western Himalaya show positive correlations with pre-monsoon precipitation. In moisture-stressed sites, narrower rings align with drought years. This makes deodar a good proxy for reconstructing past hydroclimate (Singh et al. 2024).
2. The temperature role is site-dependent; at some high-altitude sites, growth is limited by cold winter/ spring temperatures, so ring widths correlate with pre-monsoon/winter temperature (warmer = more growth). But in many lower elevations, monsoon-dominated areas, higher pre-monsoon temperatures often correlate negatively with growth because they boost evaporation demand and intensify drought stress. In short: temperature matters, but usually through its influence on moisture (evapo-transpiration, snowmelt timing) (Borgaonkar et al. 2009).
3. The key seasons/months vary by site, but studies repeatedly point to pre-monsoon (March–May) and the beginning of the monsoon as the critical window when moisture vs. temperature most strongly affect radial growth (Singh et al. 2024).
4. Physiological and age effects also count. Tree age and stand conditions modulate signal strength — older tree stands, and moisture-stressed stands often show a clearer climatic signal than young or dense stands. Also, intra-annual density fluctuations (IADFs) in deodar rings indicate episodic water-stress events (Dhyani et al. 2022).

Dhyani et al. (2022) examined the age effect on the growth responses of deodar to climate change by comparing two age classes, young age (<100 years) and old (>100 years of age), for the period 1950 to 2015. Using the generalised additive model (GAM), the study modelled stem basal increment (BAI) from 1950 to 1990. The BAI in old age increased at the rate of 0.13 cm²/yr, whereas in young age it decreased at the rate of "0.27 cm²/yr. However, from 1990 onwards, tree BAI declined in both age classes, presumably because of warming and a decrease in precipitation (Dhyani et al. 2022). The growth of trees of the two age classes was adversely affected by pre-monsoon water stress and warming, which was intensified by global warming. In brief, the overall trend of BAI as predicted by GAM from 1950 to 2015 was a decline in young stands and an increase in the old stands.

Tiwari et al. (2024) studied the growth responses of deodar to climate change in western Nepal (Mugu and Jumla districts). The study showed a negative correlation between radial growth and early growing season (March) temperatures and a positive correlation between radial growth and rainfall in June. At the two study sites, radial growth was found to be negatively correlated with early growing season temperature, while late growing season temperature had a positive effect on growth.

Future prediction under climate change

At low and mid-latitude / monsoon-dominated sites, most modelling and tree-ring-based projection work indicates declines in growth (up to ~30–40% in some projections) under moderate-to-high warming scenarios (RCP4.5–8.5) because higher temperatures increase evaporative demand and reduce effective soil moisture and spring snowmelt. On the other hand, at high-elevation sites, warming may relieve cold limitation and lengthen the growing season, producing stable or modest increases in growth at the highest elevations — at least until other limits (nutrients, extreme drought, pests) appear (Zheng et al. 2021).

Regional heterogeneity is expected as the Himalaya is climatically complex — some places are influenced by monsoon variability, others by western disturbances and snow. Therefore, responses of deodar could be spatially variable: decline in monsoon-dominated zones, possible gains where temperature is currently limiting, and mixed outcomes where changes in seasonality (earlier snowmelt, shifted monsoon timing) occur (Islam et al. 2024).

Practical implications

1. Vulnerability mapping: Deodar populations in mid/ low elevations and monsoon margins are most vulnerable to future drought stress. This warrants some studies and prioritisation of monitoring and conservation there (Bhattacharyya et al. 2023).
2. Passive adaptation, which may involve assisted migration or protecting higher-elevation refugia. This could help conserve genetic diversity and maintain suitable habitat (Dhyani et al. 2025).
3. Hydrological coupling: Because deodar's growth integrates snowmelt and monsoon moisture, forest management should consider catchment hydrology (snowpack, groundwater recharge) alongside tree health. This kind of hydrological coupling could go a long way in addressing the issue (Singh et al. 2024).
4. Long-term monitoring is required as continued tree-ring sampling across elevations and climates will refine projections. Furthermore, age-structure and stand condition must be included to avoid misleading inferences (Dhyani et al. 2022).

To conclude for *C. deodara* in the Himalaya, drought / moisture limitation is the dominant control on growth across most monsoon-influenced sites, while temperature becomes limiting at the coldest, highest sites.

Climate change will likely reduce growth in many low-to-mid elevation populations (via increased evapotranspiration and altered snow/monsoon patterns) while possibly boosting growth only at the highest elevations — overall a heterogeneous, region-dependent outcome (Bhattacharyya et al. 2023). More data from different situations are required to confirm these findings. If the predictions described above are going to occur, deodar may move up and form a treeline along with firs and birch.

Climate sensitivity and growth responses

A study based on dendrochronological technique from 17 deodar forest sites on quantification and prediction of future growth showed that deodar would be adversely affected in lower ranges by intensification of climate change (Bhattacharya et al. 2023). The pre-monsoon (March-May) drought stress in the lower part of the elevational range is likely to intensify because of a decline in precipitation and an increase in temperature. In higher ranges, the effect of climate change is predicted to be favourable because of increased snowfall due to the increased westerlies activity.

Using the Generalised Least Squares (GLS) regression model for emission scenarios RCP 4.5 and RCP 8.5, Bhattacharya et al. (2023) predicted that the growth of deodar would decrease in areas of lower latitudes (such as Uttarakhand) because of the increase in warming-induced evapo-transpiration loss and reduced availability of snow melt water during the pre-monsoon growth. In higher latitudes, on the other hand, the growth of deodar is expected to increase as snowfall is predicted to increase because of the higher western disturbances.

CONCLUSIONS

Known widely for its high timber quality and majestic appearance, *C. deodara* is one of the iconic tree species of the Himalaya, but the amount of research carried out is not consistent with its place in forestry. As for its timber quality, only teak (*Tectona grandis*) is comparable in the country. It is considered among the most suitable species for studies on the relationships between tree ring growth and climate. However, even the optimal environmental conditions for its growth are not properly defined. It occurs abundantly in the dry inner ranges of the western Himalayas, where snowfall is high, and there is a lack of competition with oaks and other broad-leaved species, which fail to occur in the inner ranges. However, its growth is more in the moist outer ranges than the dry inner ranges.

In the inner ranges, deodar forests appear to be late successional, following *P. wallichiana*, which is considered to be a pioneer. The other pioneer species could be *Populus ciliata* and *Salix* species in areas of deodar's domination. However, research is required to examine how effective deodar is in regenerating under its own canopy.

More importantly, there is a general lack of information on basic ecosystem structure and functioning, such as litter decomposition, nutrient resorption from senescing leaves, and nutrient and carbon storage patterns in woody and green components. Information on the role of ectomycorrhizae in the growth and expansion of deodar in a harsh environment is scarce.

Dependence of seed, dispersal by birds and herbaceous growth and regeneration of deodar needs to be investigated. Both are likely to be lower in the inner ranges than in the outer ranges. How deodar is adapted to seasonal drought is almost unknown. Seedling mortality due to droughts is common. Whether it is an isohydric species, like many members of Pinaceae, needs to be examined thoroughly. The role of old-growth deodar forest in biodiversity needs to be identified, particularly in view of the fact that stand longevity positively influences forest soil.

How structural and functional features of deodar vary along the gradient of proportional increase in non-monsoon precipitation? Do the phenological characters of deodar in Kashmir, where monsoon months account for less than 30% of annual precipitation, differ from those in Uttarakhand, where the monsoon season accounts for 70-80% of annual precipitation?

In brief, deodar and other tree species which occur abundantly in inner ranges need to be investigated in view of the precipitation seasonality, amount and proportion of snow in precipitation, mycorrhizal association, the impact of shrub and herbaceous growth and the effect of age.

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