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Spatial Patterns of Forest Structure and Heterogeneity in a Western Himalayan *Cedrus deodara* Stand

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Abstract

An understanding of stand structural variation is critical in assessing forest status, analyzing tree size variation, and ensuring ecologically sound management of Himalayan conifer forests. Nonetheless, relying on stand-level data of averages could conceal significant spatial differences in terms of stocking and structural variability. This study explored the structural characteristics and spatial differences of a *Cedrus deodara* stand located in the Western Himalaya through tree- and quadrat-level measurement. The study incorporated measurements of total of 578 trees across nine sampling quadrats to evaluate density, basal area, diameter at breast height (DBH), quadratic mean diameter (QMD), tree height, and structural variability. Also, diameter and height inequality were estimated through coefficients of variation and Gini coefficients, while tree diameter- and height-class distribution was measured for the stand. To combine several aspects of structural variation, the Relative Structural Condition Index (RSCI) was developed by integrating three components of structural stocking, Diameter structural heterogeneity, and vertical structural heterogeneity. The stand showed rather high dimensions of trees with average DBH being 74.38 cm, QMD, 80.81 cm, and basal area 131.75 m^2 ha^{-1}. The diameter structure was much more heterogeneous than that of heights as seen from DBH CV (42.49%) and Gini coefficient (0.227) and height CV (17.41%) and Gini coefficient (0.098). The most dominant DBH class was 60–<80 cm and 74.57% of trees fell within height between 20 and <30 m, indicating a relatively concentrated vertical structure. The quadrats demonstrated noticeable variations within the stand, since tree density varied from 148 to 384 trees ha^{-1} and basal area from 72.28 to 206.45 m^2 ha^{-1}. The RSCI indicated large variations in relative structural condition being between 12.99 and 85.87. The conclusions drawn from this study suggest that stocking measures can no longer solely define the *Cedrus deodara* stand. The integration of tree size inequality, horizontal differentiation, vertical structure, and quadrat variation is essential for the extensive evaluation of stand structural conditions. The RSCI provides a means of effectively comparing the structural conditions of the stands and facilitating the management of *Cedrus deodara* forests.

Keywords: *Cedrus deodara*; stand structure; structural heterogeneity; Gini coefficient; quadrat-level variation; Relative Structural Condition Index

1. **Introduction**

Forest structure refers to the physical organization of trees in a forest and plays an important role in understanding stand development, distribution of resources, habitat variability, and ecosystem functioning. Traditional forest inventory methods often describe a stand in terms of density, basal area, diameter distribution, quadratic mean diameter (QMD), or tree height. While these variables are certainly key to an understanding of forests, although focusing on individual structural features can result in a partial understanding of a forest organization since forests can display variations of tree size, stocking intensity, and vertical and horizontal complexities at the same time. As a result, much focus has switched to multi-dimensional settings of forest structures that present forests not as an object described by a single metric but as a set of several interacting components (Ehbrecht et al., 2021; Mensah et al., 2020)

Structural complexity of forests has high importance as it is responsible for effects such as arrangement of trees and size variability, affecting the canopy formation, take up of light, distribution of resources, and habitat provision. At the level of a stand, structural complexity is consisting of the changes in how trees and their canopies are in three-dimensional space. Global studies confirmed that structural complexity varies a lot in different forest biomes and that it relates to climatic conditions and biodiversity patterns, which shows that structural features possess information on the subjects that are not related to normal estimations of biomass or canopy height (Ehbrecht et al., 2021). Additionally, various recent observational studies proved that structural complexity may be related to biodiversity and ecosystem processes, providing the second reason to consider different aspects of forest structures in the stand analysis (Mensah et al., 2020; Perles-Garcia et al., 2021).

The significance of structural assessment is particularly evident in mountain forests, as the strong environmental gradients contribute to a considerable amount of spatial variability in stand development. Elevation, rainfall, temperature, geography, as well as disturbances, can have a bearing on tree growth, species composition, biomass distribution, and spatial structure of forests. The recent findings from the Himalayas have proved that forest structure reveals a strong response to environmental gradients, whereas the latest studies that utilize three-dimensional measurements of forest structure have placed importance on the need for considering tree architecture and structural complexity in mountain ecosystems (Das et al., 2025). The recent assessment conducted in the Central Himalayas has indicated that forest structure depends on climatic and elevation gradients, thus proving that the study of structural dynamics must be conducted at appropriate spatial levels rather than relying on the assumption that forests have uniform structural organization.

The Himalayan region provides an excellent basis for such studies, as its forests are being subjected to significant environmental variations, including climatic and anthropogenic pressures. In the Western Himalayas, *Cedrus deodara (Roxb.) G.* Don is one of the important coniferous species in terms of ecology and economy and is thriving across large areas of suitable temperate habitats. The studies indicate that *Cedrus deodara* is sensitive to climatic variations and environmental conditions, with factors like age particularly affecting its growth patterns and vulnerability to climate stress (Dhyani et al., 2022; Bhattacharyya et al., 2023). Furthermore, recent investigations have pointed to the need for better understanding of the distribution, community structure, growth patterns, and conservation needs of Himalayan cedar considering changing environmental conditions (Kumar et al., 2024; Singh et al., 2026).

Several species provide evidence for significant networks formed because of forest biome variability across the Himalayas. A study carried out in the Central Himalayas documented relationships between community structure, species richness, and carbon stock. Research from the Western Himalayas also discovered spatial differences in plant community structure as well as plant regrowth and response to environment. Finally, several studies explicitly concerning *Cedrus deodara* explored its regeneration, growth, vulnerability, and distribution, but focused on specific ecological processes or environmental gradients instead of unifying multiple aspects of the evaluation of intra-community structural variability.

The tendency to use stand-wide averages in traditional forest assessment methods is a major limitation of those approaches. For instance, two quadrats may show similar average DBH, but they may differ greatly in diameter variations, tree density, basal area, and height variability among others. Conversely, the quadrat densely stocked with trees may not always be the one that exhibits the highest structural differences. The significance of this issue is even more profound in the case of mature coniferous forests in which large trees could make a great contribution to basal area and diverge in size and height distribution due to the development of the stand and the specific local conditions.

Multidimensional relative assessment can solve this problem by integrating comparable structural indicators after data standardization. In this study, three structural indices were introduced: the first one is structural stocking which indicates the amount of contribution made by tree quantity and size; the second one is Diameter structural heterogeneity which is illustrated by diversity in tree diameters; and the third one is vertical structural heterogeneity indicated by difference in tree heights. All these indices were used in the Relative Structural Condition Index (RSCI). It should be noted that RSCI is meant to be a comparative index within this research, i.e. it is not an absolute indicator of ecological sustainability; instead, it indicates how well each sampling square performs compared to the structural range found among nine squares. Such an approach is very useful because it helps to determine structurally different parts of a forest and can be used as a starting point for further research.

Measurements were collected from 578 trees across nine quadrats in a stand of *Cedrus deodara* in the Himalayas. The information derived from the analysis enables the assessment of stand-level attributes such as the variables of diameter and height distribution and spatial variability with respect to stocking. The analyses provided enable researchers to tell the differences between the colonization structure of overall stands and the structure of the given stands. Therefore, the purpose of the study was not only to characterize the studied stand, but to assess where the structural conditions differ in the various quadrats.

1.1 Objectives of the study

The study specifically aimed to:

1. Characterize the overall structural attributes of the Cedrus deodara stand using tree density, basal area, DBH, QMD, tree height, coefficient of variation, and Gini coefficients.

What this achieves:

This establishes the stand-level structural baseline and determines whether diameter and height exhibit similar or contrasting patterns of variability. In the present dataset, this objective

demonstrates substantially greater inequality in diameter than in height, providing the foundation for subsequent structural interpretation.

2. Quantify the diameter- and height-class structure of the sampled population to identify the dominant tree-size and height classes and assess the degree of structural concentration.

What this achieves:

This identifies the developmental structure of the stand and reveals whether the population is dominated by small, intermediate, or large trees. The results show that the 60–<80 cm DBH class dominates the diameter distribution, while 74.57% of trees occur between 20 and <30 m height, demonstrating stronger concentration in vertical structure than in diameter structure.

3. Evaluate spatial variation in structural stocking and tree-size heterogeneity among the nine sampling quadrats using density, basal area, mean DBH, QMD, DBH CV, and height CV.

What this achieves:

This determines whether the stand is structurally uniform or spatially differentiated. The observed differences—from 148 to 384 trees ha^{-1} in density and approximately 72.28 to 206.45 m^2 ha^{-1} in basal area—demonstrate substantial within-stand variation.

4. Develop a Relative Structural Condition Index (RSCI) by integrating structural stocking, Diameter structural heterogeneity, and vertical structural heterogeneity into a common 0–100 comparative scale.

What this achieves:

This converts several measurements expressed in different units into comparable structural scores, allowing each quadrat to be evaluated simultaneously rather than independently. The three components can then be combined to produce a single relative structural-condition score for each quadrat.

5. Rank the sampling quadrats according to their relative structural condition and identify structurally contrasting areas within the sampled stand.

What this achieves:

This provides the management-oriented outcome of the study. Rather than simply reporting that Q9 has high density or Q4 has high basal area, the RSCI identifies the quadrats that have the strongest overall combination of stocking and structural heterogeneity. In the current results, RSCI ranges from 12.99 to 85.87, clearly demonstrating strong spatial differentiation in relative structural condition.

1.2 *Research gap and rationale for developing RSCI*

Although it is increasingly acknowledged that forest structural complexity has multiple dimensions, there are still important gaps in methodologies and geographical applications. International studies demonstrate that forest structural complexity can be evaluated according to different criteria, and structural complexity plays an important role in biodiversity and the functioning of ecosystems (Ehbrecht et al., 2021). However, many sophisticated approaches are based only on the use of terrestrial laser scanning, airborne LiDAR, or other three-dimensional devices, which can provide detailed measurements of forest structure but might be inconvenient

in ordinary field inventories, particularly in difficult-to-access mountain forests. Other indices that measure structural complexity mainly measure tree position, diameter, architectural features, or three-dimensional architecture of canopies.

This is specifically applicable in the case of Himalayan forests. Modern studies performed in the Central Himalaya show a correlation between stand structure, variety of species, large trees features, and biomass as well as provide evidence of insufficient and unstable information on structure of Himalayan forests (Kaushal & Baishya, 2021). However, investigations of the Himalayan region have mainly focused on stand composition, biomass, carbon stocks, regeneration, diversity of the region or various reactions to environmental impacts. It is still important to find an approach that would link several routinely measured characteristics of structure and produce a general comparative value of ecological health of a stand especially concerning sampling units that might reveal big differences within the stand that looks similar.

Another difference concerns different aspects of horizontal and vertical structural heterogeneity, as separation and combination of factors occurs. Diameter fluctuation sheds light on the differences in tree size and horizontal stand configuration, while height fluctuation brings other information about vertical differentiation. It has been shown that horizontal, vertical, and internal characteristics of structural complexity can behave differently and have different ecological meaning, which implies that structural complexity cannot be described using only one indicator (Ma Q. et al., 2022). Thus, the evaluation made based on any single factor such as density, basal area, mean DBH, or some measure of structural complexity can miss important differences between the sampling units.

1.3 From research gap to RSCI

In response to this issue, a Relative Structural Condition Index (RSCI) is introduced in the current research, which combines three interrelated aspects of stand structure: (i) structural stocking, in terms of density, basal area, mean diameter of trees, and mean diameter; (ii) Diameter structural heterogeneity, in terms of diameter of trees variability; and (iii) vertical structural heterogeneity, in terms of height variability. All its measures are standardized on the same scale to create the relative metric for every quadrat under study. Unlike absolute sustainability indexes or ecological health indexes, the RSCI is meant to be used for assessing within-stand variation, that is, what is the structural state of a particular quadrat in comparison to the range of structures observed in the neighboring quadrats. This considers a concept according to which forest structure must be estimated from different complementary perspectives while remaining an easy-to-use method that can be used without advanced technologies (Ehbrecht et al.,2021).

Thus, one major contribution of this work is not the suggestion of yet another universal structural-complexity index, but rather the construction and use of a simple, transparent, field-based comparative framework for detecting spatial differences in structural condition in a *Cedrus deodara* stand. By utilizing conventional inventory parameters along with the indicators of heterogeneity of diameters and height of trees, the RSCI enables movement from separate structural measurements to multilevel assessment of the overall structure and ranking of quadrats. In this study, the framework is applied to the sampled *Cedrus deodara* stand to assess whether it exhibits uniformity of structural organization or a certain extent of spatial differentiation, as well as to determine which quadrats possess relatively high or low structural condition.

"The principal contribution of the study is therefore not the introduction of another universal structural-complexity index, but the development and application of a simple, transparent, field-derived comparative framework for identifying spatial differences in structural condition within a *Cedrus deodara* stand."

2. Materials and Methods

2.1 *Study area*

The present study was conducted in Section: Deoban (1344ha), Beat: Matkangda (283.70 ha), Compartment / Block: Deoban 11 (106ha), Kanasar Range, situated in the western Himalayan region of Uttarakhand. The area falls under Chakrata Forest Division and is well known for its dense stands of *Cedrus deodara*. The study area represents a temperate Himalayan Forest environment characterized by substantial variation in tree size, stand density and vertical development. *Cedrus deodara* is an ecologically and economically important conifer of the Western Himalaya, where it forms both pure and mixed forest stands. The selection of the Deoban–Chakrata region was motivated by the ecological importance of *Cedrus deodara* forests and the need to characterize their structural organization using field-based quantitative measurements.

2.2 *Sampling design and field data collection*

A quadrat-based sampling design was adopted to quantify the structural characteristics of the *Cedrus deodara* stand. Nine quadrats, each measuring 50 × 50 m (0.25 ha), were established within representative portions of the study stand. Thus, the total sampled area was 2.25 ha. Within each quadrat, all qualifying *Cedrus deodara* trees were enumerated and measured. A total of 578 trees were included in the final cleaned dataset.

The field inventory recorded the principal tree-level variables required for subsequent structural analysis, including diameter at breast height (DBH) and total tree height. These measurements were subsequently aggregated at the quadrat level for construction of the RSCI.

2.3 *Measurement of tree variables*

2.3.1 Diameter at breast height

Diameter at breast height (DBH) was measured at 1.37 m above ground level using standard forest mensuration procedures and expressed in centimeters (cm). DBH was selected as a principal structural variable because diameter distributions provide important information about tree-size differentiation and stand organization.

2.3.2 Tree height

Total tree height was measured in meters (m) using a suitable hypsometric instrument following standard field procedures. Tree height was used to characterize the vertical dimension of stand structure. Differences in tree height among individuals reflect vertical differentiation and contribute to the structural heterogeneity of forest stands.

2.4 Stand structural variables

For each quadrat, the following structural attributes were calculated: tree density (trees ha^{-1}), basal area (m^2 ha^{-1}), quadratic mean diameter (QMD; cm), mean DBH (cm), DBH coefficient of variation (DBH CV; %), and height coefficient of variation (Height CV; %). These variables

collectively represent stocking, tree-size structure, horizontal differentiation and vertical differentiation.

2.4.1 Tree density

Tree density was expressed as the number of trees per hectare:

$$D = \frac{N}{A}$$

where D = tree density (trees ha^{-1}), N = number of trees recorded in the quadrat, and A = quadrat area in hectares.

Basal area was calculated from individual tree DBH values as:

$$BA = \sum \frac{\pi d^2}{4}$$

where BA = basal area, d = tree diameter at breast height, and $\pi = 3.1416$. The resulting basal area was expressed as $m^2\ ha^{-1}$.

2.4.3 Quadratic mean diameter

Quadratic mean diameter was calculated as:

$$QMD = \sqrt{\frac{\sum d^2}{N}}$$

where QMD = quadratic mean diameter (cm), d = DBH of individual trees, and N = number of trees in the quadrat.

2.5 Measures of structural heterogeneity

2.5.1 DBH coefficient of variation

The coefficient of variation of DBH was calculated as:

$$DBH\ (CV) = \frac{SDDBH}{Mean\ DBH}\ x\ 100$$

where SDDBH = standard deviation of DBH and mean DBH = mean diameter. Higher DBH CV indicates greater differentiation in tree diameter and therefore greater horizontal size heterogeneity within the quadrat.

2.5.2 Height coefficient of variation

Height variability was calculated as:

$$Height\ (CV) = \frac{SDH}{Mean\ H}\ x\ 100$$

where SDH = standard deviation of tree height and mean H = mean tree height. Higher Height CV indicates greater vertical differentiation among trees.

2.6 Descriptive and statistical analysis

The quadrat-level data were summarized using mean, minimum, maximum, standard deviation (SD), coefficient of variation (CV), and Gini coefficient, where appropriate. The Gini coefficient was used as an additional descriptive measure of inequality in tree-size distributions, particularly for DBH and height, but was not incorporated into the final RSCI.

Pearson correlation analysis was used where appropriate to examine relationships among structural variables. Correlations among component indicators were also considered when evaluating possible redundancy within the composite framework, because strongly related indicators can contribute overlapping information to composite indices (Soler-Font et al., 2021). Statistical calculations were performed using statistical software, and graphical representations were prepared to visualize variation among the nine quadrats.

2.7 Development of the Relative Structural Condition Index (RSCI)

2.7.1 Conceptual framework

In this study, the Relative Structural Condition Index (RSCI) was created to combine all the significant features of the analyzed *Cedrus deodara* stand and present these data in a general aspect. This concept is based on the original understanding that the structure of a forest is multidimensional and should be assessed using several structural properties rather than one or two variables (Ehbrecht et al., 2021; Põldveer et al., 2021; Ma et al., 2022). Therefore, RSCI is not an absolute measure of ecological sustainability or forest health, but rather a relative one that refers to the structural condition of the quadrat relative to the other quadrats. Hence, a quadrat with a higher RSCI value shows a higher total value of all chosen parameters than other quadrats observed in the study.

2.7.2 Three structural pillars

The RSCI consisted of three structural pillars: Pillar I—Structural stocking and tree-size condition (P_1); Pillar II—Diameter structural heterogeneity (P_2); and Pillar III—Vertical structural heterogeneity (P_3).

Pillar I — Structural stocking condition (P_1)

Pillar I represent the stocking and tree-size condition of each quadrat and incorporates density, basal area, QMD and mean DBH. The normalized values of these four indicators were averaged:

$$P_1 = \left(\frac{D' + BA' + QMD' + DBH'}{4}\right) x\ 100$$

where D′, BA′, QMD′ and DBH′ are the normalized scores of densities, basal area, QMD and mean DBH, respectively.

Pillar II — Diameter structural heterogeneity (P_2)

Pillar II represents diameter differentiation and is based on DBH coefficient of variation:

$$P_2 = DBHCV'\ x\ 100$$

where DBH CV′ is the normalized DBH coefficient of variation.

Pillar III — Vertical structural heterogeneity (P_3)

Pillar III represents vertical structural differentiation and is based on the coefficient of variation of tree height:

$$P_3 = \text{Height CV}' \text{ x } 100$$

where Height CV′ is the normalized height coefficient of variation.

2.7.3 Min–Max normalization

As the structural indicators had been measured using various units and had different value ranges, it was necessary to standardize data in advance. Normalization is a routine procedure in the formation of composite indices as the indicators reported in disparate units must be normalized before aggregation (OECD/European Union/EC-JRC, 2008; Mazziotta & Pareto, 2022).

For a positive-direction indicator:

$$I_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

where I_i = normalized indicator scores for quadrat i; X_i = observed value for quadrat i; Xmin = minimum observed value across the nine quadrats; and Xmax = maximum observed value across the nine quadrats. The normalized score ranges from 0 to 1.

For a negative-direction indicator, reverse normalization was applied:

$$I_i = 1 - \left[\frac{X_i - X_{min}}{X_{max} - X_{min}}\right]$$

In the current RSCI framework, the chosen technical indicators were viewed as indicators of the positive nature. The meaning of this term lies in its analytical, depending on the context of the study, nature: the greater the values, the higher the relative expression of the relevant parameters of the study trees within the *Cedrus deodara* stand. It does not imply that higher density, larger trees, or greater heterogeneity are universally optimal ecological conditions.

2.7.4 Aggregation of the three pillars

Following normalization, the three pillar scores were combined using equal weighting:

$$RSCI = \frac{(P_1 + P_2 + P_3)}{3}$$

Since every pillar was quantified on a scale of 0 to 100, it follows that the final value of RSCI lies between 0 and 100 as well. The same weight was assigned to all the pillars because they are regarded as structural dimensions that fit together and no scientific backing exists for using different weights. Applying pillar-based methodology also makes it impossible for P_1 to gain a larger influence than P_2 and P_3 since it has more indicators. Thus, this option is in line with the accepted composite-indicator-following principles, while sensitivity analysis is conducted since other weighting options could change the results of composite indicator (OECD/European Union/EC-JRC, 2008; Lindén et al., 2021). Consequently, the pillars' equal application became the backbone of this research while other methods of distribution were checked for viability.

2.7.5 Interpretation of RSCI

For interpretation and comparative classification, RSCI values were grouped into five descriptive categories: ≥75 = very high; 60–<75 = high; 45–<60 = moderate; 30–<45 = low; and <30 = very low.

These categories represent a specific descriptive classification of the study and not a universal set of ecological thresholds. RSCI values are derived from the expression of certain structural features in the sampled stand; thus, higher RSCI values indicate a more pronounced expression of structural aspects, while lower RSCI values point to a weaker one. As the RSCI is the result of min-max normalization of nine quadrats, the data cannot be compared between different stands unless a common reference range is defined.

2.7.6 Rationale for RSCI development.

The creation of RSCI was spurred due to the existing conventional stand structure variables that describe varying and complementary aspects of forest organization but can show different results depending on their independent application. The current number of trees is indicated mainly by the variable of density and basal area, the tree diameter is expressed by the values of QMD and mean DBH, while variation in both DBH and height coefficients of multiple Tree sizes signifies measures of diameter and vertical structure. Therefore, having integrated all these aspects allows us to compare the structural conditions of separate quadrants better than if we were to stick to only one value out of the above ones which contradicts the understanding that the structural complexity of forests is multifaceted requiring different structural signs for adequate showcasing of structural variability (Ehbrecht et al., 2021; Põldveer et al., 2021; Zhang et al., 2021; Ma et al., 2022).

Due to the discrepancy of the component variables in terms of their parameters, min–max normalization approach was necessary to render these variables comparable (Mazziotta & Pareto, 2022). At the same time, it was decided to apply equal weighting in this field to sustain transparency and replicability since there were no independent empirical grounds possible to provide for appropriate weights application. In addition, sensitivity analysis was performed to find out if the inclusion of potentially redundant size of trees indicator (mean DBH) has a significant influence on the final ranking in line with the conventions accepted in the development of composite indicators (OECD/European Union/EC-JRC, 2008; Lindén et al., 2021).

2.8 Statistical and graphical presentation

The results included information about the structural features of the quadrats, the normalized indicator scores P_1, P_2, and P_3, as well as the final RSCI values. The graphics showed how structural variables differed between quadrats and pillar scores and provided the RSCI ranking of the quadrats. The ranking was used to determine which structural units in the sampled stand of *Cedrus deodara* had relatively high or low scores.

3. Results

3.1 Overall structural characteristics of the Cedrus deodara stand

The sampled *Cedrus deodara* stand exhibited appreciable variation in tree diameter, with a mean DBH of 74.38 cm and a coefficient of variation of 42.49%. In contrast, tree height showed considerably lower variability, with a mean height of 22.66 m and a CV of 17.41%. The contrasting Gini coefficients further supported this pattern: DBH Gini was 0.227, whereas height Gini was only 0.098, indicating greater inequality in tree diameter than in tree height. Thus, although trees

differed substantially in their horizontal size structure, their vertical distribution was comparatively more uniform. The relatively high QMD (80.81 cm) and stand basal area (131.75 m^2 ha^{-1}) further indicate the strong contribution of relatively large trees to overall stand stocking. The overall structural characteristics of the sampled *Cedrus deodara* stand are summarized in Table 1.

Table 1. Stand-level structural characteristics

Variable	Mean	Minimum	Maximum	SD	CV (%)	Gini
Tree density (trees ha^{-1})	256.89	148	384	—	—	—
Basal area (m^2 ha^{-1})	131.75	72.28	206.45	—	—	—
DBH (cm)	74.38	2.23	239.81	31.61	42.49	**0.227**
QMD (cm)	80.81	—	—	—	—	—
Tree height (m)	22.66	11	34	3.95	17.41	**0.098**

Diameter structure is considerably more heterogeneous than height structure. Overall, the stand was characterized by relatively large tree dimensions, greater variability in diameter than height, and a comparatively concentrated vertical structure, providing a baseline for examining structural differentiation among sampling quadrats.

3.2 Diameter-class structure

The diameter structure of the sampled *Cedrus deodara* stand was dominated by intermediate-sized trees. The 60–<80 cm DBH class contained the largest proportion of trees (30.10%), followed by the 40–<60 cm (21.97%) and 80–<100 cm (19.03%) classes. Overall, 82.01% of the sampled trees occurred between 40 and <120 cm DBH, whereas trees below 40 cm accounted for 10.73% and those ≥120 cm for 7.27% of the population.

Table 2. DBH-class distribution

DBH class (cm)	Number of trees	Percentage (%)
<40	62	10.73
40–<60	127	21.97
60–<80	174	30.10
80–<100	110	19.03
100–<120	63	10.90
120–<140	26	4.50
140–<160	8	1.38
≥160	8	1.38
Total	**578**	100.00

The 60–<80 cm class is clearly dominant, with 174 trees. The 60–<80 cm class was the dominant diameter class, containing 174 trees (30.10% of the sampled population)

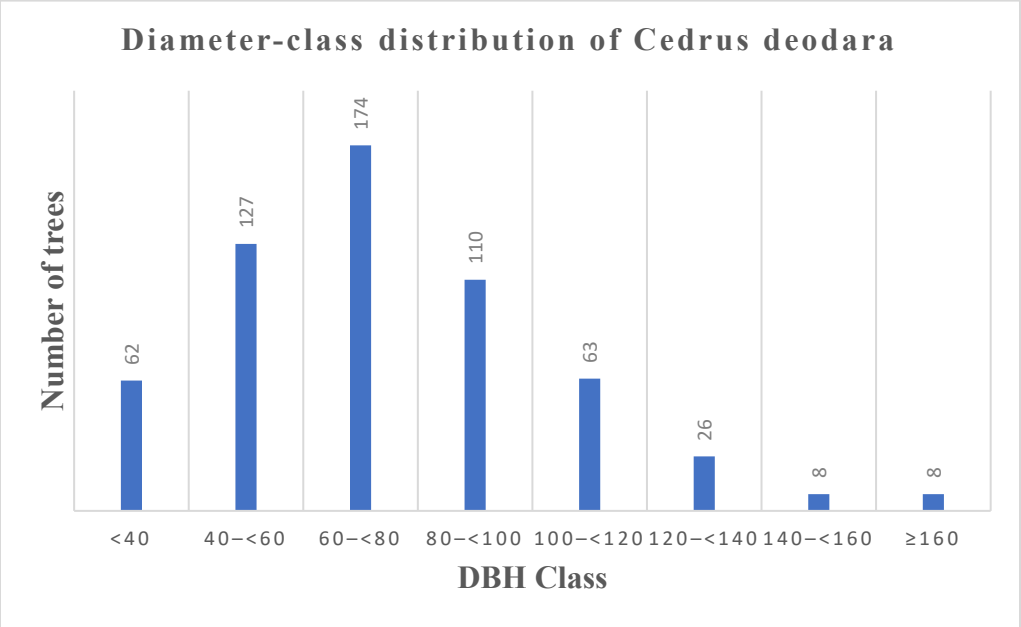


Figure 1: DBH-class distribution

The predominance of intermediate diameter classes indicates that the sampled population was structurally concentrated around medium-to-large trees, while the relatively small representation of trees below 40 cm and above 120 cm suggests limited contribution of the smallest and largest diameter classes to the sampled stand.

3.3 Height-class structure

The vertical structure of the sampled *Cedrus deodara* population was concentrated within the intermediate height classes. The 20–<25 m class contained the largest proportion of trees (251; 43.43%), followed by the 25–<30 m class (180; 31.14%). Collectively, trees between 20 and <30 m represented 74.57% of the sampled population. Trees below 15 m and those ≥30 m accounted for only 2.60% and 2.77%, respectively, indicating a relatively concentrated vertical structure.

Table 3. Height-class distribution

Height class (m)	Number of trees	Percentage (%)
<15	15	2.60
15–<20	116	20.07
20–<25	251	43.43
25–<30	180	31.14
≥30	16	2.77
Total	578	100.00

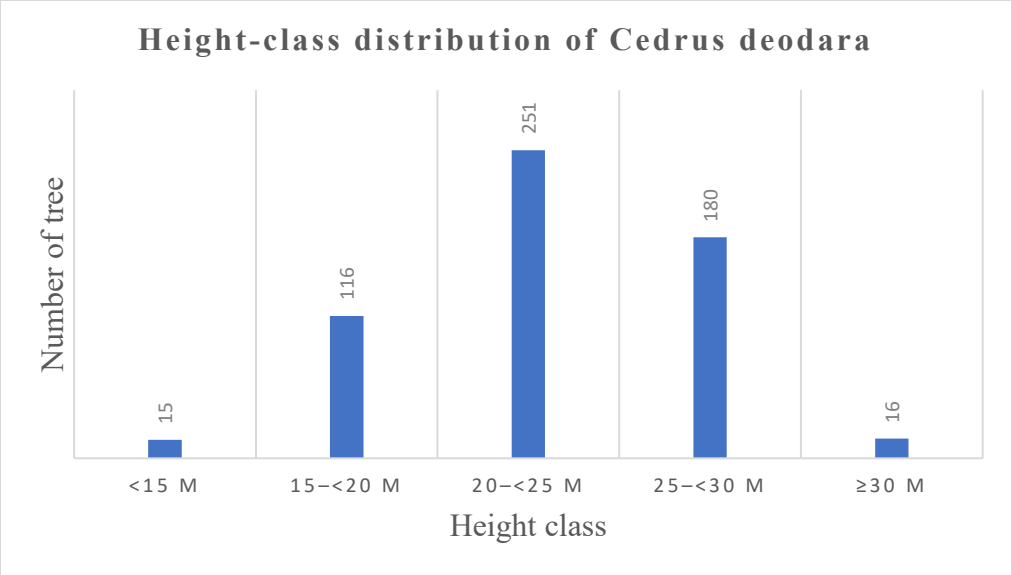


Figure 2. Height-class distribution of *Cedrus deodara* trees in the sampled stands of the Western Himalaya.

The concentration of nearly three-quarters of the sampled trees within the 20–<30 m height range indicates relatively limited vertical differentiation compared with the wider variation observed in diameter structure.

3.4 Quadrat-level structural variation

Considerable spatial variation was observed among quadrats. Tree density ranged from 148 trees ha^{-1} in Q3 to 384 trees ha^{-1} in Q9, while basal area varied from approximately 72.28 to 206.45 m^2 ha^{-1}. Q4 had the largest QMD (90.63 cm) and highest mean DBH (84.22 cm), whereas Q2 had the smallest QMD (66.54 cm) and mean DBH (65.00 cm). Diameter heterogeneity was greatest in Q7 (CV = 51.06%) and lowest in Q2 (22.05%), whereas height heterogeneity ranged from 12.29% in Q3 to 21.54% in Q9. These contrasting spatial patterns indicate that stand stocking, tree size and structural heterogeneity were not uniformly distributed among the sampling quadrats.

Table 4. Quadrat-level variation in structural attributes of the sampled *Cedrus deodara* stand in the Western Himalaya.

Quadrat	Density (trees ha^{-1})	Basal area (m^2 ha^{-1})	Mean DBH (cm)	DBH CV (%)	Mean height (m)	Height CV (%)
Q1	200	91.38	69.73	44.76	23.02	16.77
Q2	284	98.77	65.00	22.05	23.24	13.51
Q3	148	72.28	73.58	39.06	21.57	12.29
Q4	320	206.45	84.22	40.03	22.55	16.53
Q5	276	133.44	71.61	45.10	22.68	17.22
Q6	304	176.00	79.82	39.89	22.75	17.29
Q7	172	89.24	72.56	51.06	23.02	16.62

Q8	224	120.50	74.37	49.27	22.43	19.85
Q9	384	197.71	74.37	43.27	22.45	21.54

Collectively, the quadrat-level results demonstrate substantial spatial heterogeneity in both structural stocking and tree-size differentiation, providing the basis for an integrated relative assessment of structural condition.

3.4.1 Graphical representation of quadrat variation

Figure 3A — Density by quadrat

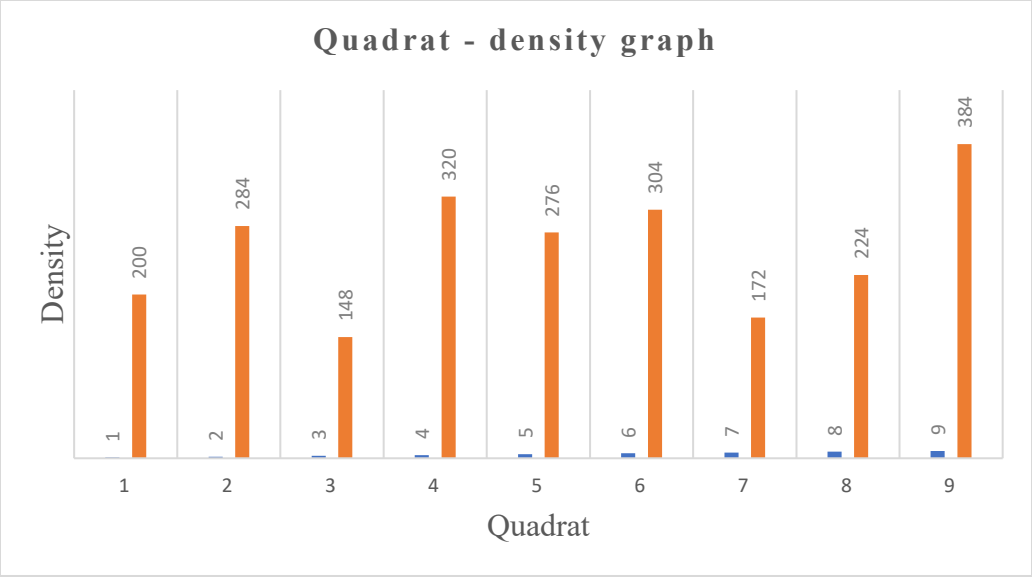


Figure 3. Quadrat-level variation in tree density and basal area of the sampled *Cedrus deodara* stand

Figure 3B — Basal area by quadrat

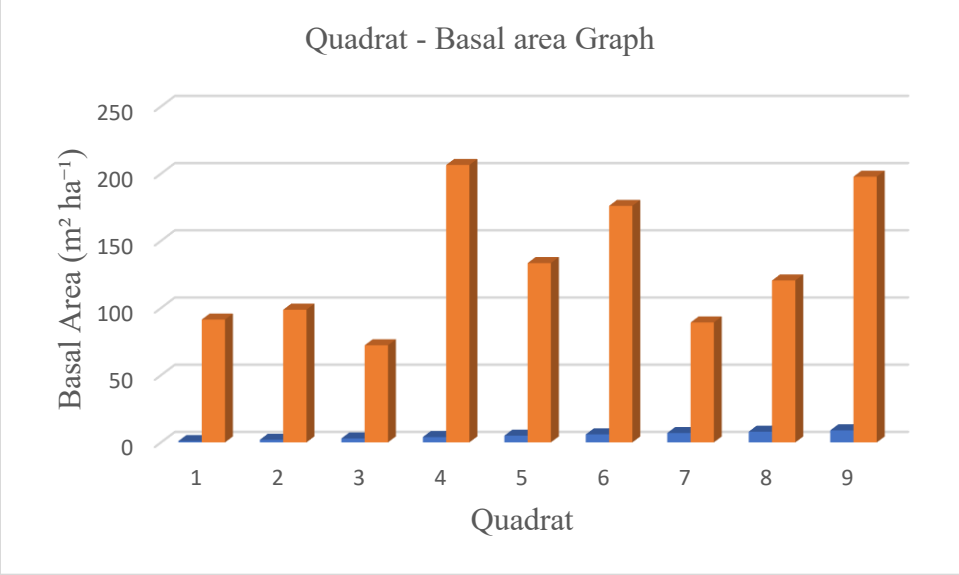


Figure 4. Quadrat-level variation in diameter and height heterogeneity of the sampled *Cedrus deodara* stand.

The graphical patterns reinforce the numerical results and demonstrate that differences among quadrats were expressed not only in stocking intensity but also in the degree of structural heterogeneity.

3.5 Relative Structural Condition Index (RSCI)

To integrate the major dimensions of stand structure and facilitate comparison among the nine sampling quadrats, a Relative Structural Condition Index (RSCI) was developed. The RSCI represents the relative structural condition of each quadrat based on three complementary structural dimensions: structural stocking (P_1), Diameter structural heterogeneity (P_2), and vertical structural heterogeneity (P_3). The index was intended as a comparative measure among quadrats rather than as an absolute measure of ecosystem sustainability.

Pillar I — Structural stocking (P_1)

Structural stocking was represented by four stand-level indicators:

• Tree density (D)

• Basal area (BA)

• Quadratic mean diameter (QMD)

• Mean DBH

These indicators collectively describe stocking intensity and tree-size characteristics. Because all four indicators were considered positive-direction indicators for structural stocking, their normalized scores were combined to obtain the stocking component:

$$P_1 = [\,(\frac{D' + BA' + QMD' + DBH'}{4})]\, x\, 100$$

where D′, BA′, QMD′, and DBH′ are the normalized scores of tree density, basal area, QMD, and mean DBH, respectively.

Pillar II — Diameter structural heterogeneity (P_2)

Diameter structural heterogeneity was represented by the coefficient of variation of DBH (DBH CV). Higher DBH variability indicates greater differentiation in tree diameter within a quadrat. The horizontal heterogeneity component was therefore calculated as:

$$P_2 = DBHCV'\, x\, 100$$

where DBHCV′ is the normalized DBH coefficient of variation.

Pillar III — Vertical structural heterogeneity (P_3)

Vertical structural heterogeneity was represented by the coefficient of variation of tree height (Height CV). Higher height variability indicates greater differentiation in the vertical structure of a quadrat. The vertical heterogeneity component was calculated as:

$$P_3 = HeightCV'\, x\, 100$$

where HeightCV′ is the normalized coefficient of variation of tree height.

Normalization of structural indicators

For each structural indicator, X denotes the observed value for a quadrat, whereas X_{min} and X_{max} denote the minimum and maximum observed values, respectively, across the nine quadrats. Because the indicators were expressed in different units and scales, they were normalized before aggregation.

For a positive-direction indicator, where a higher value contributes positively to the structural dimension:

$$I = \frac{X - X_{min}}{X_{max} - X_{min}}$$

For a negative-direction indicator, where a lower value represents better relative structural condition:

$$I = \frac{X_{max} - X}{X_{max} - X_{min}}$$

where I is the normalized indicator score ranging from 0 to 1. The normalized scores were subsequently expressed on a 0–100 scale for ease of interpretation.

Calculation of RSCI:

The three structural components were integrated with equal weighting to obtain the Relative Structural Condition Index:

$$RSCI = \frac{P_1 + P_2 + P_3}{3}$$

The RSCI therefore integrates structural stocking, Diameter structural heterogeneity, and vertical structural heterogeneity into a single comparative score ranging from 0 to 100. Higher RSCI values indicate comparatively stronger structural condition within the sampled set of quadrats, whereas lower values indicate comparatively weaker structural condition. The RSCI should be interpreted as a relative index within the sampled stand and not as a direct measure of ecosystem sustainability, ecosystem health, or long-term forest persistence.

3.7 Relative Structural Condition Index across quadrats

The RSCI values and component scores for the nine quadrats are presented in Table 5. The ranking integrates structural stocking, Diameter structural heterogeneity, and vertical structural heterogeneity.

Table 5. Relative Structural Condition Index (RSCI) and component scores across the nine sampling quadrats.

Rank	Quadrat	Structural stocking (P_1)	Horizontal heterogeneity (P_2)	Vertical heterogeneity (P_3)	RSCI

1	Q9	84.46	73.15	100.00	85.87
2	Q8	45.16	93.83	81.73	73.57
3	Q4	90.96	61.98	45.84	66.26
4	Q6	74.54	61.50	54.05	63.36
5	Q5	49.77	79.46	53.30	60.84
6	Q7	28.00	100.00	46.81	58.27
7	Q1	25.55	78.28	48.43	50.76
8	Q3	17.05	58.63	0.00	25.23
9	Q2	25.79	0.00	13.19	12.99

The RSCI ranking indicates clear differentiation among quadrats. Q9 recorded the highest RSCI (85.87), followed by Q8 (73.57) and Q4 (66.26), whereas Q2 (12.99) and Q3 (25.23) recorded the lowest values.

3.8 Interpretation of the Relative Structural Condition Index

Q9 recorded the highest relative structural condition (RSCI = 85.87), reflecting the combined contribution of strong structural stocking and relatively high horizontal and vertical structural heterogeneity. Q9 had the highest tree density (384 trees ha^{-1}) and the highest height CV (21.54%).

Q8 ranked second (RSCI = 73.57), despite having only intermediate structural stocking. Its relatively high RSCI was associated particularly with high horizontal and vertical structural heterogeneity, demonstrating that structural complexity contributed substantially to its overall relative structural condition.

Q4 ranked third (RSCI = 66.26) and exhibited the strongest structural stocking characteristics, including the highest basal area (206.45 m^2 ha^{-1}), QMD (90.63 cm), and mean DBH (84.22 cm). However, its comparatively moderate heterogeneity scores resulted in a lower overall RSCI than Q9 and Q8.

Q2 and Q3 recorded the lowest RSCI values (12.99 and 25.23, respectively). Q2 was characterized by particularly low diameter heterogeneity, whereas Q3 combined relatively low structural stocking with the lowest vertical heterogeneity score. These results demonstrate that relative structural condition differed among quadrats because of the combined effects of stocking and structural heterogeneity rather than any single stand attribute.

Overall, the RSCI provides a compact comparative representation of spatial variation in structural condition and identifies quadrats that may warrant greater attention in stand-level assessment and management.

3.9 Relative structural condition classes

For comparative interpretation, RSCI values were classified into five relative structural-condition categories using the study-defined thresholds shown in Table 6. These categories are intended for comparison within the sampled stand and are not presented as universally validated ecological thresholds.

Table 6. Study-defined relative structural-condition classes based on RSCI scores.

RSCI score	Relative structural condition
≥75	Very high
60–<75	High

45–<60	Moderate
30–<45	Low
<30	Very low

Based on these classes, Q9 fell within the very-high relative structural-condition category; Q8, Q4, Q6, and Q5 were classified as high; Q7 and Q1 were moderate; and Q2 and Q3 were very low.

The RSCI results complement the stand-level and quadrat-level structural analyses by integrating stocking intensity with horizontal and vertical structural differentiation. The index should therefore be used as a relative screening and comparison tool for the sampled quadrats rather than as a stand-alone indicator of ecological sustainability.

3.10 Robustness and sensitivity of the RSCI

To assess the robustness of the Relative Structural Condition Index (RSCI), a sensitivity analysis was conducted by comparing the original formulation, in which P_1 incorporated density, basal area, QMD and mean DBH, with an alternative formulation excluding mean DBH. QMD and mean DBH showed a strong positive correlation ($r = 0.959$), reflecting their common representation of tree-size structure. However, exclusion of mean DBH produced only minor changes in the resulting RSCI values. The correlation between the original and alternative RSCI scores was very high ($r = 0.9975$), and the relative ranking of all nine quadrats remained unchanged. The original ranking was Q9 > Q8 > Q4 > Q6 > Q5 > Q7 > Q1 > Q3 > Q2, which was identical to the ranking obtained from the alternative formulation. The mean absolute difference between the two RSCI estimates was 1.22 index points, while the maximum difference was 2.98 points. These results indicate that the relative structural ranking generated by RSCI was robust to the removal of mean DBH and was therefore not disproportionately dependent on the inclusion of this correlated tree-size indicator."

Table 7. Sensitivity analysis of the Relative Structural Condition Index (RSCI) under alternative P_1 formulations.

Quadrat	RSCI (original)	RSCI (without Mean DBH)	Rank	Alternative Rank
Q1	50.68	50.76	7	7
Q2	10.84	12.99	9	9
Q3	27.53	25.22	8	8
Q4	67.01	66.26	3	3
Q5	59.56	60.84	5	5
Q6	63.57	63.36	4	4
Q7	59.21	58.27	6	6
Q8	73.87	73.57	2	2
Q9	82.89	85.87	1	1

4. Discussion

4.1 Structural characteristics indicate a well-developed but heterogeneous Cedrus deodara stand

The first objective of the study was to characterize the overall structural condition of the *Cedrus deodara* stand using conventional forest mensuration variables. The results demonstrate that the sampled stand possesses a substantial stocking base, but that its structural attributes are not uniformly distributed across the nine quadrats. Mean tree density was 256.89 trees ha^{-1}, ranging from 148 to 384 trees ha^{-1}, while basal area averaged 131.75 m^2 ha^{-1}, with values ranging from 72.28 to 206.45 m^2 ha^{-1}. The combination of considerable basal area and a relatively high mean DBH (74.38 cm) indicates that the sampled population is strongly represented by comparatively large trees.

This pattern is important because density alone cannot adequately describe the structural condition of a mature conifer stand. Two quadrats may contain similar numbers of trees but differ markedly in basal area because of differences in tree size. The present results demonstrate this clearly: quadrats with relatively high density were not necessarily those with the highest basal area. Consequently, the simultaneous consideration of density, basal area, QMD and mean DBH provides a more informative representation of stocking than any single parameter.

Comparable evidence from the Central Himalaya demonstrates that stand structure, particularly the occurrence and contribution of larger trees, is closely associated with important ecosystem attributes such as biomass carbon storage. Kaushal and Baishya (2021) reported that stand structural attributes and the presence of large trees substantially influence biomass carbon stocks across Himalayan Forest types. Similarly, recent work in the Hindu Kush–Himalaya has shown that *Cedrus deodara* forests can possess substantial carbon stocks where higher stand density and larger trees occur together, reinforcing the importance of structural attributes in understanding ecosystem functioning (Ahmad et al., 2025).

The basal area values observed in the present study are also noteworthy in the context of Himalayan forests. However, direct comparison of basal area between studies should be undertaken cautiously because stand age, site quality, elevation, forest type, sampling design and inclusion criteria can produce substantial differences. Recent studies from Uttarakhand have also found significant variation in the forest biomass, carbon stocks and regeneration of forest types along an altitudinal gradient, thus indicating the need to mention the specific environmental factors at the site when explaining Himalayan Forest structure (Pandey et al., 2025).

The important ecological message is therefore not simply that the Deoban stand has "high density" or "high basal area." Rather, the stand contains a substantial structural capital distributed unevenly among quadrats. This distinction becomes particularly important for management because stand-level averages can conceal localized areas of lower stocking or different developmental conditions.

4.2 Large-tree dominance and diameter inequality indicate differentiated stand development

The mean DBH of **74.38 cm**, together with a DBH range extending to approximately **239.81 cm**, demonstrates the strong contribution of large trees to the stand. The DBH coefficient of variation was approximately **42.49%**, indicating appreciable variability in tree diameter. The DBH Gini coefficient (**0.227**) provides complementary evidence of diameter inequality, although the

magnitude of the Gini coefficient should not be interpreted independently of the underlying diameter distribution.

This combination—large mean diameter together with substantial diameter variability—is more informative than either statistic alone. It suggests that the stand is not composed of trees belonging to a narrowly similar size class. Instead, individuals of different dimensions coexist within the sampled area, producing a differentiated diameter structure.

Such differentiation is ecologically meaningful because variation in tree size affects competition for light, growing space and below-ground resources. Structural differentiation can also influence canopy organization and resource partitioning. Global analyses have demonstrated that forest structural complexity is strongly associated with ecosystem processes and biodiversity, and that structural complexity varies substantially among forest types and environmental conditions (Ehbrecht et al., 2021).

The result is particularly relevant for *Cedrus deodara* because large, mature individuals constitute an important component of the ecological and carbon-storage value of Himalayan forests. Research on *Cedrus deodara* in the Western Himalaya has also shown that its growth response varies with tree age, highlighting the importance of maintaining representation of different developmental stages rather than focusing only on overall tree abundance (Dhyani et al.,2022).

Therefore, the observed diameter differentiation should not automatically be interpreted as evidence of disturbance or instability. In an unevenly structured natural stand, variation in diameter may represent the accumulated outcome of recruitment, growth, mortality and microsite differences over time. The more appropriate interpretation is that the stand retains **considerable structural differentiation**, which deserves to be maintained rather than simplified through uniform management.

4.3 Vertical structure is less heterogeneous than diameter structure

The second important structural dimension was vertical organization. Mean tree height was **22.66 m**, with observed heights ranging from **11 to 34 m**, while Height CV was approximately **17.41%**. The height Gini coefficient was only **0.098**, substantially lower than the DBH Gini coefficient of 0.227.

The contrast between DBH and height inequality is particularly informative. It suggests that trees differ considerably in diameter but occupy a comparatively narrower vertical range. In other words, the stand exhibits stronger **horizontal/tree-size differentiation than vertical height differentiation**.

This is an important finding that would be lost if the structural assessment relied only on mean height. A mean height of 22.66 m describes the central tendency of the stand, but it does not reveal whether trees are distributed across multiple vertical strata. The combination of Height CV and height Gini provides additional information about the degree of vertical differentiation.

The comparatively lower vertical heterogeneity may reflect the architectural characteristics of *Cedrus deodara* and the developmental history of the stand. A mature conifer stand can contain substantial diameter variation without producing equally large differences in total height because tree height approaches species- and site-specific asymptotic limits more rapidly than diameter increases. Consequently, large differences in DBH do not necessarily translate into proportional differences in height.

This interpretation is consistent with the increasingly multidimensional treatment of forest structural complexity. Recent studies emphasize that horizontal, vertical and internal structural components can behave differently and can have different relationships with biodiversity and ecosystem productivity (Ma et al., 2022).

Recent Himalayan research also reinforces the importance of examining structural attributes at multiple dimensions rather than reducing forest condition to a single stand statistic. In mountain forests of the Annapurna region, tree architecture and structural complexity were explicitly examined as components of forest organization, demonstrating the growing importance of structural approaches in Himalayan Forest ecology (Das et al., 2025).

4.4 Quadrat-level variability reveals spatial heterogeneity hidden by stand averages

One of the most important findings of this study is the substantial variation among the nine quadrats. Density varied from **148 to 384 trees ha^{-1}**, while basal area ranged from **72.28 to 206.45 m^2 ha^{-1}**. Mean DBH also varied among quadrats, and both DBH CV and Height CV showed appreciable spatial variation.

This indicates that the Deoban *Cedrus deodara* stand should not be considered a structurally homogeneous unit. Instead, it consists of relatively different structural patches embedded within the same forest stand.

This finding has a direct methodological implication. A single stand-level mean can provide a useful summary, but it cannot identify where structural variation occurs. The quadrat-level analysis therefore adds an important spatial dimension to conventional forest inventory. This is particularly relevant in mountain forests, where topography, microsite conditions, disturbance history, canopy openings and regeneration dynamics can operate over relatively short distances.

Recent work in the Western Himalaya has similarly demonstrated substantial spatial variation in density, basal area and regeneration along environmental gradients. Rawal et al. (2025), for example, found pronounced variation in forest structure and regeneration across elevation belts and aspects in Western Himalayan forests.

The implication is that management based solely on stand-level averages may overlook structurally distinct patches. A quadrat with lower stocking but high size differentiation may require a different management interpretation from a quadrat with high stocking but limited differentiation. This is precisely the type of problem that motivated the development of RSCI in the present study.

4.5 Limitations of Conventional Structural Indicators

The different structural factors in this study indicate different and limited aspects of the status of the stand, as tree density tells how many trees are present in a given area, while basal area indicates a cross-sectional area covered by trees. At the same time, quadratic mean diameter (QMD) and mean DBH determine the size of the trees, whereas DBH coefficient of variation (DBH CV) shows differences in the size according to diameter and height coefficient of variation (height CV) gives vertical structure differentiation. Therefore, no one indicator can present a complete picture of the structural condition of the stand.

For example, a quadrat with a high tree density may have relatively small trees and vice versa—the quadrat with a smaller number of trees will have bigger trees and a larger basal area. Quadrats

with a low number of trees can show substantial diameter differentiation, so ranking quadrats based solely on one structural factor can provide completely different impressions about their status.

The recognition of this limitation is becoming more prominent in modern research concerning forests. According to Põldveer et al. (2021), it is critical to conduct a thorough analysis of forest conditions, as traditional forest characteristics cover separate elements of structural diversity. In the same manner, international studies showed that forest structure is represented by a number of components and cannot be described by a single structural aspect (Ehbrecht et al., 2021). It is due to this reason that this research goes beyond simply answering the question "How many trees are there in a forest?" to addressing a wider question of how estimate density, size and height distribution or layering of trees are combined within each studied plot.

4.6 RSCI provides a more integrated interpretation of stand structure

The principal methodological contribution of this study is the development of the **Relative Structural Condition Index (RSCI)**.

RSCI integrates three complementary dimensions:

- **P_1 — structural stocking condition**, represented by density, basal area, QMD and mean DBH;
- **P_2 — Diameter structural heterogeneity**, represented by DBH CV; and
- **P_3 — vertical structural heterogeneity**, represented by Height CV.

This three-pillar arrangement is important because it prevents one structural dimension from dominating the interpretation. A quadrat receives its final RSCI according to the combined behavior of stocking and structural differentiation rather than according to density or basal area alone.

The concept is consistent with contemporary research demonstrating that structural complexity should be examined across multiple dimensions. Ehbrecht et al. (2021) showed at global scale that structural complexity varies among forests and is ecologically meaningful for biodiversity and ecosystem functioning. More recent global remote-sensing research has further demonstrated that canopy structural complexity is related to ecosystem productivity and stability, reinforcing the ecological significance of structural organization beyond conventional stand density measures (Liu et al., 2024).

Importantly, however, RSCI should not be interpreted as a universal forest sustainability index. It is a *relative* index developed from the observed range of the nine quadrats. Its primary strength is therefore diagnostic comparison within the sampled stand.

This makes RSCI particularly suitable for field-level forest assessment because it converts multiple measurements with different units into a common 0–100 framework. Rather than asking whether a particular density or basal-area value is universally "good" or "poor," the index asks where each quadrat stands relative to the structural conditions actually observed in the study area.

4.7 Robustness of the RSCI framework

The sensitivity analysis provides important support for the robustness of the proposed RSCI framework. Although QMD and mean DBH were strongly correlated ($r = 0.959$), removing mean DBH from the stocking pillar produced only limited changes in the final index. The correlation

between the original and alternative RSCI scores was 0.9975, and, importantly, the ranking of all nine quadrats remained identical. This indicates that the principal spatial pattern identified by RSCI was not an artefact of including two closely related measures of tree size. Rather, the ranking was primarily determined by the combined contribution of stocking, diameter heterogeneity and vertical heterogeneity. The sensitivity analysis therefore strengthens confidence in the use of RSCI as a comparative diagnostic framework for the sampled *Cedrus deodara* stand.

4.8 The RSCI approach is particularly relevant for Himalayan forest management

The need for such an integrated approach is especially strong in Himalayan forests. Mountain forests are exposed to interacting pressures including climate variability, changing disturbance regimes, regeneration constraints and anthropogenic pressure. In *Cedrus deodara*, vulnerability to environmental conditions has already been demonstrated across forest sub-types of the Western Himalaya, suggesting that management cannot necessarily rely on a uniform prescription across all sites (Pandey et al., 2023).

At the same time, recent studies in the Western Himalaya show that forest structure, regeneration and carbon storage vary considerably across landscapes. For example, studies from Uttarakhand and adjacent Himalayan regions have demonstrated strong spatial variation in forest structure and regeneration status Pandey et al., 2025)

Against this background, the value of RSCI is not that it replaces conventional forest inventory. Rather, **it organizes conventional inventory information into a decision-support framework**.

A forest manager can use the individual components to understand *why* a quadrat receives a relatively low or high structural condition score:

- low (P_1) may indicate weaker stocking or smaller tree size;
- low (P_2) may indicate limited diameter differentiation;
- low (P_3) may indicate comparatively uniform vertical structure.

Thus, RSCI retains the interpretability of individual forest measurements while providing an integrated comparative outcome.

The value of RSCI lies in its ability to integrate structural information that would otherwise remain fragmented across individual inventory variables. A quadrat with high density does not necessarily possess high basal area, while a quadrat with high basal area may have relatively low diameter or height differentiation. Consequently, individual structural indicators can produce different interpretations of the same sampling unit. RSCI addresses this problem by combining stocking condition with horizontal and vertical structural heterogeneity. This multidimensional approach is consistent with contemporary forest-structure research, which recognizes that structural complexity cannot be adequately represented by a single attribute and that different structural dimensions may vary independently (Ehbrecht et al., 2021; Seidel et al., 2021; Zhang et al., 2021). The resulting index should therefore be interpreted as a comparative diagnostic measure, identifying quadrats that occupy relatively stronger or weaker positions within the structural range of the sampled stand, rather than as a universal ecological-health score.

4.9 Structural complexity should not automatically be equated with ecological health

An important conceptual point emerging from the present study is that greater structural complexity is not synonymous with universally better ecological condition.

Higher DBH CV or Height CV indicates greater structural differentiation, but the ecological meaning of that differentiation depends on stand developmental stage, species composition, regeneration, disturbance history and site conditions. Similarly, extremely high density is not necessarily desirable if it produces intense competition and suppresses regeneration.

Recent research has emphasized this context dependence. Ma et al. (2022) found that relationships between structural complexity, species diversity and productivity differed among structural dimensions and spatial scales. Likewise, global analyses show that the relationship between canopy structural complexity, productivity and stability varies across forest ecoregions (Liu et al., 2024).

Therefore, the RSCI should be interpreted as a structural condition indicator, not as a direct proxy for biodiversity, regeneration success, carbon storage or resilience.

This distinction strengthens rather than weakens the study. It prevents overinterpretation and establishes a clear pathway for future research in which RSCI could be tested against independent ecological outcomes such as regeneration density, biomass carbon, understory diversity, canopy gaps or growth rates.

4.10 Management implications: from stand description to spatially targeted management

The major practical implication of this study is that forest management can potentially move from uniform stand-level prescriptions toward structurally differentiated management.

The observed variation among quadrats suggests that the stand contains patches with different structural characteristics. Instead of treating the entire 2.25-ha sampled area as structurally identical, the RSCI framework allows managers to identify relatively stronger and weaker structural units.

This could support three broad management responses.

First, structurally stronger quadrats can be prioritized for conservation and long-term monitoring, particularly where large trees and strong structural differentiation coexist.

Second, intermediate quadrats may be treated as structurally stable units requiring routine monitoring rather than intensive intervention.

Third, relatively weaker quadrats can be investigated further to determine whether their condition reflects natural microsite variation, regeneration limitation, disturbance, excessive stocking or another site-specific factor.

This approach is consistent with the broader movement toward management strategies that recognize structural complexity as an important component of multifunctional forests. Recent research indicates that structural complexity can contribute to ecosystem productivity and stability and therefore deserves greater consideration in forest management planning (Liu et al., 2024).

4.11 Need and broader impact of the study

The need for this study arises from a practical gap between forest inventory data and integrated structural interpretation.

Conventional inventories routinely generate density, basal area, diameter and height data, but these measurements are often reported independently. Such reporting is valuable for describing a forest, yet it provides limited guidance about how multiple structural dimensions interact within individual forest patches.

The present study addresses this gap by retaining conventional mensuration variables while integrating them through RSCI. This is particularly valuable for *Cedrus deodara* forests because these forests contain ecologically important large trees and are exposed to increasing environmental uncertainty in the Western Himalaya. The documented sensitivity of *Cedrus deodara* to environmental conditions further reinforces the need for site-specific rather than uniform management approaches. (Pandey et al., 2023)

The potential impact of the framework is therefore threefold.

Scientifically, it provides a transparent way of integrating stocking, horizontal differentiation and vertical differentiation using readily measurable field variables.

Ecologically, it provides a more nuanced representation of spatial structural variation than stand-level averages alone.

Practically, it offers a simple field-oriented framework through which forest managers can identify quadrats requiring closer investigation, conservation attention or long-term monitoring.

The approach is also potentially scalable. Although the present RSCI was developed using field measurements, the same conceptual structure could eventually be linked with remote-sensing products. Advances in airborne and spaceborne lidar now allow increasingly detailed characterization of forest structural complexity over large areas (de Conto et al., 2024). Thus, the field-derived RSCI framework provides a possible conceptual bridge between plot-level forest inventory and spatially explicit digital forest monitoring.

4.12 Limitations and future research

The interpretation of RSCI should nevertheless remain within the limits of the present dataset. First, the index is based on nine quadrats covering 2.25 ha and therefore represents relative structural conditions within the sampled stand rather than the entire Deoban landscape. Second, the index uses only tree-level structural attributes and does not directly incorporate regeneration, species diversity, deadwood, canopy gaps, understory vegetation, soil characteristics or biomass carbon. Third, the equal weighting of the three pillars provides transparency but does not imply that all structural dimensions have identical ecological effects.

These limitations provide clear directions for future research. RSCI should be tested across additional *Cedrus deodara* stands, elevation zones and management histories and compared with independent indicators such as regeneration, carbon storage, productivity, biodiversity and disturbance exposure. Such validation would determine whether the relative ranking generated by RSCI consistently corresponds to broader ecological outcomes.

This is particularly important because recent research demonstrates that relationships among structural complexity, biodiversity and ecosystem functioning are scale- and context-dependent rather than universally linear (Ma et al., 2024)

4.13 Overall interpretation

Taken together, the findings indicate that the Deoban *Cedrus deodara* stand possesses substantial structural development accompanied by pronounced spatial variation in stocking and tree-size organization. The high mean DBH and basal area indicate the strong contribution of large trees, whereas the relatively high DBH CV compared with Height CV indicates that structural differentiation is expressed more strongly through tree diameter than total height.

The RSCI framework adds an important layer of interpretation by integrating these otherwise separate dimensions. Rather than reducing stand condition to density, basal area or mean tree size, it recognizes that structural condition emerges from the combined behavior of stocking, horizontal differentiation and vertical differentiation.

Consequently, the principal contribution of this study is not merely the description of *Cedrus deodara* stand structure. It is the development of a transparent, field-measurable and spatially comparative framework for diagnosing relative structural condition, with potential application to monitoring and adaptive management of Himalayan forest stands.

5. Conclusion

This study demonstrates that the structural condition of *Cedrus deodara* forests cannot be adequately represented by a single stand-level measure such as density, basal area or mean tree size. Across the nine sampled quadrats, the stand exhibited substantial stocking and a pronounced contribution of large trees, but these characteristics were accompanied by considerable spatial variation in tree-size distribution and structural heterogeneity. The contrasting ranges of density, basal area, DBH and height variability demonstrate that apparently similar portions of the same forest stand can possess markedly different structural configurations.

A particularly important finding was the stronger differentiation in tree diameter than in tree height. The relatively high DBH coefficient of variation and greater DBH inequality, compared with the comparatively lower variation in height, indicate that structural differentiation in the studied stand is expressed predominantly through tree-size variation rather than through pronounced vertical stratification. This provides a more nuanced understanding of stand organization than conventional averages alone.

The development of the Relative Structural Condition Index (RSCI) represents the principal methodological contribution of the study. By integrating structural stocking (P_1), Diameter structural heterogeneity (P_2), and vertical structural heterogeneity (P_3), RSCI transforms multiple conventional inventory measurements into a common, interpretable framework for comparing structural condition among quadrats. Importantly, RSCI is intended as a relative, stand-specific diagnostic index, rather than as a universal measure of forest health or sustainability. Its strength lies in identifying structurally contrasting sampling units within the observed range of the study stand.

The resulting RSCI ranking revealed clear spatial differentiation among the nine quadrats, with Q9 exhibiting the highest relative structural condition and Q2 the lowest, while the remaining quadrats occupied intermediate positions. This ranking demonstrates that stand-level averages can conceal meaningful internal variation and that quadrat-level structural assessment can provide additional information for forest monitoring and management. The framework therefore offers a practical means of moving from conventional forest inventory toward spatially explicit structural diagnosis.

Importantly, the robustness assessment strengthened confidence in the proposed index. Although QMD and mean DBH were strongly correlated, exclusion of mean DBH produced only minor changes in RSCI values, yielded an extremely high correlation between the two formulations ($r = 0.9975$), and did not change the ranking of any of the nine quadrats. This demonstrates that the principal structural pattern identified by RSCI was not dependent on a single potentially redundant tree-size variable.

The implications extend beyond the present *Cedrus deodara* stand. In Himalayan forests, where environmental variability, disturbance and changing climatic conditions can produce strong spatial differences in forest structure, a simple field-based framework capable of identifying structurally contrasting patches can support more targeted monitoring and management. RSCI can potentially assist in identifying quadrats requiring closer ecological investigation, conservation attention or long-term monitoring, while structurally stronger patches may provide important reference conditions for maintaining mature-tree characteristics and structural heterogeneity.

The study therefore establishes a practical bridge between conventional forest mensuration and integrated structural assessment. Its broader value lies not in replacing established structural-complexity approaches, but in providing a transparent and readily reproducible framework based on measurements that are routinely obtainable during field inventories. Future studies should test RSCI across larger areas, different *Cedrus deodara* populations, elevation gradients and management histories, and evaluate its relationship with independent ecological attributes such as regeneration, biomass carbon, biodiversity, canopy gaps and productivity.

Overall, the study shows that understanding Himalayan *Cedrus deodara* forests requires moving beyond the question of how many trees a stand contains toward understanding how stocking, tree-size differentiation and vertical structure are spatially organized. RSCI provides a practical framework for making that transition, converting conventional field measurements into an integrated structural signal that can support more informed monitoring, comparison and management of these ecologically important Himalayan forests.

Ethics declaration

‘Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

This forest inventory study is not a clinical trial, so registration details do not apply.

Plant ethics and compliance: The study involved non-destructive field measurements of standing wild *Cedrus deodara* trees in the Deoban area of Chakrata Forest Division, Uttarakhand, India. No plant parts or specimens were collected. The fieldwork was conducted in accordance with applicable local and national guidelines for plant research.

Plant identification: The standing trees were identified in the field by the research team based on their morphological characteristics. The identification is consistent with the official Working Plan for Chakrata Forest Division, which lists Deodar (*Cedrus deodara*) among the division's flora (List of Flora, p. vii). No botanist was separately engaged for species identification.

Permission to access the study area: Written permission to enter the Deoban forest and conduct the field inventory was obtained from the Forest Department.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

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