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Forest Structure, Carbon Stock and Regeneration Potential of Conifers in the Garhwal Himalaya

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Abstract

Coniferous forests serve as a crucial component of the forest community in the Garhwal Himalaya. This study investigates the structure, carbon stock and regeneration patterns of seven distinct coniferous forest types in the Garhwal region of Uttarakhand, India. Forest structure was analyzed using a nested quadrat method, revealing significant variability in tree density, basal cover and diversity. The highest aboveground biomass density (427.57 mg ha^{-1}) and carbon density (278.38 C mg ha^{-1}) were recorded in the mixed coniferous forest (FT1), while the lowest values were found in the *Pinus roxburghii*-dominated forest (FT3) with 76.40 mg ha^{-1} and 50.30 C mg ha^{-1}, respectively. Regeneration analysis showed that FT1 had the highest seedling density (4,000 individuals ha^{-1}) and sapling density (1,400 individuals ha^{-1}), while FT5 exhibited the lowest (seedling density of 680 individuals ha^{-1} and sapling density of 580 individuals ha^{-1}). FT6 and FT7, dominated by *Cedrus deodara*, had moderate total carbon densities of 150.29 C mg ha^{-1} and 176.86 C mg ha^{-1}, but showed lower sapling/tree ratios, indicating poor sapling recruitment. The study highlights the urgent need for conservation strategies, particularly for forest types like FT6 and FT7, where declining sapling densities threaten long-term forest sustainability and carbon sequestration potential in these critical Himalayan ecosystems.

Keywords : Forest community, Forest structure, Live tree carbon, Regeneration, Garhwal himalaya

The Garhwal Himalaya host a diverse conifer species that play vital ecological roles, contributing significantly to biodiversity and ecosystem stability. Presence of coniferous forests, shaped by spatial turnover and beta-diversity, form a crucial part of the regional ecosystem structure (Rahman, 2023). Mapped using spectral variables, these forests are essential for sustainable management but face threats from environmental pressures like forest fires (Liu, 2024). These forests support diverse species, enhancing ecosystem health, while early successional vegetation provides valuable forage, boosting predator populations and emphasizing the need to conserve biodiversity (Chagnon *et al.,* 2022). Beyond their rich biodiversity, these forests influence soil composition, nutrient cycling, and microbial communities, especially during land conversion (Kang *et al.,* 2022). They play a vital role in mapping soil organic carbon, estimating biomass and marking early stages of forest succession (Borłvka *et al.,* 2022 and Yuan, 2023). The region's temperate coniferous forests, dominated by *A. pindrow* and *P. wallichiana* (Shaheen *et al.,* 2015), contrast with the Eastern Himalayas, where conifers are less common and mixed with broad-leaved species (Chawla *et al.,* 2012). Shade-intolerant conifers rely on disturbances like treefalls and forest fires for regeneration (Wangda and Ohsawa, 2006), making the preservation of endangered conifers essential (Ginwal *et al.,* 2020).

Natural coniferous forests are important carbon sinks with high sequestration potential, while supporting ecosystem services such as habitat provision, water regulation, soil stabilization and biodiversity maintenance (Milanovię *et al.,* 2022 and Ganesha & Inamati, 2023). These forests store more carbon over time than deciduous forests (Pan *et al.,* 2011), while supporting understory biodiversity and ecological stability (Han *et al.,* 2021). These forests help mitigate climate change by storing carbon and reducing emissions through wood products, offering essential regulating services (Hicks e*t al.,* 2014). Rising global emissions underscore the importance of these sinks, as forest loss in the Himalayas has led to significant emissions totaling 35.22 ± 9.38 Pg C over recent decades (Sheikh *et al.,* 2021 and Liu, 2024). Land-use changes have contributed to 19 per cent of global anthropogenic carbon emissions since 1959 (Dong *et al.,* 2022). Carbon sequestration rates depend on both vegetation type and geographical location (Han *et al.,* 2010). By assessing temporal and spatial carbon storage patterns, strategies can be devised to enhance sequestration and mitigate climate impacts.

Natural forest gaps, formed by dying canopy trees or large branches are important for understanding gap dynamics and regeneration processes (Runkle, 1992). Although undisturbed forests exhibit strong regeneration and diversity, over exploitation often favors light-demanding species like *Pinus roxburghii* (Bhandari *et al.,* 2021). In the Himalayas, conifer regeneration is shaped by climatic factors, human activities, and ecological conditions. Species such as *Abies pindrow*, *Pinus wallichiana* and *Cedrus deodara* display varying regeneration patterns based on microclimatic conditions and disturbance regimes (Alam *et al.,* 2023). However, regeneration is threatened by factors such as fuelwood collection and forest fragmentation, which create gaps that hinder seedling establishment. Additionally, climate change alters growth responses, with rising temperatures and changing precipitation patterns affecting their distribution and regeneration dynamics (Sohar *et al.,* 2016). These complex interactions highlight the need for targeted conservation strategies to enhance forest resilience (Gairola *et al.,* 2012).

The role of forest ecosystems in the biogeochemical cycle and their influence on climate change has become a critical area of global and regional discourse (Arunkumar *et al.,* 2017). Climate variability profoundly influences the growth and recruitment patterns of high-elevation pines, making them particularly sensitive to climatic shifts (Shiwakoti, 2022). The cumulative effects of these disturbances may hinder the natural regeneration of these forests, leading to long-term ecological consequences (Maletha *et al.,* 2022). To preserve their ecological integrity and biodiversity, effective conservation and sustainable management strategies are essential. Understanding the factors influencing conifer diversity, ecological interactions and the impact of disturbances is essential for developing strategies to protect and restore these ecosystems. Accordingly, our study aims to (i) investigate the forest structure and carbon stock of selective coniferous forests and (ii) evaluate the regeneration patterns of these forests under varied distribution ranges.

Material and Methods

The study was conducted in the Garhwal Himalayan region of Uttarakhand, India, spanning latitudes 29°19' –31°00' N and longitudes 78°00'–80°30' E. The Garhwal Himalaya is characterized by diverse rock formations, including sedimentary, metamorphic and igneous types, such as the Lesser Himalayan Crystalline Complex, Tethyan Sedimentary Sequence, and Higher Himalayan Crystalline Series, reflecting its complex tectonic history and ongoing crustal deformation (Valdiya, 1980). The selected forest types range in elevation from 750 m to 3350 m asl, covering vegetation from sub-tropical to sub-alpine zones (Table 1). Seven distinct sites were chosen for this study (Fig. 1).

Forest types were categorized and named based on their dominant tree species, following the classification system established by Parkash (1986)

Table 1

General details of the forest types studies

Acronym	Forest Type	Elevation (m ASL)	Latitude	Longitude	Locality
FT1	Conifer mixed broad-leaf forest	2400 - 2600	30.634303	78.981911	Kanchula-dhotidhar
FT2	Mainly *Abies pindrow* forest	2550 - 2700	30.632253	78.967547	Pangair-Chopta
FT3	Pure *Pinus roxburghii* forest	750 - 1000	30.635661	78.971466	Khola-Sumadi
FT4	Pure *Pinus wallichiana* forest	3250 - 3350	30.750321	79.825907	Gamshali (Niti Valley)
FT5	Pure *Pinus wallichiana* forest	3050 -3 200	30.626934	79.21155	Bampa village (Bampa valley)
FT6	Mainly *Cedrus deodara* forest	2060 - 2180	30.622756	79.209065	Naini forest (Ghimtoli)
FT7	Pure *Cedrus deodara* forest	2000 - 2150	330.299586	78.420062	Danda chali (Ranichauri)

Abbreviations: ASL = Above Sea Level

Cedrus deodara forest

Abies pindrow forest

Pinus roxburghii forest

Pinus wallichiana forest

Fig. 1 : Some studied Coniferous forest types

(Fig. 1). Physiographic variables across the different forest types were measured using a Garmin Rino-130 GPS device. The nested quadrat method described by Kent and Coker (1992) was employed. In each stand, ten 0.1-hectare plots were systematically laid out, resulting in a total of 70 sample plots. This methodology adheres to the approaches outlined by Curtis and McIntosh (1950) and Phillips (1959). Trees were categorized into different diameter at breast height (DBH) classes to provide a detailed understanding of forest structure.

Growing stock volume density (GSVD) was estimated using volume tables and equations from the Forest Research Institute (FRI) and the Forest Survey of India (FSI). The GSVD (m^3 ha^{-1}) was converted to above ground biomass density (AGBD) using biomass expansion factors (BEFs) recommended by Brown *et al.* (1999). Below ground biomass density (BGBD) was estimated using the regression equation proposed by Cairns *et al.* (1997). The total biomass density (TBD) was calculated by summing AGBD and BGBD. Total carbon density (TCD) was then computed using the formula TCD (C Mg ha^{-1}) = Biomass (Mg ha^{-1}) x Carbon per cent. The carbon percentage applied in this calculation was in accordance with Negi *et al*. (2003) and Manhas *et al.* (2006).

To assess the regeneration pattern, within each 0.01-hectare plot, two randomly placed 5m × 5m (25m²) quadrats were established in each forest type to record saplings (≥ 1cm and ≤ 10cm dbh). Additionally, a line transects of 20m was marked in the field, along which alternating 2m × 2m quadrats were laid out to enumerate seedlings (>1cm). Key quantitative parameters such as density, frequency and abundance were calculated following the protocols outlined by Cottam and Curtis (1956). Various diversity indices, including the Shannon-Weaver Index (1963), Simpson Index (1949) and Pielou's Evenness Index (1966) were computed to provide a comprehensive analysis of species diversity and regeneration dynamics.

Results and Discussion

The study analyzed seven conifer forest types in the temperate zone of the Garhwal Himalaya, Uttarakhand, India. The studied forest types indicate that 47.17 per cent of tree species exhibit a random distribution pattern, 39.62 per cent show a contagious distribution and 13.21 per cent demonstrate a regular distribution. This highlights that nearly half of the species are randomly arranged, with significant portions forming clusters or evenly spaced. The DBH classes for FT1 and FT2 were represented across all diameter classes, with the highest density observed in the 21-40 cm DBH class. In contrast, for FT4 and FT5, the 61-80 cm and >80 cm DBH classes were absent. The highest density in the >80 cm DBH class was recorded in FT2, followed by FT7 (Fig. 2).

The analysis of tree parameters across different coniferous forest types reveals notable variation in density, basal cover and diversity. FT1 shows the

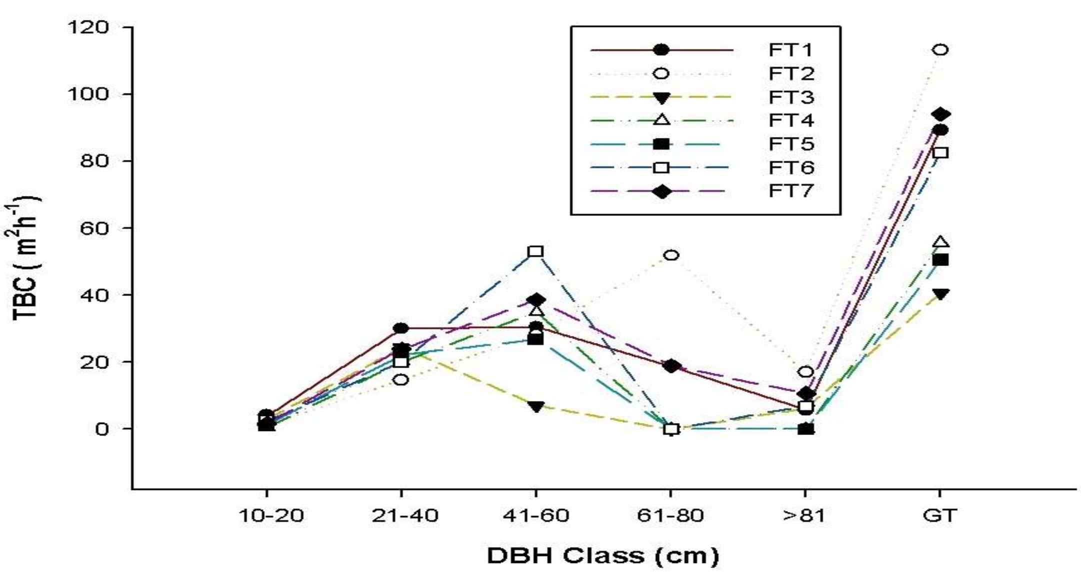

Fig. 2 : Diameter Class based distribution of Total Basal Cover (TBC) in different Forest type

highest Shannon Index (2.54), alongside a low dominance (Cd = 0.11) and a high Menhinick's diversity index (MeI = 2.10). In contrast, FT4 exhibits the lowest diversity (Shannon (H) = 0.27) and highest dominance (Cd = 0.86). FT2 has the highest total basal cover (113.26 m²/h), while FT3 and FT5 show high dominance (Cd = 0.56 and 0.63, respectively) and lower diversity.

The AGBD (Above ground biomass density) in our study ranged from 76.40 (FT3) to 427.57±27 (FT1) Mg ha^{-1}, while the BGBD (Below ground biomass density) varied between 23.92±11 (FT4) to 129.19±7 (FT1) Mg ha^{-1} (Table 2). The TBD (Total biomass density) is highest for FT1 at 556.76±34 Mg ha^{-1} and lowest for FT3 at 100.59±24Mg ha^{-1}. The total carbon density (TCD) across the forest types shows significant variation. FT1 stands out with the highest TCD at 278.38±17 C Mg ha^{-1}. Among the species within this forest type, *Quercus semecarpifolia* contributes significantly with a TBD of 115.48 Mg ha^{-1}, followed closely by *Abies pindrow* with 98.71 Mg ha^{-1}. In contrast, *Dodecadenia grandiflora* has the lowest contribution to the overall carbon density in this forest type, with a TBD of 3.68 Mg ha^{-1}. FT2 ranks second with a TCD of 236.35±37 C Mg ha^{-1}. In this forest type, the highest contribution to TBD is from *Abies pindrow* with 204.38 Mg ha^{-1}, followed by *Q. semecarpifolia* at 181.27 Mg ha^{-1}, while *Symplocos paniculata* contribute least for TBD in FT2 with 4.73 Mg ha^{-1}.

On the other hand, FT3 shows the lowest TCD at 50.30±12 Mg ha^{-1}. Within this forest type, *Pinus roxburghii* has the highest tree biomass density (TBD) at 72.86 Mg ha^{-1}. It is followed by *Syzygium cumini* with a TBD of 7.04 Mg ha^{-1} and *Mallotus philippensis* with 6.72 Mg ha^{-1}, making them the next significant contributors in this forest type. FT4 also exhibits a low Total Carbon Density (TCD) at 54.53 Mg ha^{-1}. In this forest type, the dominating forest forming species contribute a total tree biomass density (TBD) of 104.75 Mg ha^{-1}, with *Cupressus torulosa* contributing a smaller share at 4.31 Mg ha^{-1}. FT5 similarly reflects lower carbon storage with a TCD of 57.66±19 C Mg ha^{-1}. In this forest type, *Pinus wallichiana* has a TBD of 92.05 Mg ha^{-1}, while *Cedrus deodara* and *C. torulosa* contribute 15.38 Mg ha^{-1} and 7.89 Mg ha^{-1}, respectively. FT6 and FT7 fall within the intermediate range, with TCD values of 150.29±35C Mg ha^{-1} and 176.86±54 C Mg ha^{-1}, respectively. In FT6, *C. deodara* exhibits the highest TBD of 202.93 mg ha^{-1}, followed by *Taxus baccata* with 44.68 Mg ha^{-1} and *C. torulosa* with 31.34 Mg ha^{-1}. The lowest TBD is observed in *Juglans regia*, with a value of 5.11 Mg ha^{-1}. In FT7, *C. deodara* again shows the highest TBD, with a value of 302.07 Mg ha^{-1}, followed by *Machilus duthiei* with 22.13 Mg ha^{-1} and *R. arboreum* with 14.43 Mg ha^{-1}. The lowest TBD is observed in *Myrica esculenta*, with a value of 2.01 Mg ha^{-1}.

The regeneration analysis across the seven forest types highlights notable differences in diversity parameters

TABLE 2

Biomass and carbon stock value of the studied forest types

FT	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	TBD (Mg ha^{-1})	TCD (C Mg ha^{-1})
FT1	427.57 ± 27	129.19 ± 7	556.76 ± 34	278.38 ± 17
FT2	371.11 ± 59	101.60 ± 15	472.71 ± 73	236.35 ± 37
FT3	76.40 ± 19	24.19 ± 5	100.59 ± 24	50.30 ± 12
FT4	85.14 ± 40	23.92 ± 11	109.05 ± 50	54.53 ± 25
FT5	89.02 ± 30	26.29 ± 8	115.31 ± 38	57.66 ± 19
FT6	235.30 ± 56	65.27 ± 14	300.57 ± 70	150.29 ± 35
FT7	281.04 ± 88	72.69 ± 21	353.72 ± 109	176.86 ± 54

Abbreviations: FT: forest types; AGB: Above Ground Biomass; BGB: Below Ground Biomass; TBD: Total Biomass Density; TCD: Total Carbon Density; Mg ha^{-1}: Megagram per hectare; C Mg ha^{-1}: Carbon Megagram per hectare

TABLE 3
Diversity parameters in the studied forest types

FT type	Phases	Density (ind ha^{-1})	$\overline{H}$	Cd	SR	Ep	MeI
FT1	Tree	820	2.54	0.11	19	0.86	2.10
	Sapling	1400	2.68	0.07	16	0.96	1.91
	Seedling	4000	2.89	0.06	21	0.95	1.66
FT2	Tree	550	1.67	0.26	10	0.72	1.35
	Sapling	980	2.28	0.11	11	0.95	1.57
	Seedling	2600	2.17	0.13	10	0.94	0.98
FT3	Tree	530	1.03	0.56	7	0.53	0.96
	Sapling	1400	1.89	0.16	7	0.97	0.84
	Seedling	1840	2.11	0.13	9	0.96	0.94
FT4	Tree	450	0.27	0.86	2	0.39	0.30
	Sapling	600	0.89	0.48	3	0.81	0.55
	Seedling	620	1.24	0.33	4	0.89	0.72
FT5	Tree	480	0.65	0.63	3	0.59	0.43
	Sapling	580	0.94	0.44	3	0.86	0.56
	Seedling	680	1.20	0.34	4	0.87	0.69
FT6	Tree	680	1.19	0.44	6	0.66	0.73
	Sapling	1220	2.01	0.15	8	0.97	1.02
	Seedling	2300	2.32	0.12	12	0.93	1.12
FT7	Tree	640	0.99	0.54	6	0.56	0.75
	Sapling	920	2.18	0.12	10	0.95	1.47
	Seedling	1820	2.24	0.12	11	0.93	1.15

Abbreviation : SR = Species Richness; Cd = Concentration of Dominance; $\overline{H}$ = Shannon - Wiener index; Ep = Pielou Evenness; FT = Forest type, ind ha^{-1} = Individual per hectare

for both seedlings and saplings (Table 3). FT1 consistently shows the most favorable conditions, with the highest sapling density (1400 individuals ha^{-1}) and seedling density (4000 ind. ha^{-1}), species diversity (Shannon Index 2.68 for saplings and 2.89 for seedlings). FT1 also has low dominance (Cd 0.07 for saplings and 0.063 for seedlings) and high evenness (Ep 0.96 for saplings and 0.951 for seedlings). FT2 shows a sapling density of 980 ind. ha^{-1} and seedling density 2600 ind. ha^{-1}. FT1 and FT2 shows decent seedling densities but FT1 shows very low sapling density with 20 ind. ha^{-1} followed by FT2 with 80 ind. ha^{-1}.

In contrast, FT5 exhibit the least favorable regeneration conditions, with low sapling densities 580 and seedling density 680 ind. ha^{-1}. Followed by FT4 with sapling density 660 ind. ha^{-1} and seedling density 720 ind. ha^{-1}. Both forest types show high concentrations of dominance (Cd 0.50 for saplings and 0.319 for seedlings in FT4; Cd 0.624 for seedlings in FT5) and lower evenness (Ep 0.79 for saplings and 0.914 for seedlings in FT4; 0.316 in FT5), indicating a community dominated by a few species. Intermediate regeneration characteristics are observed in FT2, FT3, FT6 demonstrated good regeneration, with a seedling density of 2,300 ind. ha^{-1} and a sapling density of 1,220

TABLE 4

Regeneration performance across different forest types (indicating ratio of seedling and sapling to tree)

Forest Type (FT)	FT1		FT2		FT3		FT4		FT5		FT6		FT7	
Species	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T
Abies pindrow	3.82	0.12	2.125	0.4	-	-	-	-	-	-	-	-	-	-
Acer acuminatum	1.88	1	0/0	20/0	-	-	-	-	-	-	-	-	-	-
Acer caesium	2.08	1.33	7.5	8	-	-	-	-	-	-	-	-	-	-
Acer cappadocicum	5	2.67	50/0	40/0	-	-	-	-	-	-	-	-	-	-
Aesculus indica	13.33	2.67	-	-	-	-	-	-	-	-	200/0	80/0	-	-
Alnus nepalensis	10	0	-	-	-	-	-	-	-	-	-	-	-	-
Bombax ceiba	-	-	-	-	8	10	-	-	-	-	-	-	-	-
Buxus wallichiana	2.5	1.5	-	-	-	-	-	-	-	-	-	-	-	-
Cedrus deodara	-	-	-	-	-	-	80/0	40/0	4	4	0.35	0.30	0.36	0.16
Celtis australis	-	-	-	-	4	5	-	-	-	-	-	-	-	-
Corylus jacquemontii	3.75	1	-	-	-	-	-	-	-	-	-	-	-	-
Cupressus torulosa	-	-	-	-	-	-	7	4	3.33	1.56	3.14	1.71	20/0	0/0
Dalbergia sissoo	-	-	-	-	10	0	-	-	-	-	-	-	-	-
Dodecadenia grandiflora	22.5	10	3.5	3.6	-	-	-	-	-	-	-	-	-	-
Engelhardia spicata	-	-	-	-	4	7	-	-	-	-	-	-	-	-
Eurya acuminata	3.75	0	-	-	-	-	-	-	-	-	-	-	-	-
Griffithariavestita	-	-	0	0	-	-	-	-	-	-	-	-	-	-
Ilex dipyrena	3.75	11	42.5	4	-	-	-	-	-	-	-	-	-	-
Juglans regia	-	-	-	-	-	-	-	-	-	-	12	14	-	-
Lannea coromandelica	-	-	-	-	240/0	340/0	-	-	-	-	-	-	-	-
Lyonia ovalifolia	2.81	0.5	2.5	2.25	-	-	-	-	-	-	140/0	0/0	80/0	20/0
Machilus duthiei	9	2	-	-	-	-	-	-	-	-	40/0	0/0	5	4
Machilus odoratissimus	-	-	-	-	-	-	-	-	-	-	60/0	0/0	40/0	100/0
Mallotus philippensis	-	-	-	-	17.33	10	-	-	-	-	-	-	-	-
Melia azedarach	-	-	-	-	140/0	0/0	-	-	-	-	-	-	-	-
Meliosma dilleniifolia	5	0	-	-	-	-	-	-	-	-	-	-	-	-

Continued....

Table 4 Continued....

Forest Type (FT)	FT1		FT2		FT3		FT4		FT5		FT6		FT7	
Species	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T	See/T	Sap/T
Myrica esculenta	-	-	-	-	-	-	-	-	-	-	-	-	10	2
Neolitsea pallens	-	-	-	-	-	-	-	-	-	-	17.2	8	16	6
Picea smithiana	-	-	-	-	-	-	60/0	0/0	20/0	0/0	-	-	-	-
Pinus roxburghii	-	-	-	-	0.78	0.73	-	-	-	-	-	-	-	-
Pinus wallichiana	-	-	-	-	-	-	0.84	1.12	0.84	1.05	5	3	200/0	80/0
Pyrus pashia	25/0	0/0	-	-	-	-	-	-	-	-	-	-	40/0	20/0
Quercus floribunda	5	2	-	-	-	-	-	-	-	-	-	-	-	-
Quercus leucotrichophora	-	-	-	-	-	-	-	-	-	-	240/0	120/0	19	11
Quercus semecarpifolia	4.29	2.29	5.36	1.43	-	-	-	-	-	-	-	-	-	-
Rhododendron arboreum	4.38	2	15	3	-	-	-	-	-	-	60/0	0/0	3.33	2
Symplocos paniculata	15	10	5	4	-	-	-	-	-	-	-	-	-	-
Symplocos ramosissima	75/0	0/0	-	-	-	-	-	-	-	-	-	-	-	-
Syzygium cumini	-	-	-	-	9	6	-	-	-	-	-	-	-	-
Taxus baccata	2.5	2	10	2	-	-	-	-	-	-	1.43	2.29	-	-

Note:Species that are absent in tree form but present only in regenerative stages (i.e., as seedlings and/or saplings) are represented as fractions.
Abbreviations: Sap/T= Sapling/Tree, See/T= Seedling/Tree, FT= Forest type

ind. ha^{-1}. In FT7, the seedling density was 1,820 ind. ha^{-1}, while the sapling density was 920 ind. ha^{-1}.FT6 and FT7 exhibit moderate diversity, species richness, and evenness across both saplings and seedlings.In terms of cd, FT6 had a cd of 0.15 for saplings and 0.12 for seedlings, with a diversity index ($\overline{H}$) of 2.01 for saplings and 2.32 for seedlings. Similarly, FT7 showed a cd of 0.12 for both saplings and seedlings, with a diversity index ($\overline{H}$) of 2.18 for saplings and 2.24 for seedlings. Seeding to tree ratio and Sapling to tree ratio are given in detail for all the species of the studied forest type in Table 4.

The analysis reveals distinct forest structures across different forest types (FT) based on tree density and total basal cover (TBC) (Fig. 2). In Mixed coniferous forest (FT1), the highest density (410 ind. ha^{-1}) was observed in the 21-40 cm girth class, while TBC peaks in the 41-60 cm class (30.03 m² ha^{-1}), indicating a concentration of trees in the lower to mid-diameter range. FT2, dominated by *Abies pindrow* forest type, exhibits the highest TBC (113.26 m² ha^{-1}), with the majority in the 61-80 cm class (51.87 m² ha^{-1}) and significant density (30 ind. ha^{-1}) in the >80 cm class, suggesting an old-growth stand structure. FT3, characterized by *Pinus roxburghii* at mid-altitude, shows the lowest TBC of 40.73 m² ha^{-1}, with majority of its basal cover concentrated in the 21-40 cm class (24.47 m² ha^{-1}). *P. roxbhurghii* generally found between the altitude of 900-1500 m (Rawat *et al.,* 2020; Bhardwaj *et al.,* 2021), is a pioneer species (Ghildiyal *et al.,* 2009), hence reflecting a younger forest stand. The density of FT3 is 530 ind. ha^{-1}, predominantly within the 21-40 cm class, indicating a dense stand with limited mature. In FT4 and FT5, dominated by *Pinus wallichiana* in the subalpine zone, with lower total density, show dominance in the 21-40 cm class (320 and 230 ind. ha^{-1}), further suggesting younger stands in these regions. FT4 was observed as a monospecific stand of *P. wallichiana* at an elevation of 3000 m, similar to observation made by Khan *et al.* (2020). In FT5, *Cedrus deodara* was present as a sub-dominant species alongside *P. wallichiana*. The adaptability *P. wallichiana*'s to high-altitude conditions underscores its importance in understanding in sub-alpine forest dynamics (Hamid *et al.,* 2021). FT6 and FT7, both dominated by *C. deodara* in the moist temperate zone at higher altitudes, exhibit notable tree densities (680 ind. ha^{-1} for FT6 and 640 individuals ha^{-1} for FT7) and TBC (82.58 for m^2 h^{-1} FT 6 and 94.17 m^2 h^{-1} for FT7). FT6 has a higher concentration of trees and TBC in the 41-60 cm class, with 280 ind. ha^{-1} and 5314 m² ha^{-1}, respectively. In contrast, FT7 a more uniform distribution across all diameter classes, indicating a more uniform distribution of tree ages.

Mixed coniferous forests (FT1), characterized by a significant presence of broadleaf species, exhibited the highest biomass (TCD 278.38±17 C Mg ha^{-1}), primarily due to mature, large-girth trees, particularly *A. pindrow* and minimal anthropogenic disturbances. The maximum above-ground biomass density (AGBD) was recorded for FT1 (Table 2), aligns closely with the findings of Sharma *et al.* (2018a) (419.57±92.06 Mg ha^{-1}). Mainly *A. pindrow* forest (FT2) demonstrated substantial carbon sequestration (TCD 236.35±37 C Mg ha^{-1}).In contrast, FT3, dominated by *Pinus roxburghii*, had the lowest carbon sequestration (TCD of 50.30 C Mg ha^{-1}), as it primarily consisted of trees in lower DBH classes reflecting a young forest. At higher altitudes, FT4 and FT5, dominated by *P. wallichiana* exhibited lowest carbon sequestration, with TCD of 54.5392.06 C Mg ha^{-1} and 57.66 92.06 C Mg ha^{-1}, respectively, due to the sparse density typical of subalpine zones. Nonetheless, *P. wallichiana* contributed significantly to carbon sequestration despite its lower tree density compared to other alpine species. FT6 and FT7 dominated by *C. deodara,* showed relatively high TCD with 150.29±35 C Mg ha^{-1} for FT6 and 176.86±54 C Mg ha^{-1} for FT7. This shows high sequestration in deodars forests, particularly in FT7, which contained more mature trees with superior physiological parameters. Biomass estimates across different coniferous forest types varied substantially, highlighting the significant carbon sequestration potential of mixed coniferous forests compared to pure *P. roxburghii* stands.

In the present study, while most forest types exhibit regeneration that corresponds well with their standing wood density, some dominant forest-forming species demonstrate only average to poor regeneration (Table 4). In mixed coniferous forest (FT1) and mainly *Abies pindrow* forest (FT2), the seedling/tree (See/T) ratio is fairly decent for *A. pindrow.* However the sapling/tree (Sap/T) ratio is very low (0.1 for FT1 and 0.4 for FT2) particularlyin FT1. Das *et al.* (2021) also highlighted the poor regeneration status of *A. pindrow* in the Western Himalaya, raising concerns for this forest type. In the pure *P. roxburghii* forest (FT3), *P. roxburghii* shows decent See/T ratio of 0.78 and a Sap/T ratio of 0.73. The moderate regeneration may be attributed to frequent fires in the area. Sharma *et al.* (2023), who observed a decline in seedlings and saplings in fire-prone regions. In contrast, other species like *Syzygium cumini* and *Celtis australis* show relatively high regeneration.

The pure *Pinus wallichiana* forest (FT4, FT5) exhibited moderate to high regeneration of the dominant species, *P. wallichiana*. In FT4, the See/T ratio was 0.84 and Sap/T ratio was 1.12, while in FT5, the See/T ratio was 0.83 and Sap/T was 1.05. The study observed that regeneration was more successful in areas with reduced canopy cover and lower tree density. Being at a very high altitude FT4 has moderate seedling regeneration and good sapling regeneration while the tree density in this area is low. Sharma *et al.* (2018b) also described regeneration of *P. wallichiana* as a widely adapted. FT6 and FT7, representing pure *Cedrus deodara* forests, showed average to low regeneration levels. In FT6, the See/T ratio was calculated at 0.35 and the Sap/T was 0.30, indicating low regeneration potential. Singh *et al.* (2023) noted that natural regeneration in pure deodar stands is a significant challenge due to the species' sensitivity to sunlight, the hindrance of needle litter in seed germination and anthropogenic factors. Additionally, other species like *Lyonia ovalifolia, Machilus duthiei* and *Machilus odoratissimus* were present only at the seedling stage, signaling new regeneration. FT7 showed a slightly higher See/T ratio of 0.44, but the lower Sap/T ratio is of 0.28, suggesting that many seedlings are not successfully transitioning to the sapling stage, further underscoring regeneration challenges.

This study is crucial as it highlights the intricate balance between species diversity, regeneration and biomass in the Garhwal Himalaya's coniferous forests. By providing detailed insights into the regeneration challenges faced by key species like *Abies pindrow* and *Cedrus deodara,* it underscores the urgent need for targeted conservation efforts. Additionally, the research emphasizes the importance of accurately calculating biomass and carbon stock in these coniferous forests, given their pivotal role in carbon sequestration. This makes them vital for climate change mitigation. Overall, the findings serve as a valuable resource for developing sustainable forest management strategies that benefit both the environment and local communities.

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