International Journal of Ecology and Environmental Sciences 51: 311-320, 2025
ISSN: 2320-5199 (Online); https://doi.org/10.55863/ijees.2025.0636

Population Structure and Regeneration Status of Tree Species: An Assessment in the Ranikhet Forest of Almora District, Kumaon Himalaya, Uttarakhand, India

MIRZA ALTAF BAIG*, NAZNEEN ZEHRA AND JAMAL AHMAD KHAN
Department of Wildlife Sciences, Aligarh Muslim University, Aligarh, 202002, Uttar Pradesh, India
E-mail: gi3958@myamu.ac.in, nzehra@myamu.ac.in, secretarywsi@gmail.com
***Corresponding author**

ABSTRACT

The phytosociological data were collected and analyzed to understand tree species composition, diversity, and regeneration patterns across three distinct forest habitats (Oak, Pine, and Oak-Pine mixed) in the Ranikhet forest of Almora District, Kumaon Himalaya, Uttarakhand, India. The study was conducted from 2021 to 2022. A total of 120 plots with a radius of 10 m were established using a stratified random technique to sample tree data. Regeneration (seedlings and saplings) was quantified in 3 m radius concentric circular plots within the existing 10 m tree plots. Results reveal considerable differences in species composition and regeneration patterns across habitats. The Oak-Pine mixed habitat exhibited the highest species richness (15 species) and diversity (Shannon index: 1.625). In contrast, the Pine habitat showed the lowest diversity (Shannon index: 0.1526) with high dominance of *Pinus roxburghii* (IVI: 280.89). Tree density varied noticeably across habitats, with the highest in Oak-Pine forest (467.09 individuals/ha), followed by Pine (357.99 individuals/ha) and Oak (291.17 individuals/ha) habitats. Regeneration analysis indicated that invasive species like *Acacia dealbata* are successfully established across all habitats, while native species showed variable regeneration patterns. The Oak habitat demonstrated good overall regeneration (seedling density: 3740.77 individuals/ha), whereas Pine and Oak-Pine habitats showed fair regeneration. The high seedling-to-tree ratios for invasive species and the absence of regeneration for several native species raise significant conservation concerns. *Quercus leucotrichophora* showed fair regeneration in Oak and Oak-Pine habitats but good regeneration in Pine habitat, suggesting potential for oak expansion under favourable conditions. Similarity analysis revealed moderate habitat overlap (Simpson's similarity index: 45.45-61.53%), suggesting distinct ecological niches with the highest similarity between Oak and Pine habitats (61.53%). The findings highlight concerns about the expansion of invasive species and regeneration challenges for some native species, providing valuable insights for sustainable forest management and conservation strategies in the Western Himalayan region. The habitat-specific differences in diversity indices and regeneration patterns underscore the importance of maintaining habitat heterogeneity at the landscape scale for preserving the region's forest biodiversity.

Key words: Forest ecology; Species diversity; Regeneration; Importance Value Index; Invasive species; Western Himalaya; Habitat comparison

INTRODUCTION

Forest ecosystems in the Western Himalayas represent biodiversity hotspots that provide essential ecological services while facing increasing anthropogenic and climatic pressures (Singh and Singh 1992). Understanding the structure, composition, and regeneration patterns of these forests is crucial for their conservation and sustainable management. The regeneration dynamics of tree species within different forest habitats serves as an indicator of forest health and resilience to disturbances (Khumbongmayum et al. 2006). The Western Himalaya comprises Garhwal and Kumaon region covering an area of about 30,000 km^2 in which forests, meadows, marshes and swamps with their characteristic plant composition abound (Mehra et al. 2023). Each habitat type harbors distinctive ecological characteristics and species compositions that influence regeneration processes and overall forest dynamics (Gairola et al. 2008). These forests face numerous threats, including overexploitation, habitat fragmentation, climate change, and invasion by exotic species (Bargali et al. 2018).

The Ranikhet forest in Almora District, Uttarakhand, represents a particularly important ecological zone within the Kumaon Himalaya that merits focused research attention for several compelling reasons. First, Ranikhet's strategic location along a mid-elevation ridge (1800-2100 m asl) provides a crucial ecological transition zone between lower and higher Himalayan ecosystems, making it an ideal location to study ecological gradients and habitat interfaces. Second, the region has experienced significant land-use changes over the past century, transitioning from traditional sustainable forest use to increasing commercial exploitation, tourism development, and military establishment, creating a complex mosaic of anthropogenic impacts. Third, Ranikhet's forests provide critical ecosystem services to downstream communities, including water regulation for the Kosi and Gagas River systems, which are vital water sources for the entire Almora district.

The forests of Ranikhet are particularly vulnerable to climate change effects, as mid-elevation Himalayan zones are experiencing more rapid warming than lower regions, potentially driving upslope migration of species and altering forest community dynamics. Furthermore, while pine-dominated forests cover approximately 90% of Ranikhet's forested area, the scattered remnant patches of oak and mixed forests represent important biodiversity reservoirs that may be critical for long-term ecosystem resilience.

While several studies have examined vegetation patterns and species diversity in Himalayan forests (Rawat and Singh 1988, Khera et al. 2001, Sharma et al. 2009, Ahmed 2012), comparative analyses of regeneration dynamics across different habitats in the Ranikhet region remain limited. This knowledge gap is particularly significant given that traditional forest management approaches in the region have often applied uniform strategies across diverse forest types, potentially overlooking critical habitat-specific requirements for sustainable management. The specific regeneration challenges in Ranikhet's forests may differ substantially from other Western Himalayan regions due to its unique combination of geographical position, historical land use, and current anthropogenic pressures.

The present study therefore aims to: (1) compare tree species composition and diversity across Oak, Pine, and Oak-Pine mixed forest habitats in Ranikhet; (2) assess the regeneration status of tree species across different habitats using seedling, sapling, and tree densities; (3) evaluate the ecological importance of different tree species using the Importance Value Index (IVI); and (4) examine similarity patterns between different forest habitats.

The findings will contribute to our understanding of forest dynamics in this critical region of the Western Himalaya and provide valuable insights for conservation planning and sustainable forest management that addresses the unique ecological and socioeconomic context of Ranikhet.

MATERIAL AND METHODS

Study area

This study was carried out from November 2021 to November 2022 in Ranikhet (latitude: 29°36' to 29°42' N and longitude: 79°24 to 79° E) forest of Almora District, Uttarakhand, India (Fig. 1). It is situated in one of the ridges of the Kumaon Himalaya, which stretches halfway across the district west to east and forms the northern boundary of Kosi basin. With an average altitude of 1800 m asl, its southern summit at Chaubatia attained a height of 2100 m asl. The configuration of the whole area is based on a tract of rounded or flat ridges with subsidiary spurs and slopes of gentle to moderate gradient. It also possesses innumerable springs and small streams at the breast level. The valley of Gagas and Kosi Rivers occupy the basal portion. It covers an area of 389.9 km^2 and approximately 12.3% of the total geographical area of Almora district. The area exhibits moderate heat, which increases with the depth of the valleys. The mean annual temperature is 21.5°C with 14.44°C and 25.23°C as the annual minimum and maximum temperatures, respectively. Ranikhet typically receives about 1300 mm of precipitation annually, and nearly 75% of the rainfall is received during monsoon (July-September). While more than 90% of the forested area is dominated by *Pinus roxburghii,* a few patches of *Quercus leucotrichophora, Cedrus deodara,* and *Cupressus torulosa* are also present. In total, 15 species of mammals, 209 species of birds, 11 species of reptiles, and four species of amphibians have been reported from Ranikhet. The study area faces to its north a gigantic span of prominent Himalayan peaks, including Chaukhamba (7104 m), Trisul (7120 m), Nandadevi (7817 m), Nandakot (6904 m), and

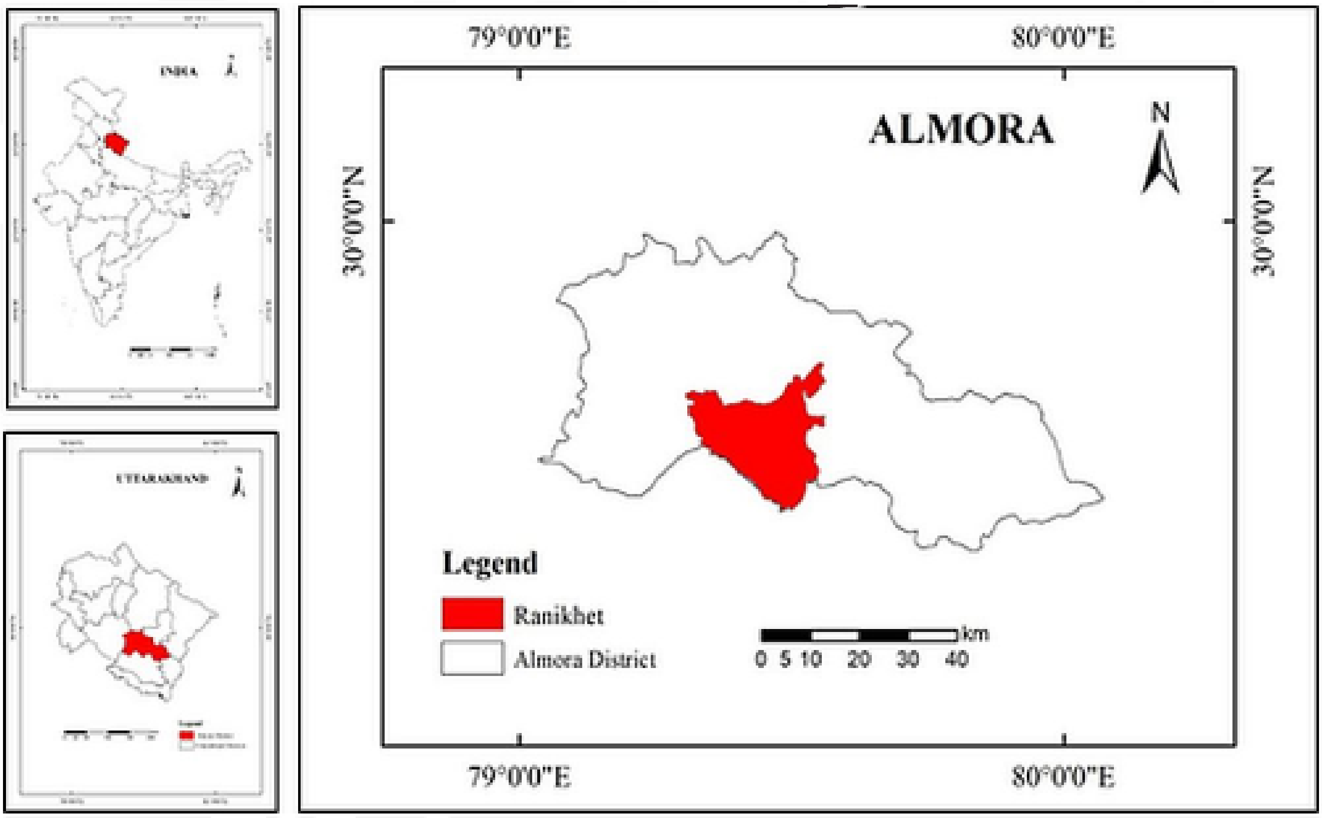

Figure 1. Location of the study area

Panchachuli (6950 m).

Data collection

Phytosociological data was collected in the forest of Ranikhet through an intensive field survey. A total of 120 sampling plots (10 m radius each) were laid in a random stratified manner across the three distinct forest communities, i.e., Oak, Pine, and Oak-Pine mixed forests. Tree data were recorded at three life stages, viz. mature trees (height > 4 m), saplings (height = 0.51 – 4 m), and seedlings (height = 0.1 – 50 cm) (Sultana 2002). The whole plot of a 10 m radius was considered a tree plot, and all the trees encountered within the plot were identified and quantified. A concentric plot of 3 m radius was nested within each tree plot to quantify saplings and seedlings. Number of individuals of each species was recorded within respective plots. Tree circumference (GBH) of all encountered trees was measured with the help of measuring tape at a height of 1.37 m from the ground. The collected data were analyzed for density, diversity indices (Shannon, Simpson, Margalef, Menhinick and Berger Parker), importance value index (IVI), Seedling-Tree density ratio, Sapling-Tree density ratio, regeneration status and Simpson's similarity index using Microsoft Excel 2019 and PAST version 4.03.

Data analysis

Vegetation structure and composition

Tree density, frequency, and basal area were calculated following standard methods (Curtis and McIntosh 1950). IVI was calculated using the following equation-

Importance value index (IVI) = RF + RD + RBA

Where, RF = relative frequency, RD = relative density, RBA = relative basal area.

Diversity indices

Shannon-Wiener diversity index (H') (Shannon and Weaver 1949): $H' = -\Sigma (p_i \ln p_i)$ where pi is the proportion of individuals of species i.

Simpson's dominance index (D) (Simpson 1949): $D = \Sigma (p_i)^2$ where pi is the proportion of individuals of species i.

Menhinick's index (Dmn) (Menhinick 1964): Dmn = S/√N where S is the number of species and N is the total number of individuals.

Margalef's index (Dmg) (Margalef 1958): Dmg = (S-1)/ln N where S is the number of species and N is the total number of individuals.

Berger-Parker index (d) (Berger and Parker 1970): d = Nmax/N where Nmax is the number of individuals of the most abundant species and N is the total number of individuals.

Regeneration assessment

Regeneration status of tree species was assessed based on the population structure (density of seedlings, saplings, and trees) following Shankar (2001) with modifications: ***Good*** if seedling > sapling > mature trees; ***Fair*** if seedling > saplings ≤ mature trees; ***Poor*** if there were saplings but no seedlings (irrespective of the relative numbers of saplings and adults); ***None*** if only adults were present, with no seedlings or saplings; ***New*** if only saplings and/or seedlings were present, with no adults.

The seedling-to-tree ratio (Se/T) and sapling-to-tree ratio (Sa/T) were calculated to quantify regeneration potential.

Similarity index

Simpson's similarity index (SI) was used to compare species composition between different habitats: SI = 2C/(A+B) × 100 where C is the number of species common to both habitats, A is the total number of species in habitat A, and B is the total number of species in habitat B.

RESULTS

Species composition and diversity

A total of 19 tree species belonging to 13 families were recorded across the three forest habitats. The highest species richness was observed in the Oak-Pine mixed habitat (15 species), followed by Pine habitat (7 species) and Oak habitat (6 species). Tree density varied considerably across habitats, with the highest density recorded in Oak-Pine habitat (467.09 individuals/ha), followed by Pine (357.99 individuals/ha) and Oak (291.17 individuals/ha) habitats (Table 1).

The diversity indices showed notable differences across the three habitats (Table 1). The Shannon diversity index was highest in Oak-Pine habitat (1.625), followed by Oak habitat (1.288), and lowest in Pine habitat (0.1526). Similarly, Simpson's index value was highest in Oak-Pine habitat (0.7381), followed by Oak (0.6543) and Pine (0.04854) habitats. The Menhinick index, which accounts for species richness relative to abundance, was highest in Oak habitat (0.75), closely followed by Oak-Pine habitat (0.7151), and lowest in Pine habitat (0.2292). The Margalef index demonstrated that species richness was markedly higher in Oak-Pine habitat (2.3) compared to Oak (1.202) and Pine (0.8774) habitats. The Berger-Parker index indicated high dominance by a single species in Pine habitat (0.9753) compared to Oak (0.5) and Oak-Pine (0.3364) habitats.

Importance value index (IVI)

In the Oak habitat, *Quercus leucotrichophora* emerged as the most important species with an IVI of 135.48, followed by *Ilex dipyrena* (90.50) and *Myrica esculenta* (36.35) (Table 2). In the Pine habitat, *Pinus roxburghii* was overwhelmingly dominant with an IVI of 280.89, while other species had considerably lower values (Table 3). The Oak-Pine habitat showed a more balanced distribution of importance values, with *P. roxburghii* (107.96) and *Q. leucotrichophora* (88.79) as co-dominant species, followed by *M. esculenta* (53.16) (Table 4).

Table 1. Habitat-wise tree density and diversity indices

Habitat	Density (individuals/ha)	IVI (Max)	Shannon	Simpson	Menhinick	Margalef	Berger Parker
Oak	291.17	135.48	1.288	0.6543	0.75	1.202	0.5
Pine	357.99	280.89	0.1526	0.04854	0.2292	0.8774	0.9753
Oak-Pine	467.09	107.96	1.625	0.7381	0.7151	2.3	0.3364

Table 2. Tree species-wise IVI in Oak habitat

Tree	No.	Density (individuals/ha)	Relative Density	Relative Frequency	Relative Dominance	IVI
Aesculus indica	2	9.10	3.13	6.67	3.35	13.15
Ilex dipyrena	19	86.44	29.69	26.67	34.15	90.50
Quercus leucotrichophora	32	145.59	50.00	40.00	45.48	135.48
Cedrus deodara	2	9.10	3.13	6.67	5.59	15.38
Myrica esculenta	8	36.40	12.50	13.33	10.51	36.35
Rhododendron arboreum	1	4.55	1.56	6.67	0.92	9.15
Total	**64**	**291.17**				

Table 3. Tree species-wise IVI in Pine habitat

Tree	No.	Density (individuals/ha)	Relative Density	Relative Frequency	Relative Dominance	IVI
Pinus roxburghii	910	349.17	97.53	85.42	97.94	280.89
Quercus leucotrichophora	5	1.92	0.54	3.13	0.14	3.80
Rhododendron arboreum	1	0.38	0.11	1.04	0.12	1.26
Myrica esculenta	12	4.60	1.29	6.25	1.49	9.03
Cedrus deodara	2	0.77	0.21	2.08	0.14	2.44
Prunus persica	2	0.77	0.21	1.04	0.13	1.38
Acacia dealbata	1	0.38	0.11	1.04	0.04	1.19
Total	**933**	**357.99**				

Table 4. Tree species-wise IVI in Oak-Pine habitat

Tree	No.	Density (individuals/ha)	Relative Density	Relative Frequency	Relative Dominance	IVI
Pinus roxburghii	148	157.11	33.64	24.49	49.83	107.96
Myrica esculenta	92	97.66	20.91	23.47	8.79	53.16
Quercus leucotrichophora	142	150.74	32.27	28.57	27.95	88.79
Phoebe lanceolata	2	2.12	0.45	1.02	0.08	1.56
Ilex dipyrena	16	16.99	3.64	5.10	1.83	10.57
Aesculus indica	3	3.18	0.68	2.04	1.76	4.49
Rhododendron arboreum	10	10.62	2.27	3.06	1.49	6.82
Persea duthiei	2	2.12	0.45	2.04	0.21	2.70
Cedrus deodara	8	8.49	1.82	2.04	4.87	8.73
Lyonia ovalifolia	6	6.37	1.36	1.02	0.41	2.80
Prunus cerasoides	1	1.06	0.23	1.02	0.28	1.53
Pyrus pashia	3	3.18	0.68	3.06	0.25	3.99
Sapium insigne	1	1.06	0.23	1.02	0.13	1.38
Eucalyptus globulus	4	4.25	0.91	1.02	1.02	2.95
Cupressus torulosa	2	2.12	0.45	1.02	1.10	2.57
Total	**440**	**467.09**				

Table 5. Regeneration in Oak habitat

S.No.	Species	Density (individuals /ha)			Regeneration
		Seedling	Sapling	Tree	
1	*Aesculus indica*	-	-	9.10	None
2	*Ilex dipyrena*	2022.04	303.31	86.44	Good
3	*Quercus leucotrichophora*	151.65	-	145.59	Fair
4	*Cedrus deodara*	-	-	9.10	None
5	*Myrica esculenta*	-	-	36.40	None
6	*Rhododendron arboreum*	202.20	-	4.55	Fair
7	*Acacia dealbata*	960.47	50.55	-	New
8	*Pinus roxburghii*	404.41	-	-	New
	Total	**3740.77**	**353.86**	**291.17**	**Good**

Table 6. Regeneration in Pine habitat

S.No.	Species	Density (individuals /ha)			Regeneration
		Seedling	Sapling	Tree	
1	*Pinus roxburghii*	2332.05	21.32	349.17	Fair
2	*Alnus nepalensis*	332.54	29.84	-	New
3	*Mallotus philippensis*	8.53	-	-	New
4	*Myrica esculenta*	51.16	29.84	4.60	Good
5	*Quercus leucotrichophora*	85.27	4.26	1.92	Good
6	*Cedrus deodara*	21.32	-	0.77	Fair
7	*Prunus persica*	4.26	-	0.77	Fair
8	*Acacia dealbata*	243.01	4.26	0.38	Good
9	*Rhododendron arboreum*	-	-	0.38	None
	Total	**3078.13**	**89.53**	**357.99**	**Fair**

Table 7. Regeneration in Oak-Pine habitat

S.No.	Species	Density (individuals/ha)			Regeneration
		Seedling	Sapling	Tree	
1	*Pinus roxburghii*	2819.06	35.39	157.11	Fair
2	*Myrica esculenta*	141.54	70.77	97.66	Fair
3	*Quercus leucotrichophora*	967.21	11.80	150.74	Fair
4	*Phoebe lanceolata*	-	-	2.12	None
5	*Ilex dipyrena*	11.80	-	16.99	Fair
6	*Aesculus indica*	-	-	3.18	None
7	*Rhododendron arboreum*	-	-	10.62	None
8	*Persea duthiei*	-	-	2.12	None
9	*Cedrus deodara*	-	-	8.49	None
10	*Lyonia ovalifolia*	70.77	-	6.37	Fair
11	*Prunus cerasoides*	-	-	1.06	None
12	*Pyrus pashia*	-	-	3.18	None
13	*Sapium insigne*	-	-	1.06	None
14	*Eucalyptus globulus*	-	-	4.25	None
15	*Cupressus torulosa*	-	-	2.12	None
16	*Acacia dealbata*	23.59	11.80	-	New
17	*Alnus nepalensis*	11.80	-	-	New
	Total	**4045.77**	**129.75**	**467.09**	**Fair**

Regeneration patterns

The overall regeneration status was assessed as "Good" in Oak habitat, whereas both Pine and Oak-Pine habitats showed "Fair" regeneration (Tables 5, 6, 7). The seedling density was highest in Oak-Pine habitat (4045.77 individuals/ha), followed by Oak (3740.77 individuals/ha) and Pine (3078.13 individuals /ha) habitats. However, sapling density was highest in Oak habitat (353.86 individuals /ha), followed by Oak-Pine (129.75 individuals /ha) and Pine (89.53 individuals /ha) habitats.

Species-wise regeneration status varied considerably across habitats (Table 8). *Q. leucotrichophora* showed fair regeneration in Oak and Oak-Pine habitats but good regeneration in Pine habitat. *P. roxburghii* exhibited fair regeneration in Pine and Oak-Pine habitats but was present only as seedlings (new) in Oak habitat. Notably, invasive species like *Acacia dealbata* showed new regeneration status in Oak and Oak-Pine habitats and good regeneration in Pine habitat. Several species, particularly in the Oak-Pine habitat, showed no regeneration, including *Rhododendron arboreum*, *Phoebe lanceolata*, and *Eucalyptus globulus*.

Table 8. Species-wise regeneration across habitats

Species	**Habitats**		
	Oak	**Pine**	**Oak-Pine**
Quercus leucotrichophora	Fair	Good	Fair
Pinus roxburghii	New	Fair	Fair
Rhododendron arboreum	Fair	None	None
Myrica esculenta	None	Good	Fair
Cedrus deodara	None	Fair	None
Prunus persica	-	Fair	-
Aesculus indica	None	-	None
Ilex dipyrena	Good	-	Fair
Phoebe lanceolata	-	-	None
Persea duthiei	-	-	None
Lyonia ovalifolia	-	-	Fair
Prunus cerasoides	-	-	None
Pyrus pashia	-	-	None
Sapium insigne	-	-	None
Acacia dealbata	New	Good	New
Eucalyptus globulus	-	-	None
Cupressus torulosa	-	-	None
Mallotus philippensis	-	New	-
Alnus nepalensis	-	New	New

The seedling-to-tree density ratio (Se/T) and sapling-to-tree density ratio (Sa/T) revealed distinct regeneration patterns across species and habitats (Table 9). *Q. leucotrichophora* showed a low Se/T ratio in Oak habitat (1.04) but higher ratios in Pine (44.41) and Oak-Pine (6.42) habitats. Conversely, *P. roxburghii* had high Se/T ratios in Oak (404.41/0) and Oak-Pine (17.94) habitats. Invasive species like *A. dealbata* showed high Se/T ratios across habitats where it occurred.

Table 9. Habitat-wise sapling-tree and seedling-tree ratio

Tree	**Ratio**	**Oak**	**Pine**	**Oak-Pine**
Quercus leucotrichophora	**Se/T**	1.04	44.41	6.42
	Sa/T	0/145.59	2.22	0.08
Pinus roxburghii	**Se/T**	404.41/0	6.68	17.94
	Sa/T		0.06	0.23
Rhododendron arboreum	**Se/T**	44.44	0/0.38	0/10.62
	Sa/T	0/4.55	0/0.38	0/10.62
Myrica esculenta	**Se/T**	0/36.40	11.12	1.45
	Sa/T	0/36.40	6.49	0.72
Cedrus deodara	**Se/T**	0/9.10	27.69	0/8.42
	Sa/T	0/9.10	0/0.77	0/8.42
Prunus persica	**Se/T**		5.53	
	Sa/T		0/0.77	
Aesculus indica	**Se/T**	0/9.10		0/3.18
	Sa/T	0/9.10		0/3.18
Ilex dipyrena	**Se/T**	23.39		0.69
	Sa/T	3.51		0/16.99
Phoebe lanceolata	**Se/T**			0/2.12
	Sa/T			0/2.12
Persea duthiei	**Se/T**			0/2.12
	Sa/T			0/2.12
Lyonia ovalifolia	**Se/T**			11.11
	Sa/T			0/6.37
Prunus cerasoides	**Se/T**			0/1.06
	Sa/T			0/1.06
Pyrus pashia	**Se/T**			0/3.18
	Sa/T			0/3.18
Sapium insigne	**Se/T**			0/1.06
	Sa/T			0/1.06
Acacia dealbata	**Se/T**	960.47/0	639.5	23.59/0
	Sa/T	50.55/0	11.21	11.80/0
Eucalyptus globulus	**Se/T**			0/4.25
	Sa/T			0/4.25
Cupressus torulosa	**Se/T**			0/2.12
	Sa/T			0.12
Mallotus philippensis	**Se/T**		8.53/0	
	Sa/T			
Alnus nepalensis	**Se/T**		332.54/0	11.80/0
	Sa/T		29.84/0	

Similarity index

Simpson's similarity index revealed moderate overlap in species composition between the three habitats (Table 10). The highest similarity was observed between Oak and Pine habitats (61.53%), followed by Oak and Oak-Pine habitats (57.14%), while Pine and Oak-Pine habitats showed the lowest similarity (45.45%).

DISCUSSION

Species diversity and habitat characteristics

Our study reveals significant differences in tree species diversity across the three forest habitats in the Western Himalayas. The Oak-Pine mixed habitat exhibited the highest species richness and diversity, which aligns with the intermediate disturbance hypothesis (Connell 1978) and ecotone effect, where transitional zones between two distinct habitats often support higher biodiversity (Risser 1995). Similar patterns have been reported in other Himalayan forest studies (Gairola et al. 2008, Sharma et al. 2009), where mixed forests typically harbor greater species diversity than pure stands.

The remarkably low diversity in Pine habitat (Shannon index: 0.1526) coupled with high dominance (Berger-Parker index: 0.9753) reflects the ecological strategy of *P. roxburghii*, which often forms near-monoculture stands through allelopathic interactions, fire adaptation, and competitive resource utilization (Singh and Singh 1992, Bargali et al. 2018). This dominance pattern is further evidenced by the extremely high IVI value (280.89) of *P. roxburghii* in Pine habitat, constituting 93.6% of the maximum possible IVI value (300).

The Oak habitat showed intermediate diversity values but supported several unique species like *Aesculus indica* that were absent or rare in other habitats. This habitat specialization suggests niche partitioning and highlights the importance of maintaining diverse habitat types within the landscape for overall biodiversity conservation (Rawat and Singh 1988, Khera et al. 2001).

Regeneration dynamics

The regeneration analysis revealed complex patterns across habitats and species, raising several ecological concerns. The overall "Good" regeneration status in Oak habitat contrasts with "Fair" regeneration in Pine and Oak-Pine habitats, suggesting that Oak forests may have greater resilience and sustainability in the current environmental conditions. This finding is consistent with previous studies in Western Himalayan forests (Thadani and Ashton 1995, Gairola et al. 2012), which have noted better regeneration in Oak forests compared to Pine-dominated stands.

The species-wise regeneration patterns highlight several important trends. First, the principal native dominants (*Q. leucotrichophora* and *P. roxburghii*) showed fair regeneration in their respective habitats but variable patterns elsewhere. *Q. leucotrichophora* exhibited good regeneration in Pine habitat despite its low adult tree density, suggesting potential for oak expansion into pine-dominated areas under favorable conditions. Conversely, *P. roxburghii* showed establishment in Oak habitat (new regeneration) without adult trees, indicating possible habitat shifts or succession dynamics.

Second, the high seedling-to-tree ratios for invasive species like *A. dealbata* across all habitats raise substantial conservation concerns. This species is known for its aggressive colonization and potential to alter ecosystem processes (Bargali et al. 2018). The successful establishment of this invasive, even in relatively intact forest habitats, suggests underlying disturbance factors or changing environmental conditions that may favor non-native species over native forest components.

Third, the absence of regeneration (classified as "None") for several species, particularly in the Oak-Pine habitat, warrants attention. Species like *Rhododendron arboreum*, *Cedrus deodara*, and *E. globulus* appear to be failing to regenerate despite the presence of adult trees. This regeneration failure could be attributed to various factors including herbivory pressure, unfavorable microsite conditions, or climate change impacts (Khumbongmayum et al. 2006, Sharma et al. 2014).

The varying ratios of seedlings and saplings to trees across species and habitats suggest different bottlenecks in the regeneration process. For instance, *I. dipyrena* in Oak habitat shows good overall regeneration but a much higher seedling-to-tree ratio (23.39) compared to sapling-to-tree ratio (3.51), indicating significant mortality between seedling and sapling stages. Understanding these stage-specific limitations is crucial for targeted conservation interventions.

Ecological implications and conservation perspectives

The Simpson similarity indices (45.45-61.53%) indicate moderate overlap between habitats but also substantial uniqueness in species composition. This differentiation underscores the ecological value of maintaining habitat heterogeneity at the landscape scale (Risser 1995). The higher similarity between Oak and Pine habitats (61.53%) compared to either with Oak-Pine mixed habitat is somewhat counterintuitive but may reflect the ecological distinction of the mixed forest as a unique ecosystem rather than simply an intermediate state.

The dominance patterns revealed by the IVI analysis provide important insights into forest structure and competitive dynamics. In Oak habitat, the co-dominance of *Q. leucotrichophora* (IVI: 135.48) and *I. dipyrena* (IVI: 90.50) suggests a relatively stable mixed broadleaf community. In contrast, the overwhelming dominance of *P. roxburghii* in Pine habitat (IVI: 280.89) indicates limited resource availability for other species, potentially exacerbated by the allelopathic effects of pine needles (Singh and Singh 1987).

The invasion potential of species like *A. dealbata* across all habitats represents a significant threat to native biodiversity. This species showed new regeneration in Oak and Oak-Pine habitats and good regeneration in Pine habitat, suggesting it may become increasingly prevalent in the future forest composition. These invasive dynamics align with global patterns of increasing biotic homogenization in forest ecosystems due to human-mediated species introductions and disturbances (Bargali et al. 2018).

From a conservation perspective, our findings highlight several priorities: (1) monitoring and potential control of invasive species, particularly in areas where they show high regeneration success; (2) investigating regeneration limitations for species showing no regeneration despite adult presence; (3) maintaining habitat heterogeneity at landscape scales to preserve the distinct biodiversity values of each forest type; and (4) implementing targeted management interventions based on habitat-specific regeneration challenges.

CONCLUSIONS

This study provides a comprehensive assessment of tree species composition, diversity, and regeneration patterns across three distinct forest habitats in the Western Himalayas. Our findings reveal that Oak-Pine mixed forests support the highest species diversity, while Pine forests show the lowest diversity with strong dominance by *Pinus roxburghii*. The regeneration analysis indicates habitat-specific patterns with overall good regeneration in Oak forests but only fair regeneration in Pine and Oak-Pine habitats. Of particular concern is the successful establishment of invasive species across all habitats and the regeneration failure of several native species. The habitat-specific approach employed in this study offers valuable insights for forest management and conservation planning. It highlights the importance of maintaining diverse forest habitats within the landscape and addressing habitat-specific regeneration challenges. Future research should focus on long-term monitoring of regeneration dynamics, investigating the factors limiting recruitment of species showing poor regeneration, and developing strategies to mitigate the spread of invasive species in these ecologically important forests.

The findings contribute to our understanding of forest dynamics in the Western Himalaya and provide a scientific basis for sustainable forest management in the face of ongoing environmental changes and anthropogenic pressures. Conservation strategies should prioritize maintaining the structural and functional integrity of these forests while addressing the specific regeneration limitations and invasion threats identified in this study.

Authors' contributions: All authors contributed equally.

Conflict of interest: Authors declare no conflict of interest.

REFERENCES

Ahmed, A. 2012. Analysis of forest vegetation in Ranikhet, Kumaon Himalaya, Uttarakhand, India. Indian Journal of Fundamental and Applied Life Sciences, 2(4), 16-23. https://

www.cibtech.org/J-LIFE-SCIENCES/PUBLICATIONS/2012/ Vol_2_No_4/04-005...Ahmed...Analysis...India.pdf

Bargali, K., Manral, V., Padalia, K., Bargali, S.S. and Upadhyay, V.P. 2018. Effect of vegetation type and season on microbial biomass carbon in Central Himalayan forest soils, India. Catena, 171, 125-135. https://doi.org/10.1016/j.catena.2018.07.001

Berger, W.H. and Parker, F.L. 1970. Diversity of planktonic foraminifera in deep-sea sediments. Science, 168(3937), 1345-1347. https://doi.org/10.1126/science.168.3937.1345

Connell, J.H. 1978. Diversity in tropical rain forests and coral reefs. Science, 199(4335), 1302-1310. https://doi.org/10.1126/science.199.4335.1302

Curtis, J.T. and McIntosh, R.P. 1950. The interrelations of certain analytic and synthetic phytosociological characters. Ecology, 31(3), 434-455. https://doi.org/10.2307/1931497

Gairola, S., Rawal, R.S. and Todaria, N.P. 2008. Forest vegetation patterns along an altitudinal gradient in sub-alpine zone of west Himalaya, India. African Journal of Plant Science, 2(6), 42-48. https://doi.org/10.5897/AJPS.9000126

Khera, N., Kumar, A., Ram, J. and Tewari, A. 2001. Plant biodiversity assessment in relation to disturbances in mid-elevational forest of Central Himalaya, India. Tropical Ecology, 42(1), 83-95.

Khumbongmayum, A.D., Khan, M.L. and Tripathi, R.S. 2006. Biodiversity conservation in sacred groves of Manipur, northeast India: population structure and regeneration status of woody species. Biodiversity & Conservation, 15(8), 2439-2456. https://doi.org/10.1007/s10531-004-6901-z

Margalef, R. 1958. Information theory in ecology. General Systems, 3, 36-71.

Mehra, A., Tewari, L.M. and Rawal, R.S. 2023. Structure and Composition of Vegetation and Status of Invasion in Different Forest Types of Western Himalaya. Advances in Zoology and Botany, 11(1), 12-29. https://doi.org/10.13189/azb.2023.110102

Menhinick, E.F. 1964. A comparison of some species individuals diversity indices applied to samples of field insects. Ecology, 45(4), 859-861. https://doi.org/10.2307/1934933

Rawat, Y.S. and Singh, J.S. 1988. Structure and function of oak forests in Central Himalaya. I. Dry matter dynamics. Annals of Botany, 62(4), 397-411. https://doi.org/10.1093/oxfordjournals.aob.a087674

Risser, P.G. 1995. The status of the science examining ecotones. BioScience, 45(5), 318-325. https://doi.org/10.2307/1312492

Shankar, U. 2001. A case of high tree diversity in a sal (*Shorea robusta*)-dominated lowland forest of Eastern Himalaya: floristic composition, regeneration and conservation. Current Science, 81(7), 776-786. https://www.jstor.org/stable/24106397

Shannon, C.E. and Weaver, W. 1949. The mathematical theory of communication. University of Illinois Press, Urbana.

Sharma, C.M., Baduni, N.P., Gairola, S., Ghildiyal, S.K. and Suyal, S. 2012. Tree diversity and carbon stocks of some major forest types of Garhwal Himalaya, India. Forest Ecology and Management, 291, 57-67. https://doi.org/10.1016/j.foreco.2012.01.040

Sharma, C.M., Gairola, S., Ghildiyal, S.K. and Suyal, S. 2009. Forest dependent livelihood in relation to socio-economic status of the people in temperate villages of Garhwal Himalaya, India. Mountain Research and Development, 29(4), 308-319. https://doi.org/10.1659/mrd.00018

Sharma, C.M., Mishra, A.K., Krishan, R., Tiwari, O.P. and Rana, Y.S. 2016. Variation in vegetation composition, biomass production, and carbon storage in ridge top forests of high mountains of Garhwal Himalaya. Journal of Sustainable Forestry, 33(8), 747-768. https://doi.org/10.1080/10549811.2016.1188371

Simpson, E.H. 1949. Measurement of diversity. Nature, 163(4148), 688. https://doi.org/10.1038/163688a0

Singh, J.S. 1992. Forests of Himalaya: structure, functioning, and impact of man. Gyanodaya Prakashan, Nainital.

Singh, J.S. and Singh, S.P. 1987. Forest vegetation of the Himalaya. The Botanical Review, 53(1), 80-192. https://doi.org/10.1007/BF02858183

Sultana, A. 2002. Ecology and Conservation of avian communities of Middle Altitude Oak Forest of Kumoan Himalaya, Uttar Pradesh, India. Ph.D. Thesis. Department of Wildlife Science, AMU, Aligarh.

Thadani, R. and Ashton, P.M.S. 1995. Regeneration of banj oak (*Quercus leucotrichophora* A. Camus) in the central Himalaya. Forest Ecology and Management, 78(1-3), 217-224. https://doi.org/10.1016/0378-1127(95)03559-X

Received: 30th November 2024
Accepted: 8th April 2025