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Carbon dynamics, regeneration and forest normality in temperate Himalayan fir-spruce forest ecosystem, India

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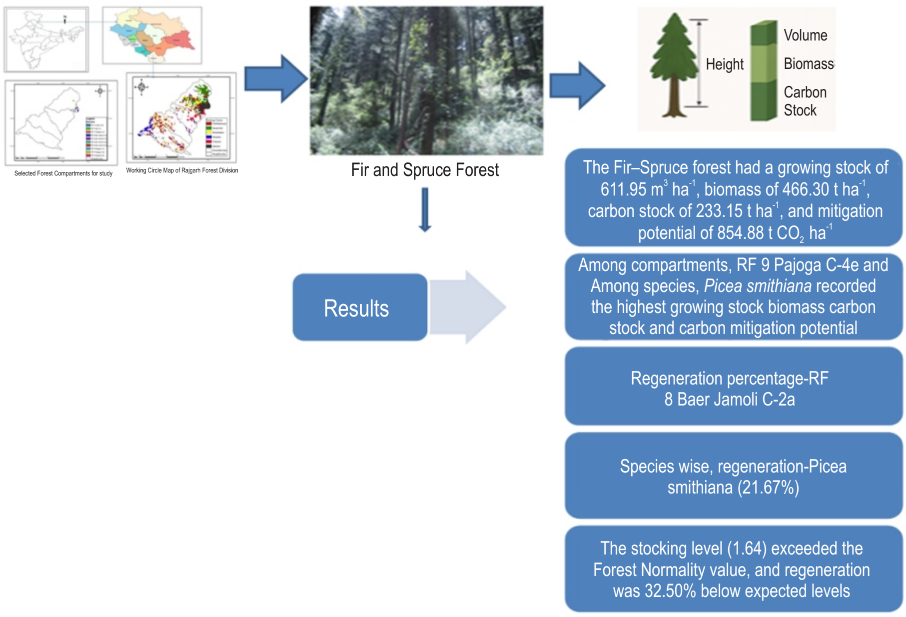
Abstract

Aim: To assess the carbon dynamics, regeneration status and forest normality of Fir-Spruce forest in the Sirmaur district of Himachal Pradesh.

Methodology: The study was conducted in the Fir–Spruce (Selection) working circle at elevations ranging from 2,150 to 3,600 m asl. Ten compartments were randomly selected based on crop composition and density. Tree measurements (DBH and height) were used to quantify volume, biomass, and carbon stock following IPCC and FRI standard methodologies, while regeneration was assessed using systematic quadrat sampling and Chacko's methods.

Results: Among the compartments, RF 9 Pajoga C-4e recorded the highest growing stock (762.94 m^3 ha^{-1}), biomass (588.93 t ha^{-1}), carbon stock (294.47 t ha^{-1}), and carbon mitigation potential (1079.71 t ha^{-1}). Overall, the Fir–Spruce forest had a growing stock of 611.95 m^3 ha^{-1}, biomass of 466.30 t ha^{-1}, carbon stock of 233.15 t ha^{-1}, and mitigation potential of 854.88 t CO_2 ha^{-1}. Among species, *Picea smithiana* exhibited the highest growing stock (420.16 m^3 ha^{-1}), biomass (305.17 t ha^{-1}), and carbon stock (152.59 t ha^{-1}), followed by *Abies pindrow*. Regeneration percentage was highest in RF 8 Baer Jamoli C-2a (50.00%) and lowest in RF 5 Narh C-3 (13.89%). Species wise, regeneration was highest in *Picea smithiana* (21.67%), with lower values in *Abies pindrow, Quercus dilatata, Q. semecarpifolia, Rhododendron arboreum* and *Q. leucotrichophora* and absent in *Pinus wallichiana* and *Cedrus deodara*.



Interpretation: The prevalence of mature and over-mature trees, along with insufficient regeneration, highlights critical management challenges in these forests under the selection system, requiring targeted silvicultural interventions to restore forest normality.

Key words: Carbon stock, Forest normality, *Picea smithiana*, Regeneration status, Stocking level, Selection system

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Introduction

Forests play a pivotal role in sustaining biodiversity at both local and global scales while mitigating climate change through essential ecosystem services, including carbon sequestration, soil conservation, and water regulation. Ecosystem approach and services concept represents a contemporary shift in natural resource management, with significant implications for forest policy (Quine *et al.,* 2013). Forests provide diverse ecological, economic and social benefits but face increasing overexploitation from unsustainable extraction of timber, fuelwood, and non-timber forest products. Such pressures result in soil erosion, landslides, floods, droughts, altered habitat and land cover, climate change impacts, native species extinction, and biological invasions (Canadell *et al.,* 2021). Globally, countries including India are urged to improve forest conditions through planned resource use. Forests are key to the global carbon cycle, serving as sinks by storing atmospheric CO_2 in biomass and soil (Chaudhury *et al.,* 2016).

Forests carbon sequestration potential depends on traits such as diameter, height, and density, along with age, species composition, soil, geography, and climate. Industrialization and deforestation have further accelerated CO_2 rise since the preindustrial era. Globally, ecosystems act as carbon sinks with varying CO_2 absorption capacities. Between 2010–2019, human activities emitted 10.9 ± 0.9 PgC yr^{-1}, of which 46% remained in the atmosphere, 23% was absorbed by the oceans, and 31% sequestered by terrestrial vegetation (Canadell *et al.,* 2021). Forests, covering 4.1 billion ha (31% of land) in 2020, store about 861 Gt with 44% in soil, 42% in live biomass, 8% in dead wood, and 5% in litter (FAO, 2024). Biomass storage varies with forest type, canopy cover, stand age, altitude, and structure, shaping sustainable forest management and ecosystem services. Natural regeneration is vital for forest sustainability, shaping plant communities and conserving diversity through seed dispersal and establishment (Rahman *et al.,* 2019). Seedling–sapling dynamics indicate regeneration potential, while forest normality serves as a benchmark for effective management (Wani *et al.,* 2023).

Forest normality, though data-intensive to assess, provides an effective benchmark for management. The environmental variables shape Himalayan tree communities, making sustainable management vital for biodiversity and livelihoods. Habitat-specific species pools and floristic sampling support accurate assessments (Mugloo *et al.,* 2021). Tree diversity strengthen ecosystems and is influenced by vegetation, topography, and soils (Gairola *et al.,* 2011a). Seed quality, survival and recruitment, with regular monitoring, are crucial, as dominant trees drive ecological gradients and diversity. The effective forest management requires controlling stocking, a key manageable factor that determines how increment varies with stand density. In view of the above, this study aimed to comprehensively evaluate biomass, carbon stock, regeneration status, and forest normality in Fir-Spruce forests of the Selection Working Circle in the temperate Himalayan region of Himachal Pradesh.

Materials and Methods

Study area: The study was carried out in the Rajgarh Forest Division of Sirmaur district in Himachal Pradesh, spanning 30° 38'40" to 31° 01'14" N latitude and 77° 01' 5" to 77° 26' 13"E longitude, covering an area of 82,002 ha. Fir-Spruce forests are located at elevations ranging between 2,150 to 3,600 m asl (Luna, 1996). Ten Fir and Spruce-dominated forest compartments were selected for their broader geographical range, maximizing species richness, diversity and microclimates within the temperate region (Fig. 1). Temperature ranged between 0.3°C to 42°C, with heavy snowfall on higher reaches and frost from November to February. Monsoon rainfall varied between 557.50 mm to 1585.50 mm, and the total precipitation ranged between 900 mm to 2176.80 mm in all seasons.

Measurement of Biomass and Carbon: In the Selection (Fir–Spruce) working circle, ten compartments were randomly selected based on crop composition and density to analyze growing stock, carbon stock, and regeneration. In each compartment, ten randomly distributed plots of 0.1 ha (31.62 × 31.62 m^2) were laid out proportionate to compartment area for data collection (Negi *et al.,* 2021). Structural parameters such as DBH and height were measured, and tree volume was estimated using species-specific regional equations of the Forest Survey of India (FSI, 1996). Biomass was derived using species-wise wood density values from published literature (Table 1).

Aboveground tree biomass (AGB) was estimated by multiplying the stem volume with species specific wood density and a biomass expansion factor, following the methodology recommended by IPCC (2006);

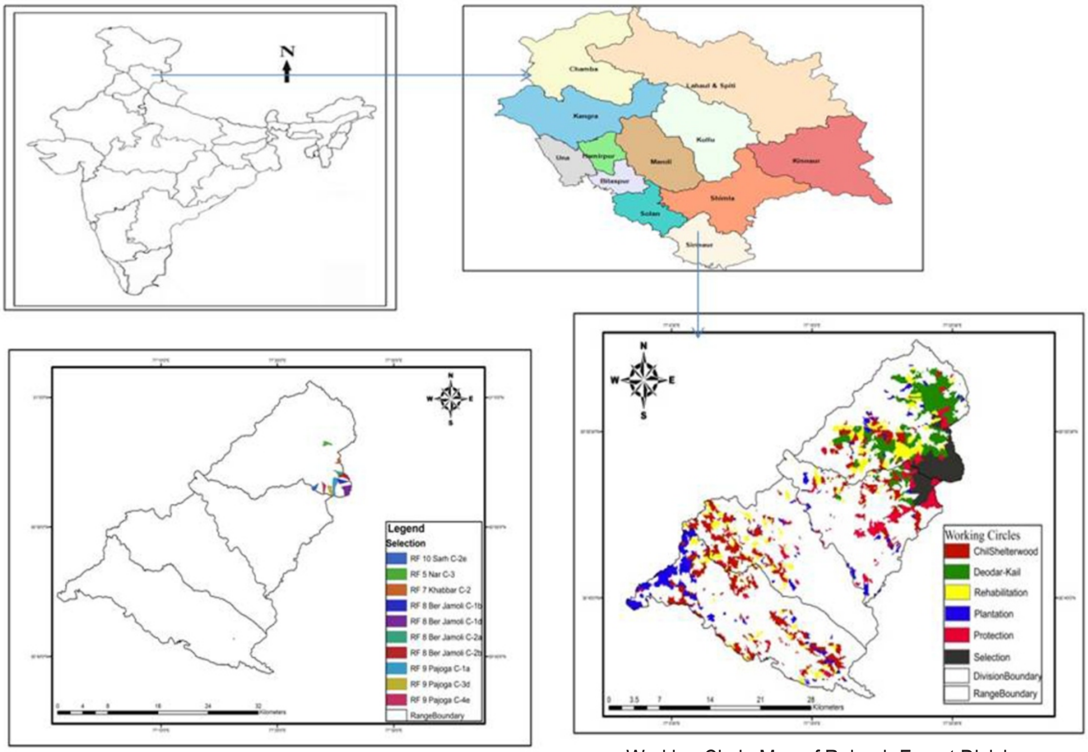
Belowground biomass (BGB) was estimated by the root-to-shoot ratio method as proposed by Cairns et al. (1997):

Total biomass (TB) was calculated as the sum of aboveground biomass (AGB) and belowground biomass (BGB)

Total carbon stock (C) was estimated by multiplying the total tree biomass by a conversion factor of 0.50, which represents the average carbon content in tree biomass (IPCC 2006):

Carbon Mitigated (CO_2 Equivalent): Carbon stock content was multiplied by 44/12 to estimate carbon mitigated:

Regeneration studies: In each compartment, 50 recording units were established, each with five 2 × 2 m quadrats laid randomly within 31.62 × 31.62 m^2 tree plots. Regeneration was assessed as recruits (current-year seedlings), unestablished (seedlings <2 m), and established regeneration (>2 m), along with established stocking percentage and regeneration success, following Chacko (1965). The density of recruits, un-established, and established regeneration was estimated following the method described by Chacko (1965).



Selected Forest Compartments for study

Working Circle Map of Rajgarh Forest Division

Fig 1: Map of study area.

Established stocking per cent (ESP)

$$ESP = 100\ (I_1 \times I_2)$$

Where, I_1 and I_2 were calculated by the formulae

$$\text{Establishment Index } (I_1) = \frac{\text{Weighted average height}}{\text{Establishment height}}$$

The weighted height was determined as:

$$\text{Weighted average height (m)} = \frac{\text{Total height of unestablished individuals} + (\text{number of established individuals x establishment height})}{\text{Total unestablished individuals} + \text{Total established individuals}}$$

$$\text{Stocking index } (I_2) = \frac{1}{2500} \quad \frac{(\text{Unestablished individuals regeneration ha}^{-1} + \text{established individuals regeneration ha}^{-1})}{4}$$

Regeneration success

Regeneration success (%) = Stocking index (SI) X 100

Evaluation of forest for normality: In selection system of management, stems (ha^{-1}) and volume were compared with ideal stocking and normal growing stock under Selection forest as given by Singh (1975).

Per cent deviation from normal stems (ha^{-1}) =

$$\frac{\text{Normal stems ha}^{-1} - \text{Observed stems ha}^{-1}}{\text{Normal stems ha}^{-1}} \text{ X } 100$$

Per cent deviation from standard volume (m^3 ha^{-1}) =

$$\frac{\text{Standard Volume-Observed Volume}}{\text{Standard volume}} \text{ X } 100$$

$$\text{Stocking (\%)} = \frac{\text{Observed Volume}}{\text{Standard volume}} \times 100$$

Data analyses: The experimental data were statistically analyzed following Gomez and Gomez (1984), with RBD at 5% for compartment comparisons. OP Stat (Sheoran *et al.,* 1998) was used for statistical tests, while PCA and correlation (Gopinath *et al.,* 2020) identified similarities and variations in biomass and carbon across compartments.

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Results and Discussion

The perusal of data showed that the maximum stem density (586.58 individuals ha^{-1}) was recorded in RF 8 Baer Jamoli C-2a, followed by RF 9 Pajoga C-4e (578.24 individuals ha^{-1}), while the minimum (455.92 individuals ha^{-1}) was in RF 7 Khabbar C-2. RF 9 Pajoga C-4e also showed the highest growing stock (762.94 m^3 ha^{-1}), biomass (AGB 448.80 t ha^{-1}, BGB 140.13 t ha^{-1}, TB 588.93 t ha^{-1}), carbon stock (ABC 224.40 t ha^{-1}, BGC 70.07 t ha^{-1}, TC 294.47 t ha^{-1}), and carbon mitigation (1079.71 t ha^{-1}) (Tables 2, 3). PCA explained 88.24% variance with eigenvalue 7.492 for the first component, with all variables showing strong positive loadings, confirming statistical robustness. PCA effectively identified and separated RF 9 Pajoga C-4e, RF 9 Pajoga C-1a, and RF 10 Sarh C-2e, which were characterized by the highest biomass and carbon stock values. A notable outcome of the PCA biplot was the clear segregation of RF 5 Narh C-3 on the extreme left, indicating its association with the lowest biomass and carbon stock values. (Fig. 2).

The Selection working circle was dominated by *Picea smithiana,* followed by *Abies pindrow*. Total stem density was 522.08 individuals ha^{-1}, ranging from 299.68 individuals ha^{-1} (*P. smithiana*) and 137.61 individuals ha^{-1} (*A. pindrow*) to 3.61 individuals ha^{-1} in *Cedrus deodara* and *Quercus leucotrichophora.* Overall growing stock was 611.95 m^3 ha^{-1} with tree biomass of 360.12 t ha^{-1} (AGB), 106.18 t ha^{-1} (BGB), and 466.30 t ha^{-1} (TB). Carbon stocks were 180.06 t ha^{-1} (AGC), 53.09 t ha^{-1} (BGC), and 233.15 t ha^{-1} (total), with total carbon mitigation of 854.88 t ha^{-1}. Among species, *P. smithiana* recorded the maximum growing stock (420.16 m^3 ha^{-1}), biomass (AGB 241.09, BGB 64.09, TB 305.17 t ha^{-1}), followed by *A. pindrow* (AGB 83.72, BGB 22.25, TB 105.97 t ha^{-1}). The highest tree above ground carbon (120.54 t ha^{-1}), tree below ground carbon (32.04 t ha^{-1}) and tree total carbon (152.59 t ha^{-1}) was observed for *Picea smithiana* followed by *Abies pindrow* with the value of 41.86 t ha^{-1}, 11.13 t ha^{-1} and 52.99 t ha^{-1} for tree above ground carbon, tree below ground carbon and tree total carbon stock respectively (Table 4, 5). The variation in structural attributes, biomass and carbon in different compartments may be due to that *Picea smithiana* and *Abies pindrow* are the main species of selection working circle. *Abies pindrow* predominated at higher altitude an comparision to *Picea simithiana.* The majority of the forests largely mixed stands of fir and spruce, with Kharsu oak (*Quercus semecarpifolia*) and Moru oak (*Quercus floribunda*) at higher elevations, Ban oak (*Q. leucotrichophora*) at lower ranges, and occasional patches of kail and deodar, either pure or mixed with spruce (Table 2).

The total stem density in the selection forest (493–1180 stems ha^{-1}) is comparable to moist temperate forests of Garhwal Himalaya (Gairola *et al.,* 2011a) and Kumaun temperate forests which is 920–1345 stems ha^{-1} (Lodhiyal *et al.,* 2014). Sharma *et al.* (2018) reported the highest mean density (708 ± 153 trees ha^{-1}) in *Abies spectabilis*-*Quercus semecarpifolia* stands. The present growing stock, biomass, and carbon stock in fir-spruce forests exceed earlier estimates for mixed fir-spruce stands (Ahmad *et al.,* 2014), surpass reported volumes of 383.10 m^3 ha^{-1} (Haripriya, 2000), and align with higher carbon ranges reported by Sharma *et al.,* 2008. Biomass across the Himalaya varies widely, from 1158 t ha^{-1} in Himachal Pradesh (Sharma *et al.,* 2008) and 215.5–486.2

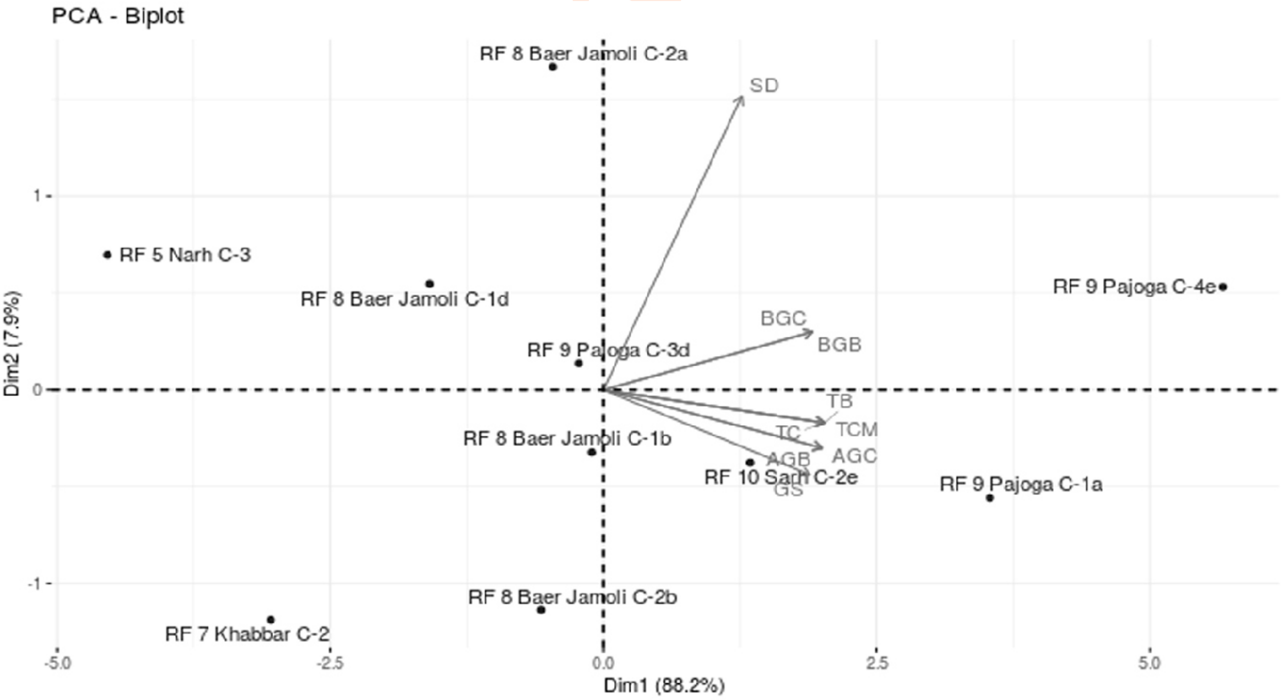

Fig. 2: Principal component analysis of structural attributes biomass carbon and study sites.

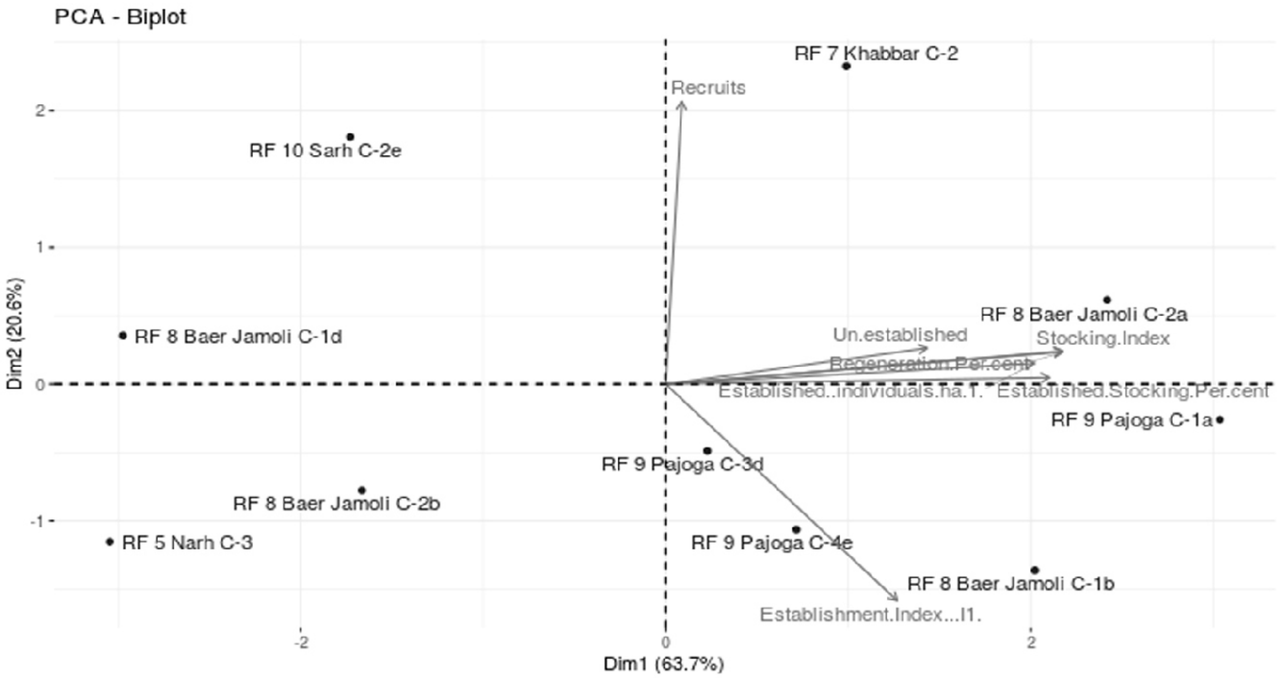

Fig. 3: Principal component analysis of regeneration attributes and study sites.

Table 1: List of volumetric equations and species specific gravity values used in the present study

Species	Volume Equations	Wood Density (g cm^{-3})
Picea smithiana	V=0.151+0.232D2H	0.380
Abies pindrow	V=0.859831+0.250497D2H	0.340
Quercus dilatata	V/D2=0.0988/D2-1.5547/D+10.1631	0.826
Quercus semecarpifolia	V=0.08355+1.28586D+8.76867D2+1.12150D3	0.826
Pinus wallichiana	V=0.2232-2.3509D+11.9067D2	0.427
Rhododendron arboreum	V=-0.02861+2.3069D-023517D2	0.512

Mg ha^{-1} in Garhwal (Gairola *et al.,* 2011c) to 546.7–695.1 Mg ha^{-1} in temperate old-growth forests of Italy (Di Matteo *et al.,* 2023). Carbon stocks in Indian Himalayas range from 59.20–270.98 Mg C ha^{-1} (Gairola *et al.,* 2011b; Sharma *et al.,* 2018; Haq *et al.,* 2022; Tiwari *et al.,* 2023), though present values remain lower than the higher biomass (566.17–1280.79 Mg ha^{-1}) and carbon (258.22–577.77 Mg C ha^{-1}) reported by Kaushal and Baishya (2021) (Table 3). Abiotic and biotic factors strongly influence the biomass and carbon, with local topography (elevation, slope, and aspect) further affecting species survival, regeneration density, and composition (Liang and Wei, 2021) (Fig. 2,3). Table 6 shows that the maximum recruits were recorded in RF 7 Khabbar C-2 (2777.78 individuals ha^{-1}), followed by RF 10 Sarh C-2e (2222.22 individuals ha^{-1}), while the minimum recruits (833.33 individuals ha^{-1}) occurred in RF 8 Baer Jamoli C-1b and RF 9 Pajoga C-4e. Unestablished regeneration peaked in RF 8 Baer Jamoli C-2a (2777.78 individuals ha^{-1}), whereas established regeneration was highest in RF 9 Pajoga C-1a (833.33 individuals ha^{-1}).

The maximum establishment index (I_1=2.11) and per cent stocking (31.39%) were also observed in RF 9 Pajoga C-1a, while RF 8 Baer Jamoli C-2a showed the highest stocking index (I_2= 0.50) and regeneration percentage (50.00%), with the minimum (13.89%) in RF 5 Narh C-3. PCA explained 63.67% variance across six components (eigenvalues: 4.456–0.012), with all variables showing strong positive loadings on the first component. PCA separated compartments with higher regeneration (RF 8 Baer Jamoli C-2a, RF 9 Pajoga C-1a, RF 8 Baer Jamoli C-1b, RF 9 Pajoga C-4e, RF 9 Pajoga C-3d) from those with lower regeneration (RF 10 Sarh C-2e, RF 5 Narh C-3, RF 8 Baer Jamoli C-2, RF 8 Baer Jamoli C-2b) (Fig. 3).

The regeneration status of species in the selection working circle is summarized in Table 7. Overall values recorded were 1444.44 recruits ha^{-1}, 1472.22 unestablished ha^{-1}, 444.44 established ha^{-1}, establishment index (I_1) 1.52, stocking index (I_2)

Table 2: Growing stock and carbon stock in compartments of Fir-Spruce forest (Selection working circle)

Forest compartments	Stem density (SD) (Individual ha^{-1})	Growing stock (GS) (m^3 ha^{-1})	Biomass (t ha^{-1})		
			Tree AGB (t ha^{-1})	Tree BGB (t ha^{-1})	Tree TB (t ha^{-1})
RF 7 Khabbar C-2	455.92±23.04^{h}	544.29±16.21^{h}	317.37±17.02^{h}	88.13±7.30^{g}	405.5±19.45^{h}
RF 8 Baer Jamoli C-2b	480.9±15.99^{g}	625.19±35.48^{d}	362.63±6.14^{d}	98.97±9.87^{e}	461.60±14.60^{e}
RF 8 Baer Jamoli C-1b	511.52±26.52^{f}	613.48±16.86^{e}	363.06±18.83^{d}	103.92±13.33^{d}	466.99±7.75^{d}
RF 8 Baer Jamoli C-2a	586.58±17.15^{a}	570.56±41.21^{g}	344.97±7.41^{f}	102.50±4.09^{d}	447.47±4.54^{f}
RF 5 Narh C-3	486.50±32.58^{g}	373.66±46.74^{i}	264.47±11.99^{i}	95.95±5.28^{f}	360.42±12.20^{i}
RF 8 Baer Jamoli C-1d	539.32±36.29^{c}	605.00±21.46^{f}	329.20±14.04^{g}	94.84±5.38^{f}	424.04±7.81^{g}
RF 9 Pajoga C-1a	533.76±45.35^{cd}	755.99±32.76^{b}	426.22±9.20^{b}	121.70±11.99^{b}	547.92±2.93^{b}
RF 9 Pajoga C-3d	528.20±56.54^{d}	613.75±10.39^{e}	356.09±16.73^{e}	103.93±5.11^{d}	460.02±10.69^{e}
RF 9 Pajoga C-4e	578.24±23.92^{b}	762.94±30.57^{a}	448.80±11.43^{a}	140.13±9.91^{a}	588.93±6.74^{a}
RF 10 Sarh C-2e	519.86±50.67^{e}	654.62±22.84^{c}	388.36±9.41^{c}	111.75±7.87^{c}	500.11±0.67^{c}
CD (0.05)	60.84	49.141	22.531	15.208	19.285

Table 3: Carbon stock and total carbon mitigated in compartments of Fir-Spruce forest (Selection working circle)

Forest compartments	Carbon stock (t ha^{-1})			Tree Total CO_2 mitigated (TCM) (t ha^{-1})
	Tree AGC (t ha^{-1})	Tree BGC (t ha^{-1})	Tree TC (t ha^{-1})	
RF 7 Khabbar C-2	158.69 ±8.51^{g}	44.07±3.65^{g}	202.75±9.72^{g}	743.43±35.59^{h}
RF 8 Baer Jamoli C-2b	181.32±3.07^{d}	49.48±4.94^{def}	230.80±7.30^{d}	846.27±26.71^{e}
RF 8 Baer Jamoli C-1b	181.53±9.42^{d}	51.96±6.66^{d}	233.49±3.87^{d}	856.14±14.18^{d}
RF 8 Baer Jamoli C-2a	172.48±3.71^{e}	51.25±2.04^{de}	223.73±2.27^{e}	820.35±8.30^{f}
RF 5 Narh C-3	132.23±6.00^{h}	47.98±2.64^{ef}	180.21±6.10^{h}	660.78±22.33^{i}
RF 8 Baer Jamoli C-1d	164.60±7.02^{f}	47.42±2.69^{fg}	212.02±3.91^{f}	777.40±14.30^{g}
RF 9 Pajoga C-1a	213.11±4.60^{b}	60.85±6.00^{b}	273.96±1.46^{b}	1004.52±5.35^{b}
RF 9 Pajoga C-3d	178.05±8.36^{d}	51.96±2.55^{d}	230.01±5.34^{d}	843.37±19.56^{e}
RF 9 Pajoga C-4e	224.40±5.71^{a}	70.07±4.96^{a}	294.47±3.37^{a}	1079.71±12.34^{a}
RF 10 Sarh C-2e	194.18±4.70^{c}	55.88±3.93^{c}	250.06±0.34^{c}	916.88±1.23^{c}
CD (0.05)	11.26	7.61	9.64	35.30

0.33, established stocking 18.70%, and regeneration 32.50%. Eight tree species were observed across regeneration stages: four as recruits, six as unestablished, and two as established. *Picea smithiana* (833.33 ha^{-1}) and *Abies pindrow* (388.89 ha^{-1}) dominated recruits, while *P. smithiana* (722.22 ha^{-1}) and *Quercus dilatata* (277.78 ha^{-1}) showed the highest unestablished regeneration. Established regeneration was highest in *P. smithiana* (361.11 ha^{-1}), followed by *A. pindrow* (83.33 ha^{-1}), with none in *Q. dilatata, Q. leucotrichophora, Q. semecarpifolia, Rhododendron arboreum, Cedrus deodara* and *Pinus wallichiana.* Maximum I_1 (0.58), I_2 (0.22), and establishment stocking (13.33%) were recorded in *P. smithiana.* Based on percent regeneration, *P. smithiana* (21.67%) was dominant, followed by *A. pindrow* (5.28%), *Q. dilatata* (2.78%), *Q. semecarpifolia* (1.94%), *R. arboreum* (0.56%), and *Q. leucotrichophora* (0.28%), while *P. wallichiana* and *C. deodara* showed nil regeneration. Regeneration and stocking percentages varied across compartments due to site-specific factors such as microclimate, silvicultural history, grazing, and anthropogenic disturbance. Natural regeneration is influenced by abiotic and biotic factors (Liang and Wei, 2021), including grazing, browsing, trampling, seed predation, and fuelwood collection. Topography, elevation, slope, and aspect also shape species composition and regeneration success (Redmond and Kelsey, 2018), while understory competition was greater in low- and medium-density stands. Variation reflected dominance of *Picea smithiana* and *Abies pindrow,* with spruce regenerating better due to its pioneer nature and light demand (Lone *et al.*, 2018), whereas fir showed weaker regeneration linked to fewer mother trees at lower altitudes. These results align with Singh *et al.* (2011), who reported spruce regeneration at lower elevations and fir at higher elevations and also with the findings of Lone *et al.* (2018), who emphasized better regeneration under selection systems with minimal biotic pressure.

In selection forest, the observed stems (522.08 ha^{-1}) and observed volume (611.95 m^3 ha^{-1}) was recorded higher than that of the standard ideal stems (412.50 ha^{-1}) and standard volume (372.19 m^3 ha^{-1}). The per cent deviation from ideal stems and volume was observed +26.57 and + 64.42, respectively. Stocking was observed to be 1.64, which was higher than the normal stocking, *i.e.,* one. Based on this, it can be concluded that

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Table 4: Growing stock and carbon stock of different species in Fir-Spruce forest (Selection working circle)

Species	Stem density (SD)	Growing stock (GS)	Biomass (t ha^{-1})		
	(individuals ha^{-1})	(m^3 ha^{-1})	AGB (t ha^{-1})	BGB (t ha^{-1})	TB (t ha^{-1})
Picea smithiana	299.68	420.16	241.09	64.09	305.17
Abies pindrow	137.61	163.07	83.72	22.25	105.97
Quercus dilatata	28.63	9.8	15.46	9.88	25.34
Quercus semecarpifolia	20.57	5.19	8.19	5.24	13.43
Pinus wallichiana	18.9	9.56	7.8	2.88	10.68
Rhododendron arboreum	9.45	1.42	1.09	0.36	1.46
Cedrus deodara	3.61	1.69	1.11	0.41	1.52
Quercus leucotrichophora	3.61	1.05	1.66	1.06	2.73
Total	522.08	611.95	360.12	106.18	466.30

Table 5: Growing stock and carbon stock of different species in Fir-Spruce forest (Selection working circle)

Species	Carbon stock (t ha^{-1})			Total CO_2 mitigated (TCM) (t ha^{-1})
	AGC (t ha^{-1})	BGC (t ha^{-1})	Total carbon (TC) (t ha^{-1})	
Picea smithiana	120.54	32.04	152.59	559.48
Abies pindrow	41.86	11.13	52.99	194.29
Quercus dilatata	7.73	4.94	12.67	46.45
Quercus semecarpifolia	4.1	2.62	6.72	24.62
Pinus wallichiana	3.9	1.44	5.34	19.59
Rhododendron arboreum	0.55	0.18	0.73	2.67
Cedrus deodara	0.55	0.21	0.76	2.78
Quercus leucotrichophora	0.83	0.53	1.36	5.00
Total	180.06	53.09	233.15	854.88

Table 6: Natural regeneration in selected compartments of Fir-Spruce forest (Selection working circle)

Forest compartments	Recruits (ind. ha^{-1})	Un established (ind. ha^{-1})	Established (ind. ha^{-1})	Establishment Index (I_1)	Stocking Index (I_2)	Established Stocking (%)	Regeneration (%)
RF 7 Khabbar C-2	2777.78	1666.67	555.56	1.26	0.39	23.63	38.89
RF 8 Baer Jamoli C-2b	1111.11	1111.11	277.78	1.56	0.22	13.06	22.22
RF 8 Baer Jamoli C-1b	833.33	1944.44	555.56	2.07	0.42	26.24	41.67
RF 8 Baer Jamoli C-2a	1388.89	2777.78	555.56	1.42	0.50	21.60	50.00
RF 5 Narh C-3	1111.11	1388.89	0.00	1.70	0.14	5.61	13.89
RF 8 Baer Jamoli C-1d	1388.89	555.56	277.78	0.93	0.17	10.35	16.67
RF 9 Pajoga C-1a	1666.67	1388.89	833.33	2.11	0.47	31.39	47.22
RF 9 Pajoga C-3d	1111.11	1111.11	555.56	1.54	0.33	21.30	33.33
RF 9 Pajoga C-4e	833.33	1388.89	555.56	1.74	0.36	20.94	36.11
RF 10 Sarh C-2e	2222.22	1388.89	277.78	0.88	0.25	12.85	25.00

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selection forest was overstocked having higher stem density than normal. The stems per hectare deviation from ideal stems in different diameter classes, maximum per cent (+233.60) deviation was observed in diameter class ID (>90) followed by IIA (127.33 %), while minimum (-21.17 %) was observed in diameter class V (10-20) from normal/ideal stems (Table 6). The maximum stocking was observed (3.17) in diameter class ID (>90) followed by IIA (2.27), while minimum (0.66) was observed in diameter class V (10-20). Based on this it can be concluded that diameter classes from III to I D in selection forest were overstocked and higher stems per hectare than the normal and diameter classes V to IV were understocked (Table 8). The diameter distribution exhibited an uneven size structure, characterized by a monotonically decreasing tree density with increasing diameter class, up to the largest DBH class. These results are consistent with the patterns reported for other forest stands in the Himalayan region (Haq *et al.,* 2022). The results are corroborate with the findings of Nizami *et al.* (2005), who reported that the growing stock in the pine forests of Ghoragali deviated significantly from normal distribution across diameter classes. This deviation was

Table 7: Natural regeneration of different species in Fir-Spruce Forest (Selection working circle)

Species	Recruits (ind. ha^{-1})	Un established (ind. ha^{-1})	Established (ind. ha^{-1})	Establishment Index (I_1)	Stocking Index (I_2)	Established Stocking (%)	Regeneration (%)
Picea smithiana	833.33	722.22	361.11	0.58	0.22	13.33	21.67
Abies pindrow	388.89	194.44	83.33	0.33	0.05	3.22	5.28
Pinus wallichiana	166.67	0.00	0.00	0.00	0.00	0.00	0.00
Cedrus deodara	55.56	0.00	0.00	0.00	0.00	0.00	0.00
Quercus dilatata	0.00	277.78	0.00	0.32	0.03	1.07	2.78
Quercus leucotricho-phora	0.00	27.78	0.00	0.03	0.00	0.07	0.28
Quercus semecar-pifolia	0.00	194.44	0.00	0.20	0.02	0.83	1.94
Rhodo-dendron arboreum	0.00	55.56	0.00	0.07	0.01	0.18	0.56
Total	1444.44	1472.22	444.44	1.52	0.33	18.70	32.50

Table 8: Stems and volume per cent deviation from normal stems and volume among different diameter classes in Fir-Spruce forest (Selection working circle)

Diameter Classes	Normal stems* (ha^{-1})	Observed stems (ha^{-1})	Per cent deviation from normal stems (ha^{-1})	Standard volume* (m^3 ha^{-1})	Observed volume (m^3 ha^{-1})	Per cent deviation from standard volume (m^3 ha^{-1})	Stocking
V(10-20)	152.00	119.82	-21.17	18.39	12.16	-33.88	0.66
IV(20-30)	108.70	112.59	3.58	30.78	26.43	-14.12	0.86
III(30-40)	65.00	122.04	87.76	55.20	110.51	100.19	2.00
IIA(40-50)	39.50	89.79	127.33	67.17	152.71	127.35	2.27
IIB(50-60)	22.70	46.70	105.74	65.49	137.82	110.44	2.10
IA(60-70)	12.30	16.68	35.61	52.47	73.15	39.42	1.39
IB(70-80)	7.40	9.17	23.97	44.08	57.70	30.91	1.31
IC(80-90)	4.40	3.61	-17.86	34.00	26.83	-21.08	0.79
ID(>90)	0.50	1.67	233.60	4.61	14.63	217.32	3.17
Total	412.50	522.08	26.57	372.19	611.95	64.42	1.64

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attributed to poor implementation of previous management plans and mismanagement following the government imposed ban on green felling after 1985. The absence of extraction and stand management practices has led to abnormal forest conditions, affecting regeneration, forest health, and stocking.

This study assessed biomass, carbon stock, regeneration, and forest normality in Fir-Spruce forests of Himachal Pradesh. The forests demonstrated high carbon storage potential and acted as significant carbon sinks. *Picea smithiana* emerged as the dominant species in terms of biomass and growing stock contribution. However, regeneration was found to be suboptimal, with some species showing no regeneration at all. The forests were also overstocked, especially in higher diameter classes, reflecting an imbalanced stand structure. These findings highlight the need for silvicultural interventions to improve regeneration and restore ecological stability.

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