

ORIGINAL ARTICLE

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Ecosystem carbon storage, allocation and carbon credit values of major forest types in the central Himalaya

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Abstract

Himalayan forests are crucial global carbon reservoirs that contribute significantly to carbon mitigation efforts. Although situated within a single climatic zone, Himalayan forests include diverse forest types within a short distance due to variations in altitude, mountain range, slope, and aspect. This study aimed to estimate ecosystem carbon storage (including plant biomass, deadwood, litter, and soil organic carbon [SOC]) and allocation and to evaluate carbon sequestration and carbon credit potential in chir-pine plants (*Pinus roxburghii* Sarg.), deodar (*Cedrus deodara* [Roxb.] G. Don), oak (*Quercus leucotrichophora* A. Camus), and sal (*Shorea robusta* [Roth]) forests in the central Himalaya. Volumetric equations were utilized across diverse tree species and supplemented by field sampling, particularly by employing the quadrat method to quantify tree biomass. The carbon stocks within ecosystems varied considerably, ranging between 122.44 and 306.44 Mg C ha⁻¹, with discernible differences among forest types, with oak forests exhibiting the highest carbon stock, followed by deodar and sal forests, and pine forests showing the lowest. The allocation of ecosystem carbon stocks among the different components, including trees (21%–34%), soil (64%–77%), deadwood (0.9%–0.35%), and litter (0.46%–1.20%), demonstrated significant variability. The Mantel test revealed the significant influence of environmental factors on carbon storage. Carbon dioxide (CO₂) sequestration ranged from 448.98 (pine forest) to 1123.16 (oak forest) Mg CO₂ ha⁻¹, while carbon credit values ranged from 1346.96 EUR ha⁻¹ (pine forests) to 3379.49 EUR ha⁻¹ (oak forest). In this study, dominant trees in various forest types contributed to higher carbon storage in their biomass and forest soil, resulting in greater carbon credits. The present research evaluated ecosystem carbon storage, CO₂ sequestration potential, and carbon credit valuation for major forests in the central Himalaya. By incorporating these findings into forest management plans and strategies, the carbon sequestration potential and carbon trading of the central Himalayan forest ecosystem in India can be enhanced.

Highlights

- Oak forests demonstrated the greatest carbon stock, followed by deodar and sal forests.
- The carbon allocation among the plant, soil, deadwood, and litter components varied significantly.
- The potential for carbon dioxide sequestration varied between 448.98 Mg CO₂ ha⁻¹ and 1123.16 Mg CO₂ ha⁻¹.
- Carbon credit values ranged from 1346.96 EUR ha⁻¹ for pine forests to 3379.49 EUR ha⁻¹ for oak forests.
- The storage of soil organic carbon (SOC) stock varied between 64% and 77% across different forests.

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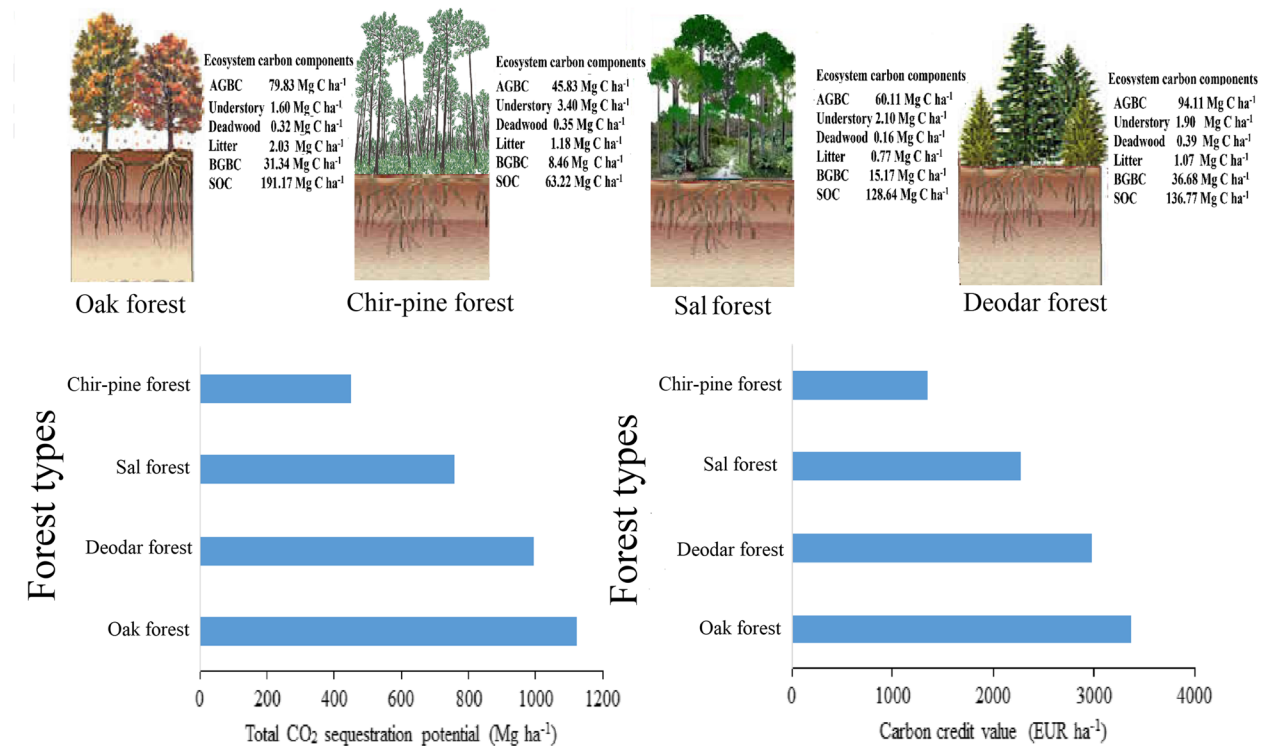
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Keywords Carbon sequestration, Ecosystem carbon components, Soil organic carbon, Above- and belowground carbon, Environmental factors, Soil properties

Graphical Abstract



1 Introduction

Forests are crucial components of the global carbon cycle and act as important repositories for carbon storage and essential agents for carbon sequestration. Forests act as carbon sinks, making it crucial to measure their ability to absorb carbon for global climate change mitigation. This process helps reduce the impact of human-induced carbon emissions on climate change (Sha et al. 2022). Carbon storage in forests refers to the quantity of carbon dioxide (CO₂) absorbed and retained within living biomass, soils, and detritus (Mukul et al. 2020). Forests serve as vast carbon reservoirs, capturing atmospheric CO₂ via photosynthesis and retaining it within organic material (Pan et al. 2011, 2013). Diverse forest ecosystems exhibit distinct carbon sequestration abilities and are impacted by elements such as species diversity, age of forest, density, and environmental conditions such as altitude, slope, aspect, temperature, precipitation, and management

strategies (Pregitzer et al. 2004). Comprehending these subtleties holds utmost importance in precisely evaluating the carbon reserves within forests and devising efficient approaches for their conservation and management.

Additionally, forests are vital for carbon sequestration and involve the extended process of extracting CO₂ from the air and integrating it into plant life and soil (Lal et al. 2018). Trees engage in the process of photosynthesis, wherein they take up CO₂ and transform it into carbohydrates and other organic substances (Prescott 2022). A fraction of this carbon is sequestered within tree biomass, with the rest being distributed among subterranean components such as organic matter in the soil (Augusto and Boča 2022). By measuring carbon sequestration rates in various forest ecosystems, we can understand the factors influencing carbon dynamics and pinpoint strategies to boost sequestration through specific management actions.

Carbon credits have emerged as a crucial tool for promoting forest conservation and sustainable management practices (West et al. 2023). These credits are largely determined by a forest's capacity for carbon sequestration, which depends on factors such as biomass productivity, soil carbon storage, and forest management methods (Mäkipää et al. 2023). Developed to measure and monetize this sequestration potential, carbon credits incentivize sustainable practices by attributing economic value to the carbon stored in forests (Akita and Ohe 2021). These products are tradable commodities on carbon markets and represent the right to emit one metric ton of CO₂ or an equivalent amount of other greenhouse gases (IPCC 2023). Understanding the value of carbon credits is essential, especially in the context of global agreements such as the Kyoto Protocol and the Paris Agreement, which emphasize reducing carbon emissions (Maizland 2021). Forests that capture and retain CO₂ can produce carbon credits, which are purchasable by organizations aiming to mitigate their carbon emissions (Conference of Parties 26 [COP26] 2021). Different forest types offer varying potential for carbon credit generation, influenced by factors such as carbon stock density, growth rates, and market demand (Putney et al. 2023). In addition to vegetation-related factors, topography and soil characteristics also affect sequestration rates (Dixon et al. 1994).

The Himalayan region serves as a vital global carbon reservoir, garnering considerable interest in research and management initiatives focused on comprehending carbon storage dynamics. Its importance is evident in its extensive scope and the nuanced diversity found within what appears to be a homogeneous climatic region. These factors include the intricate interplay of altitudes, mountain ranges, slopes, and aspects and the resulting microclimates (Garkoti 2007). The diversity of forest compositions over relatively short distances presents a distinctive challenge and opportunity for understanding ecosystem carbon dynamics comprehensively (Manish and Pandit 2018). The central Himalayan region is characterized by various forest types, each possessing a distinct composition, structure, and ecological role. Within this diverse landscape, one encounters tropical, subtropical, temperate, and alpine forest ecosystems, each exerting varied influences on the carbon sequestration process (Singh and Singh 1992).

Tropical and subtropical forests, commonly situated at lower altitudes, are distinguished by their lush canopies and rich biodiversity in the central Himalaya (Sati 2023). These features facilitate significant carbon retention in aboveground vegetation and below the soil surface. Conversely, temperate forests at mid-elevations

and alpine forests at higher altitudes exhibit unique carbon dynamics shaped by their specific climatic conditions and vegetation compositions (Gupta et al. 2024). In recent years, there has been a surge in interest surrounding the valuation of carbon credits attributed to different forest types within India (Roy and Bhan 2024). This heightened attention has arisen from the growing acknowledgment of forests as pivotal carbon sinks. Comprehending carbon credit values across diverse forest types in the central Himalaya is essential for environmental conservation and economic sustainability (Verma et al. 2024). This understanding facilitates the development of tailored conservation strategies while providing tangible financial incentives to promote sustainable forest management practices. Determining the carbon credit values of various forest types in the central Himalaya enables policymakers to create effective conservation strategies. Understanding the carbon sequestration potential of these forests is crucial for devising effective climate change mitigation strategies and implementing carbon offset programs. This study seeks to quantify the carbon credit values and the factors influencing carbon sequestration in major forest types of the central Himalaya, filling a critical knowledge gap. The findings can guide policymakers, conservationists, and local communities in preserving these ecosystems.

The present study aims to bridge the identified research gap by comprehensively evaluating ecosystem carbon storage, allocation, and carbon credit values within four primary forest types in the central Himalayan region. Specifically, this study focused on a chir-pine (*Pinus roxburghii* Sarg.), deodar (*Cedrus deodara* [Roxb.] G. Don), oak (*Quercus leucotrichophora* A. Camus), and sal (*Shorea robusta* [Roth] forests represent key vegetation types in the region. We hypothesized that the diversity of tree species and forest types in the central Himalaya, driven by variations in altitude, mountain ranges, slopes, and aspects, would result in significant differences in ecosystem carbon storage, CO₂ sequestration, and carbon credit valuation, with oak (*Quercus leucotrichophora*) forests exhibiting the highest carbon stock and sequestration capacity due to greater biomass and soil carbon content, thereby contributing more substantially to carbon mitigation efforts than did chir-pine (*Pinus roxburghii*), deodar (*Cedrus deodara*), and sal (*Shorea robusta*) forests. This study provides significant insights into the carbon dynamics of Himalayan forests, aligning with India's goals under the REDD+ policy and promoting sustainable forest management practices in the region. This research has two main objectives:

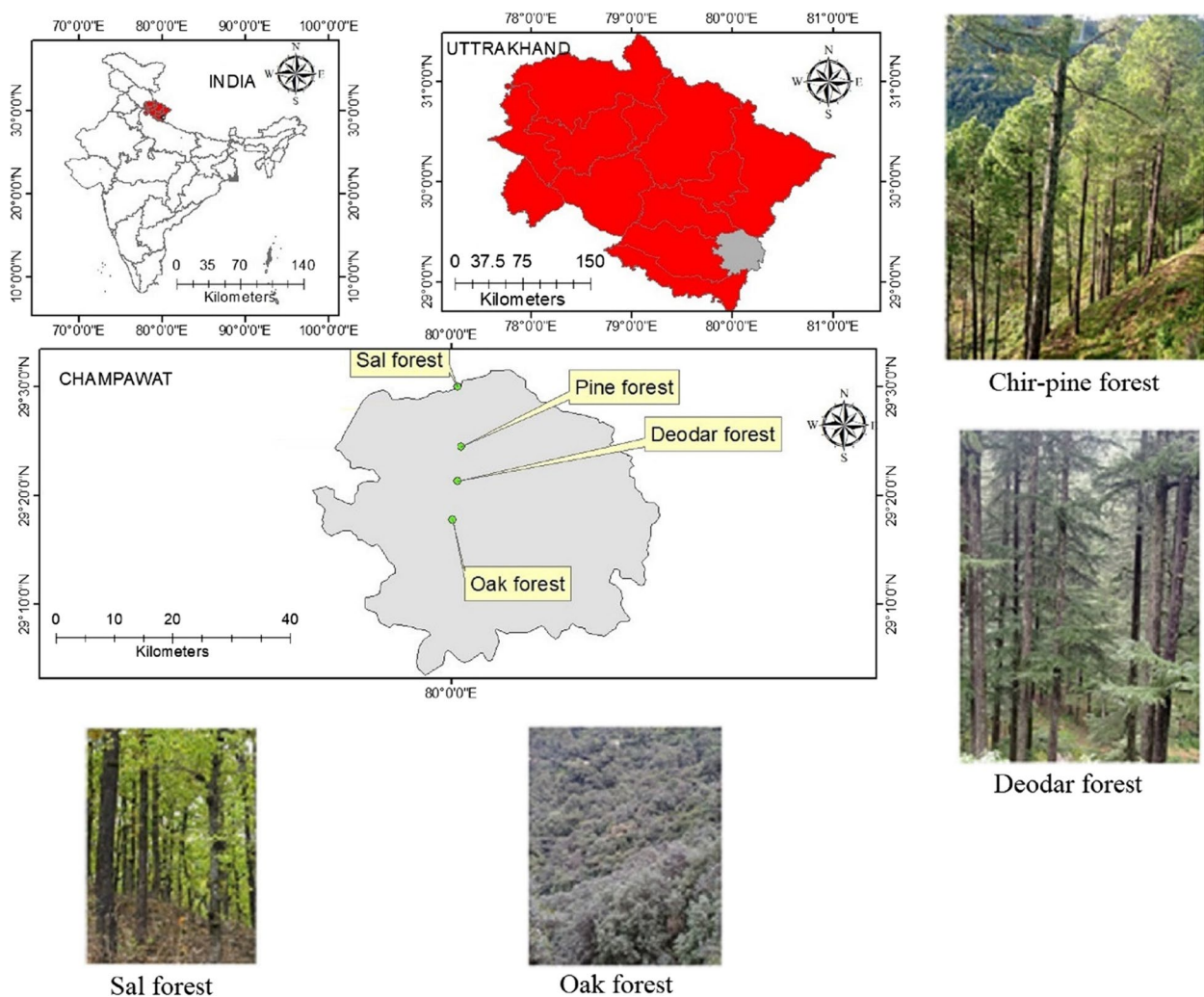


Fig. 1 Study site locations of different forest types in the Champawat district, Uttarakhand, India

1. To measure ecosystem carbon stocks, including plant biomass, deadwood, litter, and soil organic carbon, and to analyze the differences in carbon storage among various forest types. This approach will help us understand the diversity in carbon storage patterns and identify the factors influencing these differences.
2. The CO_2 sequestration potential and corresponding carbon credit values for the different forest types were assessed. By assigning monetary value to carbon credits, this study aims to provide insights into the economic implications of forest conservation and highlight the benefits of incorporating carbon trading mechanisms into climate change mitigation strategies.

2 Materials and methods

2.1 Study area

The research was conducted in the Champawat district, which is situated in the Kumaun division of Uttarakhand

and nested within the central Indian Himalayas. Geographically, the region lies between $29^{\circ}30'12.53''$ N and $29^{\circ}29'48.56''$ N and $80^{\circ}06'03.83''$ E and $80^{\circ}07'10.62''$ E, encompassing elevations ranging from 1200 to 1828 m above sea level (Fig. 1; Table 1). The area has a humid subtropical monsoon to moist temperate climate, marked by clear distinctions between the wet and dry seasons. The typical monthly maximum temperature ranges from 13°C in January to 36°C in June. Similarly, the average monthly low temperature varies from 1°C in January to 19°C in June. The average monthly rainfall ranges from 8.8 mm in November to 885.5 mm in July, with a total of 3057.8 mm annually, and is mainly concentrated between mid-June and mid-September. Additionally, moderate to heavy snowfalls occur during the winter season. The soil in the study area is moderately deep and characterized by good drainage and a fine sandy loam texture. It tends to have an acidic pH and shows slight stoniness. The key

Table 1 Geographical and forest characteristics

Parameter	Pine forest	Deodar forest	Oak forest	Sal forest
Type (according to Champion and Seth 1968)	9/C ₁ b	12/C ₁ c	12/C ₁ a	3B/C ₁ A
Altitude (m a.s.l.)	1787.95	1687.67	1635.86	828.14
Slope (°)	24.43	18.32	21.32	26.65
Latitude (N°)	29°24'29.05"	29°21'18.88"	29°17'46.10"	29°30'00.73"
Longitude (E°)	80°07'47.19"	80°05'29.97"	80°06'01.73"	80°06'32.43"
Density (Tree ha ⁻¹)	620	740	960	810
Total basal area (m ² ha ⁻¹)	39.45	58.64	49.23	52.13
Dominant tree species	<i>P. roxburghii</i>	<i>C. deodara</i>	<i>Q. leucotrichophora</i> , <i>R. arboreum</i> , <i>P. pashia</i> , <i>L. ovalifolia</i>	<i>S. robusta</i>
BD (g cm ⁻³)	1.05 ± 0.03	1.17 ± 0.02	1.22 ± 0.027	1.31 ± 0.03
Porosity (%)	61.2 ± 1.16	56.82 ± 0.83	55.15 ± 1.0	51.72 ± 1.11
Sand (%)	31.06 ± 0.66	36.93 ± 0.88	31.13 ± 1.0	40.8 ± 0.9
Silt (%)	29.66 ± 0.89	27.2 ± 0.95	40.66 ± 0.87	29.26 ± 0.9
Clay (%)	39.26 ± 1.09	35.86 ± 1.38	28.2 ± 1.0	29.93 ± 1.42
Moisture (%)	6.58 ± 0.17	7.72 ± 0.26	10.54 ± 0.48	5.91 ± 0.23
WHC (%)	44.10 ± 0.97	50 ± 1.25	58.64 ± 1.17	45.8 ± 0.75
Soil EC (d S m ⁻¹)	0.14 ± 0.06	0.20 ± 0.01	0.26 ± 0.02	0.18 ± 0.08
Soil pH	6.34 ± 0.04	5.86 ± 0.08	5.56 ± 0.89	6.28 ± 0.76
SOC (g kg ⁻¹)	14.35 ± 2.27	23.16 ± 2.6	30.86 ± 3.3	16.55 ± 2.6
TN (g kg ⁻¹)	1.41 ± 0.14	1.68 ± 1.6	2.20 ± 0.27	1.22 ± 0.18
TP (g kg ⁻¹)	0.57 ± 0.08	0.70 ± 0.07	0.86 ± 0.06	0.39 ± 0.07

BD Bulk density, WHC Water holding capacity, EC Electrical conductivity, SOC Soil organic carbon, TN Total nitrogen, TP Total phosphorus

forest types in the study area include the chirpine (*Pinus roxburghii* Sarg.), deodar (*Cedrus deodara* [Roxb.] G. Don), oak (*Quercus leucotrichophora* A. Camus), and sal (*Shorea robusta* [Roth] forests within the Shivalik range. The specific geographic and ecological attributes of the study forests are delineated in Table 1.

2.2 Experimental design and field measurements

Through field investigations, we categorized the distribution areas of coniferous (pine forest and deodar forest) and broad-leaved (sal forest and oak forest) forests and established survey plots for each forest type. The terrains of the study area consist of low- to mid-elevation hills, with altitudes ranging from 850 to 1,750 m. Variations in altitude, slope, and aspect lead to significant changes in environmental factors, which subsequently influence vegetation growth, soil properties, and tree species composition. For each selected forest type, we established a single plot spanning 0.1 hectares, positioned across diverse orientations: northeast, northwest, southeast, and southwest. We specifically targeted trees with a diameter at breast height (DBH) ≥ 10 cm, following the criteria outlined by Knight (1963), for measurement. The DBH of each tree within the plots was assessed using a tape measure, while the height of each plant was recorded using a Ravi multimeter. The stem density at

each site was calculated by counting all trees with a DBH of 10 cm or more within a plot. As a result, our investigation included a total of 16 forest stands (4 × 4 = 16 forest stands). In every stand, we established ten sample plots, each with dimensions of 10 m × 10 m, resulting in a total of 40 plots within a specific forest type to comprehensively capture the entire altitudinal gradient (Table 1).

2.3 Estimation of tree biomass and carbon stock

We assessed quantitative plant factors such as the DBH, height, and stem density to calculate the growing stock volume density (GSVD m³ ha⁻¹) for each tree species. This was accomplished using specific-to-species regional allometric volume equations developed by the Forest Research Institute (FRI) and the Forest Survey of India (FSI). The determination of aboveground biomass density (AGBD) involved the multiplication of GSVD by the biomass expansion factor (BEF), utilizing methodologies outlined by Brown et al. (1999) and Sharma et al. (2010). The regression equation developed by Cairns et al. (1997) was used to estimate the belowground biomass density (BGBD) for each forest type. The AGBD and BGBD were combined to obtain the total biomass density (TBD). The allometric equation formulated by Delaney et al. (1998) was used to calculate deadwood biomass. The total carbon density (TCD) was estimated by Eq. (1):

$$\text{Carbon (C Mg ha}^{-1}\text{)} = \text{Biomass (Mg ha}^{-1}\text{)} \times \text{Carbon percentage} \quad (1)$$

For the forest types, the C stock was calculated by multiplying the dry weight with the corresponding C content (46% to 50%) (IPCC 2006; Joshi and Garkoti 2021a).

2.4 Estimation of understory and litter carbon stocks

The biomass of the understory plants, which included herbs and shrubs, was assessed using the harvest method following the guidelines established by Joshi and Garkoti

soil over a half-submerged water tray. The soil organic carbon (SOC) was quantified using swift titration techniques following the protocol established by Walkley and Black (1934). The top of total soil nitrogen (N) was estimated via micro Kjeldahl digestion, and total phosphorus (TP) was measured using a UV-119 spectrophotometer following Misra's procedure (1968). The determination of the soil organic carbon (SOC) stock involved the use of Eq. (2), developed by Joshi and Garkoti (2023b).

$$\text{SOC (Mg ha}^{-1}\text{)} = \frac{\text{SOC concentration (g kg}^{-1}\text{)} \times D \times BD \times (1 - G)}{10} \quad (2)$$

(2021a). To assess shrub biomass, three quadrats measuring 5 m × 5 m were established alongside an equal number of 1 m × 1 m quadrats designated for forest floor litter and herbaceous biomass (Joshi and Garkoti 2020). We assessed the fresh weight of the litter components and understory in the field, and we collected representative samples that were subsequently dried at 64 °C in the laboratory until a consistent weight was achieved. The samples were dried and weighed to estimate the understory carbon stocks, and their carbon content was subsequently examined.

2.5 Estimation of soil properties and soil carbon stock

Soil samples were collected in a randomized manner from every plot within various forest types employing the plumblossom technique. Using a soil auger with a 5 cm diameter, samples were taken at three different depths: 0–10 cm, 10–30 cm, and 30–60 cm. This procedure led to the acquisition of 60 soil samples, comprising four locations, each with five plots, and encompassing three different soil depths. The freshly collected soil samples were meticulously placed into plastic bags and then brought to the laboratory. The soil samples were sieved in the laboratory with a mesh size of less than 2 mm to eliminate any discernible roots, stones, or plant debris. One portion of the composite sample was analyzed per Misra's method (1968) for soil physical properties, including texture, porosity, moisture content, and water-holding capacity (WHC), across all study sites. The soil texture was assessed using the hydrometer method (Bouyoucos 1962). The moisture content (%) was determined gravimetrically by drying the soil at 104 °C until a constant weight was reached. The soil electrical conductivity (EC) and pH were assessed using a 1:2.5 soil-to-water ratio. The WHC was measured by allowing water absorption for 12 h in a punctured brass cup containing 20 g of dry

SOC is the soil organic carbon concentration, D is the sampling depth (cm), G is the gravel content (%), and BD is the bulk density (g cm⁻³).

2.6 Estimation of the economic value of carbon credits

The cumulative carbon credits within a land use system were calculated based on the carbon dioxide equivalent (CO₂eq) values of preserved biomass and SOC within their respective systems in accordance with IPCC guidelines (1996). The calculation of CO₂eq for carbon stock and carbon sequestration rate values involved applying a CO₂:C stoichiometric ratio of 3.67, which converts carbon atoms into CO₂ molecules. The overall carbon sequestration of a specific forest type is quantified by aggregating the biomass of both above- and belowground trees, along with litterfall, shrubs, herbs, and SOC. Each metric ton of CO₂ sequestered or mitigated through plant biomass and SOC in a forest corresponds to one carbon credit. One C credit corresponds to 1 ton of CO₂ and is also valued at 3.00 euros (Goswami et al. 2014), which was utilized in the present study.

2.7 Statistical analysis

The normality of the data sets, which included vegetation, soil, litter, and environmental factors such as slope, altitude, stand density, and soil physicochemical properties, was tested using the Shapiro–Wilk test, and the homoscedasticity was tested using the Levene test. The means were evaluated via ANOVA, followed by Tukey's HSD post hoc test ($p < 0.05$). A one-way ANOVA and Mantel test (999 permutations) based on Spearman's correlation were performed to demonstrate the significant impact of different ecosystem component variables on carbon storage, considering environmental factors such as slope, altitude, stand density, and soil physicochemical

properties. Redundancy analysis (RDA), conducted via a Monte Carlo simulation with 999 randomizations, was utilized to examine the correlation between carbon storage and environmental factors. Both RDA and Mantel analyses were carried out using the "vegan", "dplyr", and "tidyverse" packages in R software (version 4.2.2).

3 Results

3.1 Stand characteristics and biomass

Significant variation ($p < 0.05$) was observed in the density, basal area, and biomass of trees across the different forest types. The tree density ranged from 620 individuals per hectare in pine forests to 960 individuals per hectare in oak forests. Notably, dominant species such as *C. deodara*, *Q. leucotrichophora*, *S. robusta*, and *P. roxburghii* exhibited varying densities, ranging from 324 to 540 individuals per hectare. These dominant species collectively represented 50.52%, 91.89%, 58.02%, and 83.87% of the total forest density in oak, deodar, sal, and pine forests, respectively. The basal area exhibited significant variation across the different forest types, with pine forests having the lowest value ($39.45 \text{ m}^2 \text{ ha}^{-1}$) and deodar forests having the highest value ($58.64 \text{ m}^2 \text{ ha}^{-1}$) ($p < 0.05$) (Table 2). The highest tree density and basal area values were recorded within the 30–70 cm DBH range, whereas the lowest values were found in the 10–20 cm and greater than 90 cm DBH categories (Fig. 2a, b). Deodar forests were found to possess the highest total biomass ($247.33 \text{ Mg ha}^{-1}$), followed by oak (231.8 Mg ha^{-1}), sal ($155.11 \text{ Mg ha}^{-1}$), and pine forests ($138.85 \text{ Mg ha}^{-1}$). The biomass distribution across the different tree species exhibited notable variations, which were directly linked to their basal area. In deodar, oak, sal, and pine forests, dominant species contributed significantly to the total biomass, accounting for between 65% and 95%. Conversely, associated species in oak and sal forests made a lesser but still noteworthy contribution, ranging from 2% to 21% of the total tree biomass. The distribution of tree biomass across different DBH classes indicated a notable biomass concentration within the 30–60 cm range across various forest types, notably oak, deodar, and sal forests. Pine forests exhibited a different pattern, with the highest biomass observed in the 40–50 cm DBH class and the lowest in the > 91 cm DBH class (Fig. 2c). In terms of biomass stocks, both AGBD and BGBD were notably greater in deodar forests than in other forest types, followed by oak forests (Table 3). The sal forest typically possess lower biomass than other forest types. Similarly, compared with deodar and oak forests, pine forests generally exhibit reduced biomass levels; however, they tend to display greater understory biomass. Litter, understory, and deadwood biomass variations were notable across forest types. Litter biomass ranged from 2.51 Mg ha^{-1} in pine

forests to 5.31 Mg ha^{-1} in oak forests. While pine forests feature lower litter biomass, they tend to exhibit higher understory biomass. Among the forest types, the deodar forest harbors the highest deadwood biomass, followed by oak, pine, and sal forests. However, the disparities in deadwood biomass among forest types were not statistically significant ($p > 0.16$).

3.2 Ecosystem carbon stock

The total biomass carbon concentration varied across the different forest types. In the pine forests, the aboveground biomass ranged from 45.83 Mg ha^{-1} to 18.46 Mg ha^{-1} for the belowground biomass. Conversely, the values were greater in deodar forests, at 94.11 Mg ha^{-1} and 36.68 Mg ha^{-1} , respectively. Oak and sal forests harbor diverse tree species, each of which accumulates varying amounts of biomass carbon. The maximum carbon stocks were observed for tree species characterized by higher tree densities and basal areas across all forest types, such as *C. deodara* in deodar forests, *Q. leucotrichophora* in oak forests, *S. robusta* in sal forests, and *P. roxburghii* in pine forests. The contribution of soil organic carbon (SOC) to the total ecosystem carbon was the predominant contributor, followed by that of AGBD carbon, in all forest types. The total carbon stored in the different ecosystem components reached $306.29 \text{ Mg C ha}^{-1}$ in oak forests, $270.91 \text{ Mg C ha}^{-1}$ in deodar forests, $206.94 \text{ Mg C ha}^{-1}$ in sal forests, and $122.43 \text{ Mg C ha}^{-1}$ in pine forests (Fig. 3). The carbon stock exhibited notable variations in value across the different study sites and species compositions (Table 4). Sal forest had the highest average soil bulk density (1.31 g cm^{-3}), while pine forest had the lowest (1.05 g cm^{-3}). Oak and deodar forests had higher total nitrogen (TN) and total phosphorus (TP) contents. A higher water holding capacity (WHC) and soil moisture were found in oak forests. Sal and deodar forests had higher sand contents, whereas pine forests had higher clay contents. Oak forest had higher soil EC, while pine forest had the lowest. The soil organic carbon (SOC) stock within the 0–60 cm depth range exhibited significant differences ($p < 0.05$), ranging from 63.22 Mg ha^{-1} in pine forests to $191.17 \text{ Mg ha}^{-1}$ in oak forests. Allocation patterns of carbon within vegetation (including aboveground and belowground components) varied among forest types. In oak forests, the carbon allocation percentages were approximately 26.06% aboveground, 10.23% belowground, 0.10% deadwood, 0.66% litter, 0.52% understory, and 62.41% soil. Similarly, in deodar forests, these percentages were approximately 34.74%, 13.54%, 0.14%, 0.39%, 0.70%, and 50.49%, respectively. In the sal forests, the percentages were approximately 29.04%, 7.33%, 0.08%, 0.37%, 1.01%, and 62.16%, respectively, and in the pine forests, these percentages

Table 2 Phytosociological attributes, biomass stocks, carbon stocks, carbon sequestration potentials and carbon credits of major forest types

Species	Family	Density (Individual ha ⁻¹)	Total basal area (m ² ha ⁻¹)	Biomass stock (Mg ha ⁻¹)	Carbon stock (Mg ha ⁻¹)	CO ₂ sequestered (Mg ha ⁻¹)	Carbon credit (Euro ha ⁻¹)
Oak forest							
<i>Quercus leucotrichophora</i> A. Camus	Fagaceae	480	26.12	140.34	65.80	241.29	723.87
<i>Myrica esculenta</i> Buch. -Ham. Ex D.Don	Myricaceae	90	8.24	19.27	8.93	32.75	98.24
<i>Rhododendron arboreum</i> Sm.	Ericaceae	80	7.27	17.65	7.99	29.30	87.90
<i>Aesculus indica</i> (Wall. Ex Cambess.) Hook.	Sapindaceae	60	3.29	12.45	5.64	20.68	62.05
<i>Symplocos ramosissima</i> Wallich ex G. Don	Symplocaceae	50	1.87	6.23	2.82	10.34	31.02
<i>Lyonia ovalifolia</i> (Wall.) Drude	Ericaceae	80	2.10	8.56	3.76	13.79	41.36
<i>Bauhinia variegata</i> (L.) Benth	Fabaceae	50	1.56	7.27	3.29	12.06	36.19
<i>Pyrus pashia</i> L.	Rosaceae	60	1.67	6.42	3.02	11.06	33.19
Deodar forest							
<i>Cedrus deodara</i> (Roxb.) G.Don	Pinaceae	680	53.23	230.23	108.10	396.40	1189.21
<i>Cupressus torulosa</i> D.Don ex Lamb	Cupressaceae	60	5.67	10.21	4.79	17.58	52.74
Sal forest							
<i>Shorea robusta</i> Gaertn	Dipterocarpaceae	470	29.45	106.54	49.82	182.69	548.07
<i>Syzygium cumini</i> (L.) Skeels	Combretaceae	150	11.51	32.76	15.04	55.15	165.46
<i>Mallotus philippensis</i> (Lam.) Müll. Arg	Euphorbiaceae	110	7.65	6.54	2.82	10.34	31.02
<i>Terminalia alata</i> Roth	Combretaceae	50	3.36	4.87	1.88	6.89	20.68
<i>Pterocarpus marsupium</i> Roxb.	Fabaceae	30	2.61	1.12	0.53	1.93	5.79
Pine forest							
<i>Pinus roxburghii</i> Roxb.	Pinaceae	520	31.23	102.14	47.94	175.80	527.39
<i>Quercus leucotrichophora</i> A. Camus	Fagaceae	40	5.14	10.26	4.70	17.23	51.70
<i>Myrica esculenta</i> Buch. -Ham. Ex D.Don	Myricaceae	30	2.24	7.76	3.29	12.06	36.19
<i>Rhododendron arboreum</i> Sm.	Ericaceae	30	2.31	9.56	4.23	15.51	46.53

were approximately 37.43%, 6.91%, 0.29%, 0.96%, 2.78%, and 51.63%, respectively (Fig. 4). These variations illustrate the diverse carbon dynamics across different forest ecosystems.

3.3 Effect of environmental factors and carbon storage

The Mantel test revealed that environmental factors (such as altitude, slope, and aspect), along with forest structure attributes and soil properties, had a significant influence on changes in carbon storage. The correlation coefficient was used to analyze the relationships among the ecological variables. The Mantel test was used to evaluate the associations between the carbon storage of each ecosystem component and its corresponding environmental variables (Fig. 5). Correlation analysis revealed that the AGBD, BGBD, deadwood, litter, understory, SOC and total ecosystem carbon stock were significantly correlated with the BD, altitude, slope, density, total basal area, WHC, soil EC, soil pH, SOC, and total nitrogen (TN) and total phosphorus (TP) contents ($p < 0.05$). The environmental factors that affected the carbon storage of ecosystem components included BD, altitude, slope, density, total basal area, total organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) contents. The

main factors influencing soil carbon storage were the WHC, soil EC, soil pH, and SOC, TN and TP contents. A strong correlation was observed between SOC and TN, which simultaneously affected the soil pH, soil EC and WHC. The factors influencing the AGBD, BGBD, deadwood, litter, and understory carbon storage were altitude, slope, tree density, and total forest basal area (Fig. 5). In the RDA, AGBD, BGBD, deadwood, litter, understory, SOC, and total ecosystem carbon stock were used as response variables, and altitude, slope, density, total basal area, WHC, BD, soil EC, soil pH, SOC, and total nitrogen (TN) and total phosphorus (TP) contents were used as the explanatory variables. According to the RDA, axis 1 and axis 2 explained 58.67% and 38.49%, respectively, of the total variance. The total explanation reached 97.16% (Fig. 6). The slope, altitude and BD had greater arrow lengths along the first axis. The main factors that affected the AGBD were the deadwood, litter, understory, and total ecosystem carbon stock.

3.4 Carbon sequestration potential and carbon credit

Oak forests demonstrated a greater capacity for CO₂ sequestration, with approximately 1123.16 Mg of CO₂ sequestered ha⁻¹, followed by deodar (993.45 Mg of CO₂

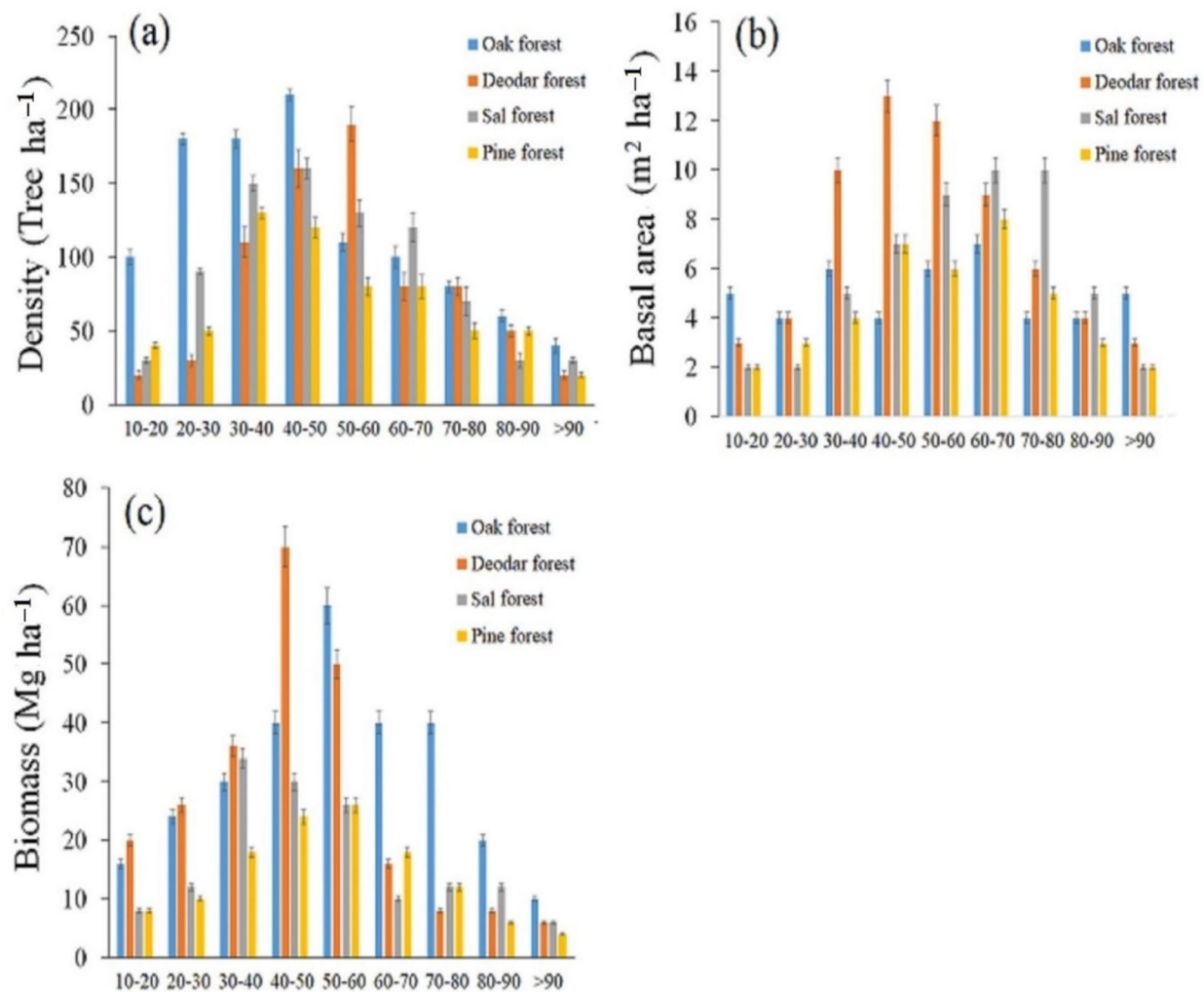


Fig. 2 Variations in (a) tree density (b) basal area and (c) biomass across the DBH classes (cm) in different forest types

sequestered ha⁻¹), sal (758.87 Mg of CO₂ sequestered ha⁻¹), and pine (448.98 Mg of CO₂ sequestered ha⁻¹). The corresponding carbon credit generation figures were approximately 3369.49 Euro ha⁻¹, 2980.36 Euro ha⁻¹, 2276.61 Euro ha⁻¹, and 1346.46 Euro ha⁻¹ for oak, deodar, sal, and pine forests, respectively (Table 4).

4 Discussion

The present results highlight notable differences in forest structural characteristics, including biomass distribution, across various forest types. These findings offer valuable insights into the ecological processes and management implications within these environments.

Table 3 Biomass stock (Mg ha⁻¹) in the different components of the different forest types

Ecosystem components	Oak forest	Deodar forest	Sal forest	Pine forest	p-Value
Aboveground biomass	167.56 ± 3.12	180.15 ± 4.54	111.40 ± 2.2	96.24 ± 4.21	0.05
Belowground biomass	52.85 ± 2.21	58.05 ± 2.12	35.28 ± 1.12	32.13 ± 2.1	0.03
Deadwood biomass	0.68 ± 0.03	0.82 ± 0.07	0.34 ± 0.032	0.74 ± 0.09	0.14
Litter biomass	5.31 ± 1.01	4.27 ± 0.04	3.63 ± 0.065	2.51 ± 0.75	0.04
Understory biomass	3.4 ± 0.45	4.04 ± 0.32	4.46 ± 0.98	7.23 ± 1.54	0.16
Total biomass stock	231.8 ± 5.2	247.33 ± 4.21	155.11 ± 3.21	138.85 ± 3.21	0.05

Values are significant at the $p < 0.05$ level and values represent the standard error of the means

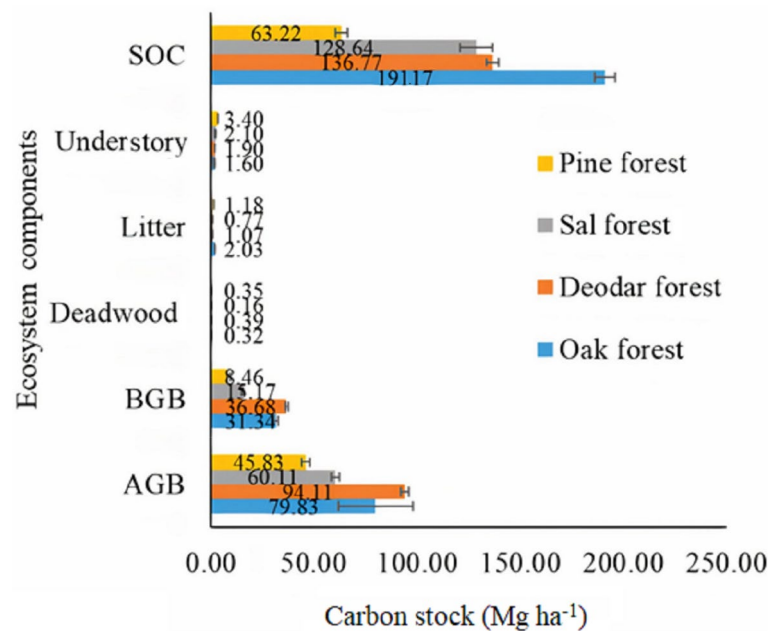


Fig. 3 Distribution of carbon stocks (Mg ha^{-1}) in different ecosystem components in major forest types. (AGB, aboveground biomass; BGB, belowground biomass; SOC, soil organic carbon)

Differences in tree density and basal area among forest types underscore the unique ecological conditions and species compositions that define each ecosystem (Schall et al. 2018). Oak forests exhibit greater tree density and basal area than deodars, sal, and pine forests, indicating the potential for increased biodiversity and productivity within oak-dominated ecosystems. The observed tree density, ranging from 620 to 920 individuals per hectare, aligns with previous reports from the central Himalayan forests (Garkoti 2007). Our study underscores the significant influence of vegetation type, species composition, and girth class on overall biomass and carbon sequestration within distinct forest ecosystems. The basal area of trees is typically affected by factors such as density, stand age, site index, and crown size (Berrill et al. 2016). Our findings indicate a decrease in basal area and DBH in pine forests, likely due to the prevalence of younger tree

species, suggesting ongoing forest development (Liang et al. 2007). These results highlight the substantial contribution of dominant species to overall forest density, reflecting both ecological adaptation and species-specific growth patterns in various forest environments in the central Himalaya. The biomass distribution across diameter classes reveals unique growth patterns and successional dynamics within various forest types (Piponirot et al. 2022). The highest tree density and basal area values, recorded within the 30–70 cm diameter at breast height (DBH) range, suggest that medium-sized trees dominate the forest structure. This indicates a forest in a mid-successional stage where trees have grown past the sapling stage but have not yet reached their maximum potential size. Lower values in the 10–20 cm DBH range could indicate fewer young, regenerating trees, potentially suggesting limited recent regeneration or high

Table 4 Ecosystem carbon stock (Mg C ha^{-1}), carbon sequestration potential and carbon credit of major forest types. The values within the parentheses represent the standard error of the means

Forest type	Total ecosystem carbon stock (Mg C ha^{-1})	CO_2 sequestered (Mg ha^{-1})	Carbon credit generation (Euro ha^{-1})
Oak forest	306.29 ± 5.32	1123.16 ± 50.23	3369.49 ± 115.54
Deodar forest	270.92 ± 6.72	993.45 ± 31.23	2980.36 ± 98.62
Sal forest	206.95 ± 3.21	758.87 ± 28.54	2276.61 ± 135.67
Pine forest	122.44 ± 2.12	448.98 ± 33.67	1346.46 ± 121.42

1 C credit is equivalent to 1 ton of CO_2 and further equivalent to 3.00 euro (Goswami et al. 2014)

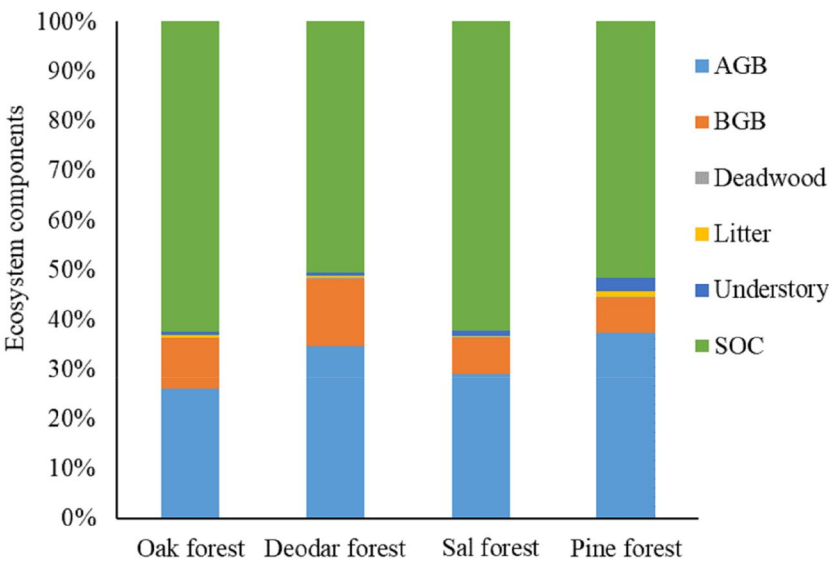


Fig. 4 Proportion (%) of the carbon allocation pattern in different ecosystem components

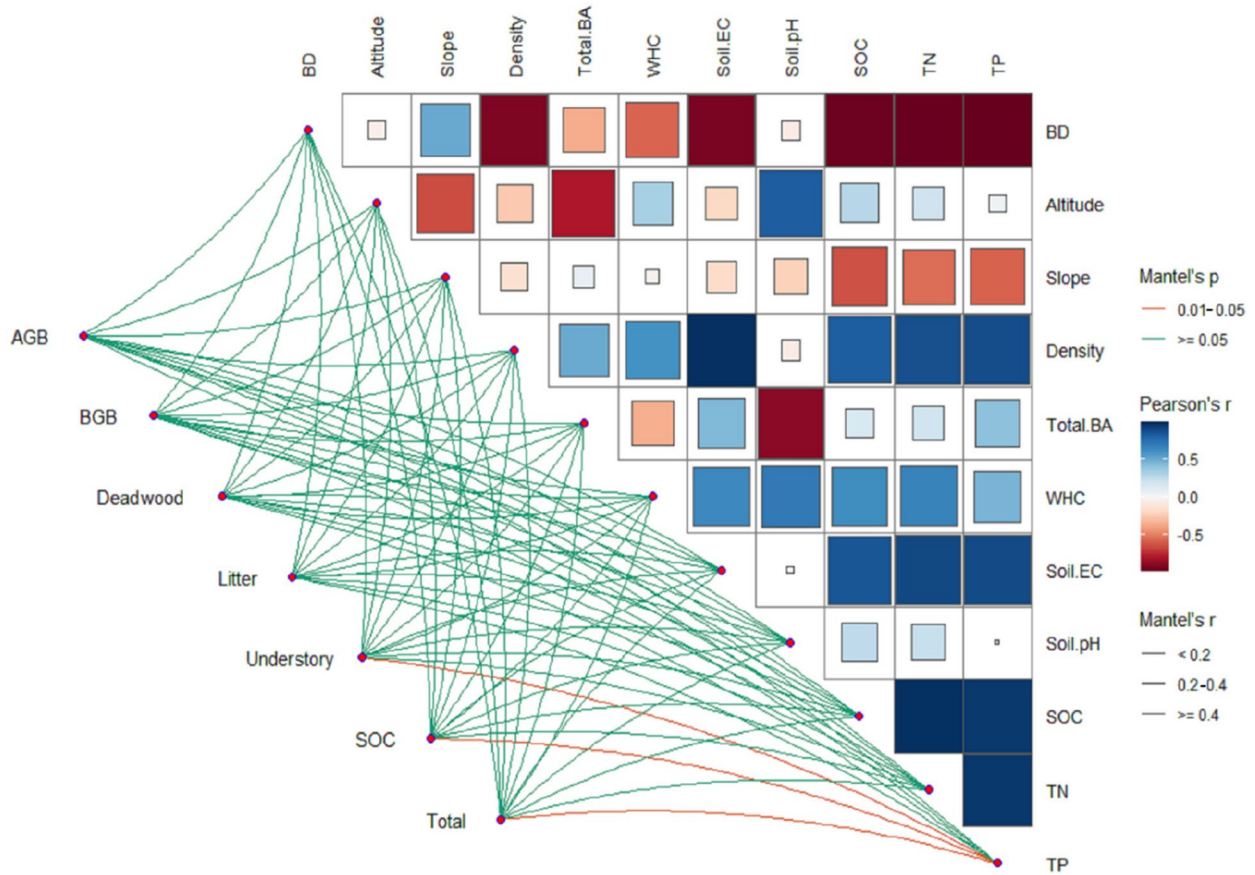


Fig. 5 Correlations between carbon storage and environmental variables obtained via the partial Mantel test. Edge width corresponds to Mantel's r statistic for the corresponding distance correlations, edge color indicates a positive or negative relationship, and line style denotes statistical significance based on 999 permutations

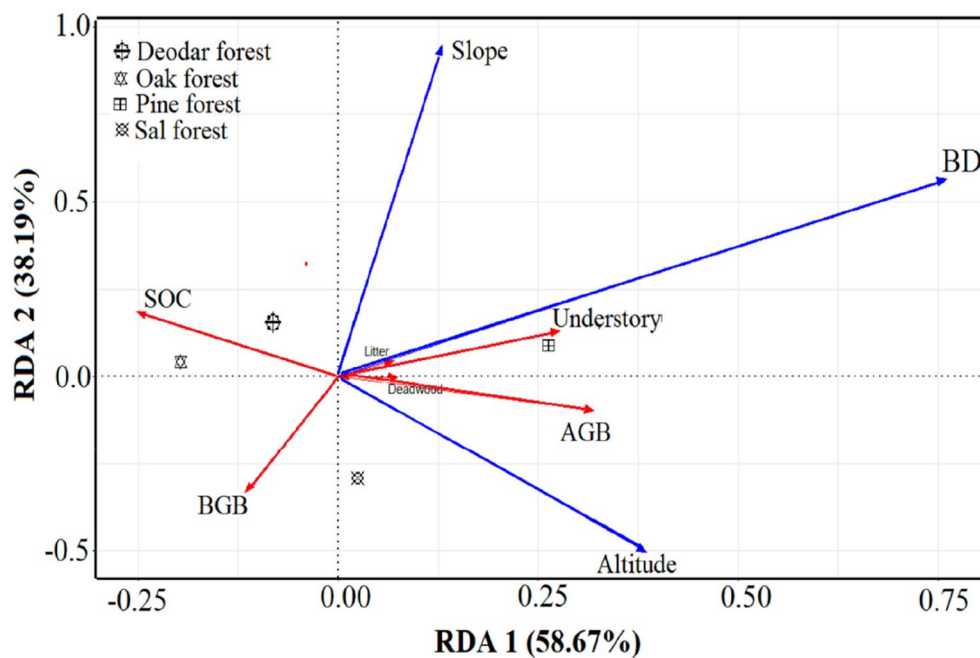


Fig. 6 Redundancy analysis (RDA) of factors influencing forest carbon storage. The blue and red arrows represent carbon storage and environmental factors, respectively

competition and mortality rates among smaller trees. Conversely, the lowest values in the greater than 90 cm DBH category indicate few large, old-growth trees. This may imply a history of disturbance, such as logging or natural events (e.g., landslides and fires), preventing trees from reaching their maximum size. In deodar and oak forests, the prevalence of larger diameter classes indicates mature stands with substantial biomass accumulation over time, likely due to favorable growth conditions and effective management strategies. Deodar forests are known for their large size and longevity, which contribute to increased biomass accumulation. These forests likely have dense canopies and significant carbon sequestration capacities, highlighting their ecological importance in carbon storage and climate regulation (Sharma et al. 2010). The elevated aboveground and belowground biomass levels in these forests highlight their significance as carbon sinks and contributors to ecosystem services. The conservation of these forest ecosystems is imperative because of their pivotal role in mitigating climate change and providing habitats.

In contrast, pine and sal forests demonstrated comparatively lower tree biomasses (128 and $149.12 \text{ Mg ha}^{-1}$, respectively) than what found by Verma and Garkoti (2019) and Pandey et al. (2023), possibly due to the prevalence of smaller individuals in lower girth classes. This reduced biomass suggests potential anthropogenic pressures or natural disturbances affecting biomass

productivity and carbon sequestration capacity in these ecosystems. The higher biomass observed in the deodar and oak forests may be attributed to their elevated tree density and reduced anthropogenic pressure. The distribution of biomass across the nine DBH classes revealed that the lower DBH classes (30–60 cm) exhibited greater biomass allocation, likely due to their greater density and basal area. Previous studies conducted in the Himalayan region (Sharma et al. 2010) and globally (Dyola et al. 2022) have also highlighted the influence of forest stand attributes on carbon stocks in various forest types.

The primary role of aboveground biomass (AGBD) in determining the total biomass stock remains consistent across various forest types. Belowground biomass density (BGBD) and its proportional contribution (18%–25%) to the total biomass stock play a significant role in belowground carbon storage across these forest types. There was notable variability in total tree biomass carbon, including aboveground and belowground biomass, among the forest types. Pine forests exhibited the lowest total tree biomass carbon, while deodar forests had the highest. This divergence likely stems from differences in tree species composition, density, and growth rates among these forests (Singh and Singh 1992).

Certain tree species contribute more substantially to carbon stocks within each forest type than others. For instance, *C. deodara* (deodar) in deodar forests, *Q. leucotrichophora* (oak) in oak forests, *S. robusta* (sal) in

sal forests, and *P. roxburghii* (pine) in pine forests were identified as species with higher carbon stocks. This highlights the importance of considering species composition in forest carbon stock assessments. Additionally, in mixed forests, the relative contributions of dominant and codominant species vary according to the composition of the forest, aligning with findings from previous studies (Kaushal and Baishya 2021).

Soil bulk density (BD) measures soil compaction and porosity and affects root penetration, water infiltration, and gas exchange. The highest average bulk density was found in the sal forest (1.31 g cm^{-3}), which suggested that the soil in this forest was more compact than that in the other forests and could restrict root growth and reduce water infiltration. The higher total nitrogen and phosphorus contents in oak and deodar forests reflect the nutrient-rich conditions in these forests. The higher TN and TP might be due to greater leaf litter and organic matter decomposition in these forests, enhancing the nutrient cycling process. These conditions are conducive to supporting diverse and dense vegetation. The interplay of these soil properties creates distinct ecological niches and influences the species composition and structure of each forest type (Rawat 2005). The variations in soil texture and nutrient content also dictate the type of microbial community and soil fauna, further influencing decomposition rates and nutrient cycling. The study results also revealed significant differences in soil organic carbon (SOC) stocks across forest types. In particular, oak forests displayed the highest SOC stocks, in contrast to those in pine forests, which had the lowest SOC stocks. This suggests that soil carbon storage is influenced by various factors, such as litter decomposition rates, microbial activity, and soil texture, which vary across diverse forest ecosystems (Lange et al. 2015). Furthermore, research has indicated that forest growth and increased litterfall over time could contribute to restoring soil carbon stocks and cycling (Feng et al. 2019). These findings are consistent with prior studies suggesting that biomass distribution and carbon stocks within forest ecosystems vary based on factors such as forest type, stand age, species composition, and soil properties, supporting our conclusions (Zhou et al. 2023).

Differences in litter and understory biomass among different forest types arise from variations in litter decomposition rates, understory vegetation dynamics, and nutrient cycling processes (Joshi and Garkoti 2023c). The carbon content of litter is influenced by several factors, including tree type, litter production, decomposition rate, and microenvironment (Xiao et al. 2019). The amount of carbon in litter reported for all forest types falls within the documented range from various studies (Neumann et al. 2018).

The distribution of carbon across various ecosystem components, such as vegetation, deadwood, litter, the understory, and soil, varied across different forest types. For instance, oak forests tended to allocate more carbon to aboveground biomass and soil. In contrast, pine forests exhibited a greater allocation of aboveground biomass with relatively less soil. These variations likely stemmed from differences in vegetation structure, litter quality, and decomposition rates among forest types (Garkoti 2011). Notably, regardless of these disparities in carbon allocation, soil organic carbon (SOC) consistently emerged as the predominant contributor to total ecosystem carbon across all forest types. This finding underscores the importance of soil carbon storage for overall carbon sequestration, thereby emphasizing the role of forests as vital carbon sinks. This observation has been supported by multiple studies (Sharma et al. 2010; Joshi and Garkoti 2021b).

The study revealed that altitude, slope, tree density, and total basal area significantly influence carbon storage in the AGBD, BGBD, deadwood, litter, and understory. These factors shape the structural characteristics of forests and influence processes such as photosynthesis, respiration, and decomposition. The Mantel test results indicate that environmental factors significantly influence changes in carbon storage, highlighting the need to consider multiple ecological variables when studying carbon dynamics. The significant correlations identified through correlation analysis highlighted the interdependence of ecosystem components and environmental conditions. The strong correlation between SOC and TN underscores their synergistic role in soil fertility and carbon storage, which also influences soil pH, EC, and WHC, demonstrating the interconnected nature of soil properties. These findings stress that carbon storage in ecosystems is a multifactorial process, with various environmental factors interacting to influence carbon dynamics (Song et al. 2024). Understanding these relationships is crucial for developing effective carbon management strategies and predicting ecosystem responses to environmental changes.

The research outcomes revealed that oak forests exhibit the highest capacity for sequestering carbon dioxide equivalents (CO_2e) per hectare, followed by deodars, sal, and pine forests, in a descending sequence. The valuation of carbon credits for primary forest types within the central Himalayan region is influenced by a blend of ecological dynamics, management practices, and methodological considerations (Negi 2022). This implies that oak forests possess superior abilities to absorb and retain carbon from the atmosphere compared to other forest types evaluated. For instance, oak forests are distinguished by their dense canopies and extensive root

systems, potentially contributing to their elevated carbon sequestration rates (Joshi and Garkoti 2023a). Conversely, pine forests, which typically demonstrate lower carbon storage capacities, may feature less dense canopies and shallower root systems. Carbon credits are financial instruments denoting a reduction in greenhouse gas emissions, typically quantified in metric tons of CO₂e (Babbar et al. 2021).

Consequently, forests exhibiting greater carbon sequestration capabilities can produce more carbon credits, which can be traded on carbon markets to incentivize forest conservation and reforestation efforts (Roy and Bhan 2024). The results showed that oak forests had the highest potential for carbon credit, followed by deodar, sal, and pine forests. This underscores the potential economic benefits of investing in the conservation and revitalization of oak forests, in addition to their environmental importance. The findings also reveal that oak forests in the central Himalayan region sequester the highest amount of CO₂ equivalents per hectare, followed by deodars, sal, and pine forests. Consequently, oak forests are identified as the top generators of carbon credits, followed by deodar, sal, and pine forests.

These findings suggest prioritizing oak forests for climate change mitigation in the central Himalayan region (Chakraborty et al. 2018). Protecting and enhancing the health of oak forests can maximize carbon sequestration and carbon credit generation, significantly contributing to global climate change mitigation efforts (Di Sacco et al. 2021). It is crucial to advocate for policy frameworks that incentivize oak forest conservation and sustainable management, such as payments for ecosystem services, carbon pricing mechanisms, and REDD+ initiatives. Such supportive policies can create economic incentives for forest conservation while addressing climate change concerns.

5 Conclusions

In conclusion, the present research offers valuable insights into the carbon storage dynamics of the main forest types in the central Himalayan region. The study revealed significant variability in carbon stocks across oak, chir-pine, deodar, and sal forest regions influenced by various ecological factors, including altitude, aspect, and slope. The significant variation in carbon stocks among the different forest types, with oak forests exhibiting the highest carbon storage and pine forests the lowest, reflects the influence of species composition and forest structure on carbon sequestration capacities. Notably, the predominance of soil organic carbon in total ecosystem carbon stocks accentuates the importance of soil conservation practices. The findings revealed that dominant tree species, such as oak, deodar,

and sal, contribute more effectively to carbon storage, offering greater carbon credit potential. Variations in carbon distribution among ecosystem components, such as plant biomass, soil organic carbon, deadwood, and litter, highlight the intricate nature of carbon dynamics within these ecosystems. This research provides essential data that can inform and enhance forest management plans to maximize carbon sequestration and foster sustainable carbon trading practices. By prioritizing the conservation and sustainable management of high-carbon-storing forest types, such as oak and deodar forests, policymakers can significantly bolster the carbon sequestration potential of the central Himalayan region.

Moreover, the valuation of carbon credits highlights the economic benefits of preserving these forests, providing a financial incentive for conservation efforts. Integrating these insights into forest management plans can bolster the carbon sequestration capacity and monetary value of central Himalayan forests, fostering sustainable development while mitigating climate change. This research highlights the ecological and economic importance of these forests, advocating for informed management practices that maximize their carbon sequestration potential and contribute to global climate goals.

Abbreviations

AGBD	Aboveground biomass density
ANOVA	Analysis of variance
BEF	Biomass expansion factor
BGBD	Belowground biomass density
BD	Bulk density
C	Carbon
CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalents
COP	Conference of the Parties
DBH	Diameter at breast height
EUR	The euro
EC	Soil electrical conductivity
FRI	Forest Research Institute
FSI	Forest Survey of India
GSVD	Growing stock volume density
IPCC	Intergovernmental Panel on Climate Change
Mg ha ⁻¹	Megagrams per hectare
REDD	Reducing emissions from deforestation and forest degradation in developing countries
RDA	Redundancy analysis
SOC	Soil organic carbon
TP	Total phosphorus
TN	Total nitrogen
TBD	Total biomass density
TCD	Total carbon density

Acknowledgements

The authors are highly grateful to the Forest Department of Uttarakhand for their help during the field investigation. We also thank the anonymous reviewers and the Editor for their insightful and constructive suggestions.

Authors' contributions

Rajendra Kumar Joshi and Satish Chandra Garkoti contributed to the conception and design of the study. Rajendra Kumar Joshi contributed to the data collection and analysis. The first draft of the manuscript was written by Rajendra Kumar Joshi and edited and commented on by Satish Chandra Garkoti. Both authors read and approved the final manuscript.

Funding

Financial support from the University Grants Commission and DST- PURSE, India, is appreciated.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

The authors have no relevant financial or nonfinancial interests to disclose.

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Received: 2 April 2024 Revised: 13 September 2024 Accepted: 7 October 2024

Published online: 14 January 2025

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