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Influence of Anthropogenic Activities on Forest Carbon Stocks—A Case Study from Gori Valley, Western Himalaya

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Abstract: Carbon stock assessment in various ecosystems is vital for monitoring the health of these ecosystems and national accounting for the United Nations convention on climate change. The influence of various anthropogenic drivers on carbon stock in different ecosystems has not been examined comprehensively. This study aims to determine the impact of anthropogenic pressures (lopping, cutting, grazing) on soil physico-chemical properties and carbon stock in four temperate broadleaf forests dominated by different species of oak, viz., Banj oak (*Quercus leucotrichophora*), Rianj oak (*Quercus lanuginosa*), Moru oak (*Quercus floribunda*) and Kharsu oak (*Quercus semecarpifolia*) along an elevation gradient from 1700–3000 m asl in Gori valley, western Himalaya. Biomass data were collected from 120 quadrats of 10 × 10 m size at three distinct altitudes (4 forest sites × 3 altitudes × 10 quadrats) and analysed for carbon stock, whereas soil samples were randomly collected in triplicate from three depths of each altitude of the forest site and further analysed for their physico-chemical properties. A total of 767 individual trees with a diameter of ≥31 cm were measured at twelve sites and standing biomass was estimated following the growing stock volume equations. Mean carbon stock was highest in Moru oak (396.6 ± 29.5 Mg C ha^{-1}) and lowest in Banj oak forest (189.3 ± 48.6 Mg C ha^{-1}). We also found soil to be the largest pool of forest carbon (43.0–59.7%) followed by aboveground biomass (31.5–45.0%), belowground biomass (8.4–11.7%) and litter (0.4–0.5%). The basal area showed significant effect on altitude and carbon stock, whereas disturbance showed significant ($p < 0.05$) negative correlation with the total carbon stock. Soil nitrogen exhibited a significant positive correlation ($R^2 = 0.60$) with the basal area, indicating that nitrogen enhances tree growth and forest carbon stock. However, anthropogenic disturbance showed a significant negative impact on the basal area, soil nutrients and carbon stock of oak forests. This concludes that forest structure, anthropogenic pressure and soil parameters contribute to the carbon stock of the area. Considering the significance of these overexploited oak forests, it is recommended to conserve the old-growth forest species in the study area, since they have the highest carbon accumulation potential.

Keywords: altitudinal gradient; anthropogenic pressure; carbon stock; oak communities; regeneration; soil; vegetation composition

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1. Introduction

Forest ecosystems act as a carbon sink and sequester around 2.4 ± 0.4 Petagrams (Pg) carbon per year globally for 1990 to 2007; on average, they can accumulate 3.58 Mg carbon per hectare of forest per year [1]. They have a huge repository of carbon, storing ca 295 Pg in living biomass (44.6%), 300 Pg in soil organic matter (45.2%), and 68 Pg in dead wood and litter (10.2%) [2]. However, the carbon stock in the forest biomass has decreased by almost 6 Pg over the last three decades globally [2]. The current total carbon pool in the forested zone of the Indian Himalayan Region (IHR) is about 2.6 Megatons, of which 48% is in the tropical forests and 13% in subtropical and temperate forests each [3]. The IHR forests store 1152.1 Mg ha^{-1} carbon, of which Uttarakhand has the second-highest growing stock and the fourth-highest carbon stock (65.7 Mg ha^{-1}; 32%) as aboveground biomass (AGB) and soil organic carbon (56%). It is reported that carbon stored in the forests of IHR has increased from 2.7 to 3.3 Mg, registering an annual increment of 0.6 Mg carbon, which is equivalent to 2.2 Mg of carbon dioxide. These forests are spread over an area of 24.2 million ha, of which 30% is degraded due to anthropogenic pressure for fuelwood, fodder, and timber [4]. Anthropogenic activities have become the second-largest source of CO_2 emission at the global level, which has severe impacts on forest carbon storage [5]. It is reported that the forests in the IHR are degrading at a rate of 0.36 km^2 per year [6] due to natural calamities (landslide, flood and wildfire), anthropogenic disturbances (lopping, cutting, fire and overgrazing) and developmental activities [7]. These human-caused disturbances on Himalayan forests may lead to rapid changes in terms of function, structure, and species composition [8–10].

A key source of active carbon is soil, which also plays a significant role in the global carbon cycle; for evaluation of any forest site quality, it is vital to consider the soil profile, pH, and nutrient cycling between the soils and trees [11]. Uttarakhand has the third-highest (68.7%) soil organic carbon content in the country. It has been reported that increasing CO_2 emissions are due to anthropogenic disturbances, which become a source of soil degradation and carbon stock depletion in the Himalayan region [12]. In terrestrial ecosystems, vegetation is the only source of carbon for the soils [13]. The physico-chemical composition of soil is highly sensitive to vegetational change and disturbance, resulting in depletion of nutrients and soil organic carbon [14]. The western Himalayan regions have distinct weather conditions, topographic variances, soil texture, and land-use patterns [9]. To formulate viable strategies to increase the soil carbon, it is critical to include soil restoration and forest regeneration, nutrient management, and improved grazing [15].

The Himalayan oak forests sustain a large number of local agro-pastoral communities in addition to providing numerous ecosystem services. These oak species are highly valued for socio-economic benefits, maintaining ecological functioning, hydrological balance, habitats for a wide range of faunal communities, and retention of soil and moisture [16,17]. The soil of broadleaf forests plays an important role in water conservation because of their great infiltration capacity [18]. Deep porous soil in temperate broadleaf forests helps to enhance the soil organic carbon in soil, enhance carbon sequestration potential and stabilize ecosystem functioning [19]. The extractive pressure results in degradation of the forest ecosystem and may affect the regeneration of climax species, especially the oaks [9,20]. The long-lived, slow-growing species of oaks have the potential to accumulate more carbon in their trunk and other parts [21], and can be an economical way to mitigate CO_2 emission with the involvement of local communities. However, this would require deeper understanding of impacts of various extractive pressures on tree carbon and soil in the form of soil organic carbon. This would help in understanding the carbon sequestration potential and develop future climate change mitigation measures.

The Himalayan region has been experiencing fast climate change over the past several decades. By better understanding how forest carbon is stored and distributed along altitudinal gradients, we can forecast how the regional and global carbon balance will alter as a result of future climate change. Anthropogenic, abiotic and biotic drivers cause unprecedented changes in the ecosystem and can ultimately affect the sustainable functioning of that ecosystem. We hypothesize that with the increasing level of disturbance on forests, diversity and carbon stock has decreased along with soil quality. Moreover, no such study has been carried out on carbon dynamics in this study site. Keeping this in view, we undertook this study across four oak forests at three distinct altitudes in Gori valley, western Himalaya in the year 2017 with the following objectives—(i) To analyse the effect of altitudinal gradient on the biomass pool and carbon stock in different oak communities. (ii) To examine the effect of disturbance on regeneration status, soil physico-chemical properties and forest carbon stock at different altitudes. (iii) To know the key factors influencing the carbon stock of oak forest in western Himalaya.

2. Materials and Methods

2.1. Study Area

The study was conducted in the lower part of Gori valley (29°45′ 11.03 to 30°20′56.20 N and 80°22′49.90 to 80°11′41.34 E). It is located in the Pithoragarh district of Uttarakhand and covers an area of 1920 km^2 (Figure 1). The valley forms approximately 3.6% of Uttarakhand and is named after the river Gori that originates from the Milam Glacier Terminus (3520 m). The annual climate of the area has three prominent seasons: winter (October to February), summer (March to mid-June), and rainy (mid-June to September). The mean maximum monthly temperature ranged from 15.1 °C (January) to 30.4 °C (June) and the minimum temperature ranged from 2.6 (January) to 18.8 (July). The average annual precipitation is 793.6 mm, and the annual mean relative humidity is 51.2% (Figure 2).

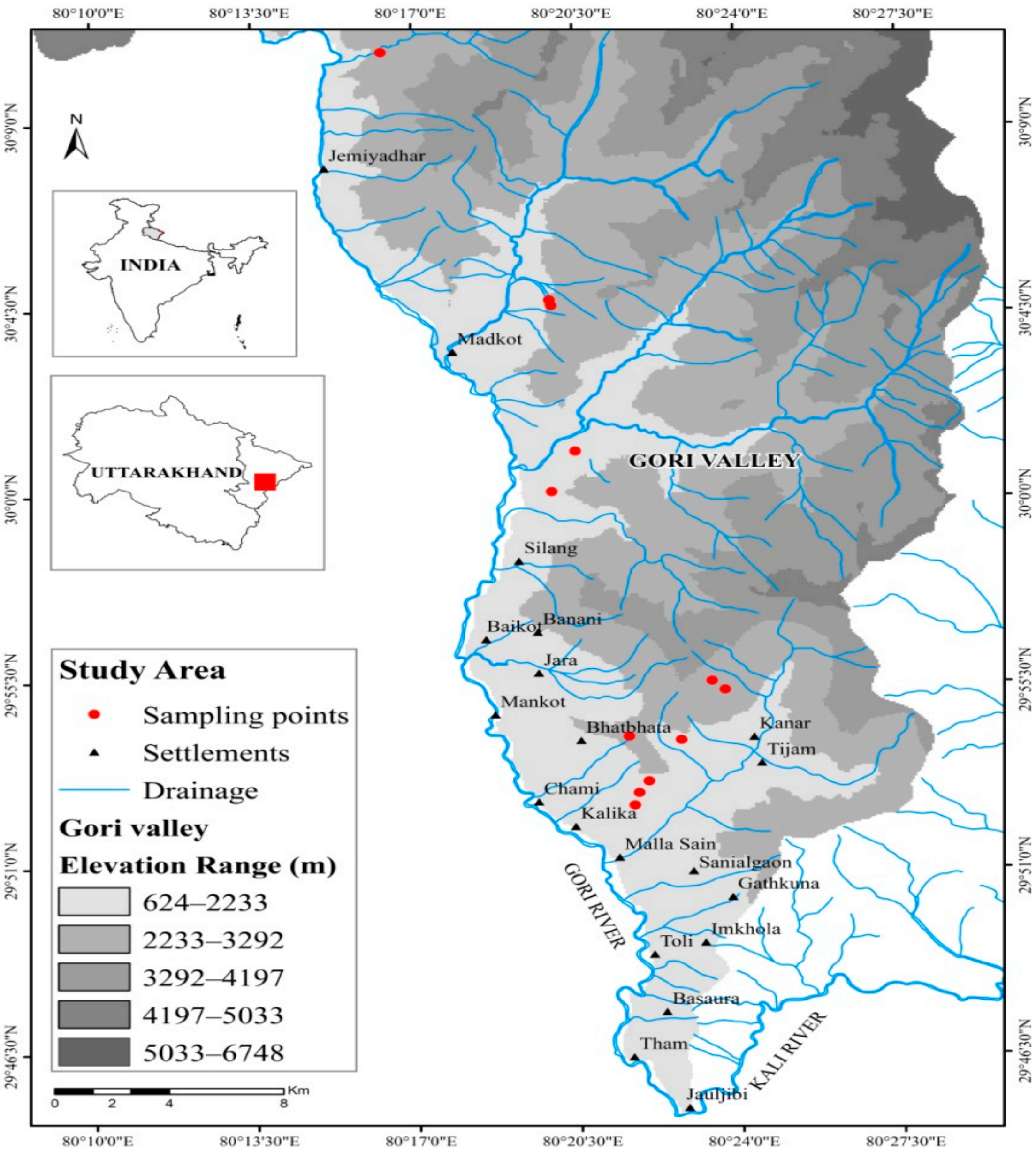

Figure 1. Map of study area showing sampling points and settlements in Gori valley, Western Himalaya.

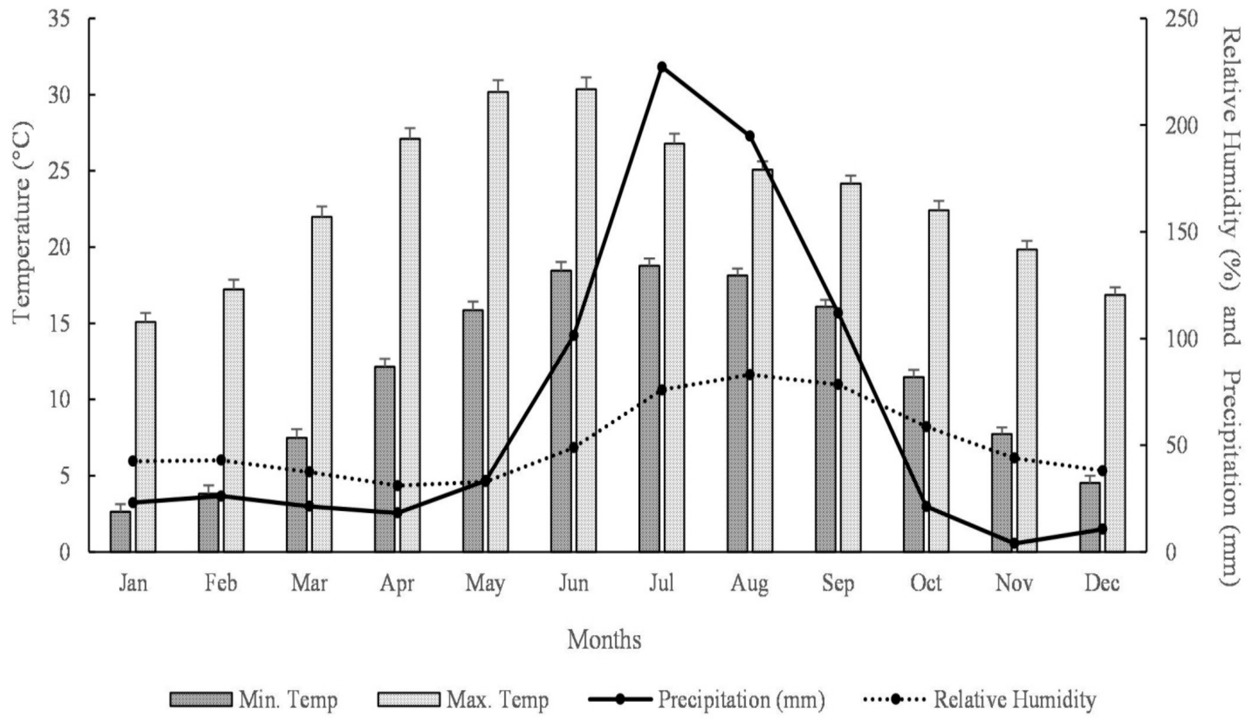

Figure 2. Meteorological data of the study area from 1981–2019 (Source: https://power.larc.nasa.gov, accessed on 6 June 2022).

The forests occupy approximately 25.5% (489.2 km^2) of the geographical area in the valley, which forms 1.3% of the forested area of Uttarakhand. Moru oak and Kharsu oak occupy the largest area (24.8%) among the forests of the valley. A large portion of the study area falls under snow (26.3%), barren (24.7%), and alpine meadow (17.8%). Other values constitute 5.7% which includes agriculture, scrub, landslide, grassy slopes, and settlement values. The valley is divisible into five climatic zones, viz., sub-tropical (<1500 m), warm-temperate (1501–2500 m), the cool-temperate (2501–3000 m), sub-alpine (3001–3500 m), and alpine (>3501 m) zones. In cool-temperate zone, four species of oak (*Quercus* spp.) predominate the forests successively along elevational gradients, viz., Banj oak (*Q. leucotrichophora*), Rianj oak (*Q. lanuginosa*), Moru oak (*Q. floribunda*), and Kharsu oak (*Q. semecarpifolia*) form pure stands (Table 1, Figure 3), except Faliyant oak (*Q. glauca*) with an exceptional diversity of orchid flora [22].

Table 1. Site characteristics of four oak forest communities in Gori valley, Western Himalaya.

Forest Types *	Altitude (m)	Dominant Tree Species (IVI)	Area (km^2)
Banj oak (12/C1a)	1700–2100	*Q. leucotrichophora* (179.3), *R. arboreum* (52.5), others (68.2)	46.3
Rianj oak	1900–2200	*Q. lanuginosa* (140.2), *L. ovalifolia* (64.2), others (95.6)	19.6
Moru oak (12/C1b)	2300–2600	*Q. floribunda* (101.3), *P. duthiei* (48.9), others (149.8)	61.9
Kharsu oak (12/C2a)	2600–3000	*Q. semecarpifolia* (195.1), *R. arboreum* (58.9), others (46.0)	59.5

* Champion and Seth [22] classification. The numbers in brackets indicate subtype of forest, where C1 indicates the lower Western Himalayan temperate forest and C2 indicates the upper Western Himalayan temperate forest.

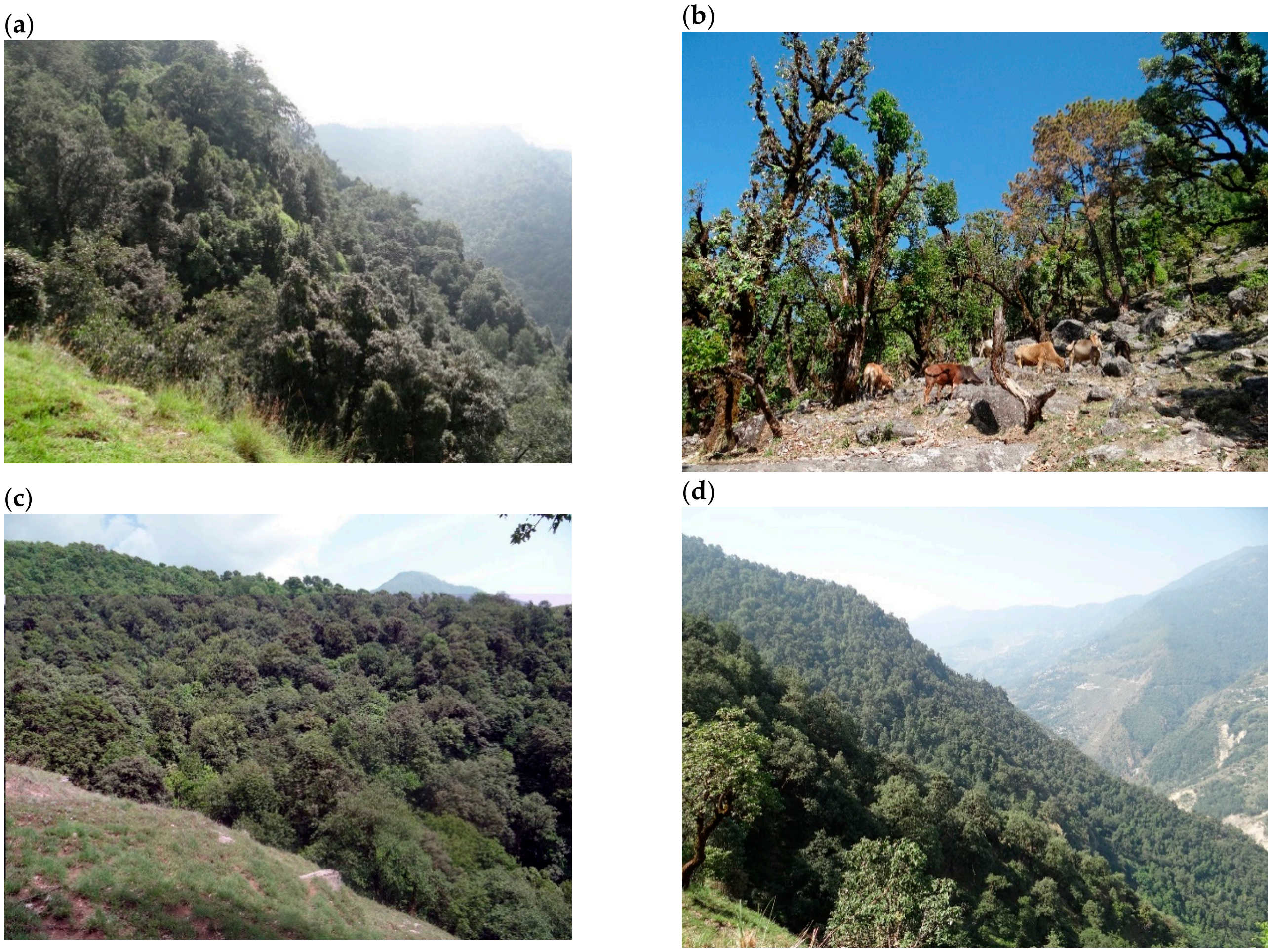

Figure 3. Four oak forest communities (**a**) dense Banj oak (*Q. leucotrichophora*), (**b**) degraded Rianj oak (*Q. lanuginosa*), (**c**) dense Moru oak (*Q. floribunda*) and (**d**) dense Kharsu oak (*Q. semecarpifolia*) in the study area.

The villages have mixed ethnic compositions of Primitive Tribe (Banraji), Scheduled Tribe (Shaukas and Barpatiyas), Scheduled Caste (Shilpkars), and Other Backward Caste (Thakur and Brahmin) populations. The inhabitants of the area (mostly other backward classes) depend on forests and agriculture for their subsistence. A total of 115 plant species are used as fodder and 31 as fuelwood [23]. The livestock (sheep, goats, cows, oxen, buffalo, horses, and mules) dependent on the forest fodder is 13 animals per household [24]. As a result, the number of households is a direct predictor of species constraints on feed and fuelwood. Extraction of high-value medicinal herbs, majorly *Ophiocordyceps sinensis*, and poaching of some animals is also practiced in the valley.

2.2. Vegetation Sampling and Data Analysis

For vegetation sampling, four temperate broadleaf forests dominated by different species of oak, viz., Banj oak (*Quercus leucotrichophora*), Rianj oak (*Quercus lanuginosa*), Moru oak (*Quercus floribunda*) and Kharsu oak (*Quercus semecarpifolia*) was selected along three altitudes (1700–3000 m asl) in the Gori valley, western Himalaya. Within each site, one hectare plot was marked and within each hectare plot ten 10 $\times$ 10 m quadrats were laid for quantification of tree layer, and for saplings and seedlings, 5 $\times$ 5 m quadrats were sampled. All individual trees were measured for circumference at breast height (CBH) at 1.37 m from the ground [9]. Details of locations (elevation, latitude, and longitude) were recorded using a global positioning system device. Following Curtis and McIntosh [25], Misra [26], Mueller-Dombois and Ellenberg [27], Saxena and Singh [28], the data were analysed for density, basal area, and IVI (Importance Value Index) of tree species for distinct forest types. The calculation of the IVI was performed by computing the values of relative frequency (RF), relative density (RD) and relative basal area (RBA). The Species diversity index was computed using the Shannon–Weiner diversity Index [29]. The species richness was calculated as the total number of species per unit area.

2.3. Regeneration Pattern

Individuals of tree species were clustered into six arbitrary CBH classes, viz., A: <10 (seedlings); B: 11–30 (saplings); C: 31–60; D: 61–90; E: 91–120; F: >121 cm [30]. In each of these classes, the total number of individuals was recorded for each tree species in the respective quadrat. The relative density in a specific size class was calculated for each species in all the sampled sites. The regeneration status of species in different forest types was estimated based on the population size of seedlings and saplings [31,32]: if seedlings >saplings >trees, the regeneration is good; if seedlings > or ≤ saplings ≤ trees, the regeneration is fair and if the saplings <, ≥ trees with no seedlings, the regeneration is poor [33].

2.4. Levels of Anthropogenic Disturbance

The anthropogenic pressures were recorded within all the sample plots. Based on the visual scale, the level of anthropogenic pressure was estimated and categorized into four main groups i.e., 1—not disturbed (No signs of lopping and cutting, grazing and fire), 2—least disturbed (<20% lopping and cutting or <20% grazing and fire), 3—moderately disturbed (>20% lopping and cutting or >20% grazing and fire), 4—highly disturbed (>60% lopping and cutting or >60% grazing and fire).

2.5. Growing Stock, Biomass, and Carbon Stock Estimation

Four forest types (12 forest sites), were sampled for biomass and carbon stock estimation. A total of 767 individual trees with diameter ≥ 31 cm at breast height (1.37 m from the ground) were measured and their standing biomass was estimated. The growing stock volume (GSV) equations [34] (Table 2) were used to estimate aboveground biomass [24,35], since allometric equations were not available for each species. The estimated GSV (m^3 ha^{-1}) was multiplied by the appropriate biomass expansion factor (BEF) [36] to convert it into aboveground biomass (AGB) viz., stems, branches, twigs, and leaves. The BEF (Mg m^{-3}) is the ratio of the AGB of all live trees with a DBH >2.54 cm to the GSV for all trees with a DBH >12.7 cm. The following equations were used to determine the BEFs:

Hardwood: BEF = exp {1.91 − 0.34 × ln (GSV)} (for GSV ≤ 200); BEF = 1.0 (for GSV > 200); Softwood: BEF = 1.68 (for GSV < 10); BEF = 0.95 (for GSV = 10–100); BEF = 0.81 (for GSV > 100).

Table 2. List of volume equations used for different tree species in the study sites based on the Forest Research Institute and Forest Survey of India.

Tree Species	Volume Equations
Hardwood	
Acer caesium Wall. ex Brandis	$V = -0.162945 + 3.109717 \times D$
Acer cappadocicum Gled.	$V = -0.162945 + 3.109717 \times D$
Acer oblongum Wall. ex DC.	$V = -0.162945 + 3.109717 \times D$
Aesculus indica Colebr. ex Wall.	$V = 0.007602 - 0.033037 \times D + 1.868567 \times D^2 + 4.483454 \times D^3$
Alnus nepalensis D. Don	$V = 0.0741 - 1.3603 \times D + 10.9229 \times D^2$
Castanopsis tribuloides (Sm.) A.DC.	$V = -0.02301 + 0.12721 \times D + 2.4127 \times D^2 + 8.12834 \times D^3$
Lyonia ovalifolia (Wall.) Drude.	$V = 0.03468 - 0.56878 \times D + 4.72282 \times D^2$
Machilus odoratissima Nees	$V = 6.678 \times D \times D - 0.240 \times D - 0.024$
Myrica esculenta Buch.—Ham. ex D.Don	$V = 0.007602 - 0.033037 \times D + 1.868567 \times D^2 + 4.483454 \times D^3$
Perseaduthiei (King) Kosterm.	$V = 6.678 \times D \times D - 0.240 \times D - 0.024$
Pyrus pashia Buch. -Ham. ex D.Don	$V = 0.046 - 0.646 \times D + 4.272 \times D^2$
Quercus floribunda Lindl. ex A. Camus	$V = 0.0988 - 1.55471 \times D + 10.16317 \times D^2$
Quercus lanuginosa D.Don	$V = 0.0988 - 1.55471 \times D + 10.16317 \times D^2$
Quercus leucotrichophora A.Cam. ex Bah.	$\sqrt{V} = 0.240157 + 3.820069 \times D - 1.39452 \times \sqrt{D}$
Quercus semecarpifolia Sm.	$V = 0.0988 - 1.55471 \times D + 10.16317 \times D^2$
Rhododendron arboreum Sm.	$V = 0.06007 - 0.21874\sqrt{D} + 3.63428 \times D^2$
Symplocos chinensis (Lour.) Druce	$V = -0.212798 + 3.288996 \times D + 0.046417 \times \sqrt{D}$
Softwood	
Cupressus torulosa D.Don	$V = 0.007602 - 0.033037 \times D + 1.868567 \times D^2 + 4.483454 \times D^3$
Pinus roxburghii Sarg.	$\sqrt{V} = 0.05131 + 3.9859 \times D - 1.0245 \times \sqrt{D}$
Rest of the species	$V = 0.007602 - 0.033037 \times D + 1.868567 \times D^2 + 4.483454 \times D^3$

V—volume (m^3) under bark, D—diameter at breast height (1.37 m) over bark in meters.

We used Cairns et al. [37] equation [BGB = exp $\{-1.059 + 0.884 \times \ln(\text{AGB}) + 0.284\}$] to estimate belowground biomass (BGB), which reflects the biomass of root components. The sum of AGB and BGB yielded the total biomass for trees (TB, Mg ha^{-1}). For total carbon stock (TC, Mg C ha^{-1}), we multiplied TB with carbon factor, where the C factor of 46% was used for forest types where all conifers collectively constituted more than half of the forest composition. The C was taken as 45% for forest types where conifers and broadleaved species coexisted or where broadleaved species constituted more than half of the total [38].

2.6. Litter Fall Estimation

Litter fall input was estimated by placing 5 wooden litter traps (0.5 × 0.5 m × 0.15 m) randomly at different locations (beneath canopy, between canopy of trees and in open area) at each forest site. The litter accumulated in the litter traps were collected seasonally i.e., winter (October to February), summer (March to May) and rainy (June to September). The collected litter was separated into leaf and wood litter and then oven dried at 60 °C to a constant weight to obtain dry litter mass. The 45% dry litter mass was considered as litter carbon content [38].

2.7. Soil Sampling and Analysis

The soil samples from each forest site were collected from three depths (0–10 cm, 10–20 cm and 20–30 cm) in triplicate with the help of a soil corer (metal core cylinder) of known volume; these samples were properly mixed to form a composite sample. The collected soil samples were packed separately in zip lock bags and rapidly transferred to the laboratory. Manual removal of coarse items such as stones, roots, and litter was carried out. The soil balls were crushed to separate the soil particles, and then field damp soil samples were sieved with a 2 mm mesh and air dried to test soil physico-chemical characteristics.

The soil moisture (Mo) was determined gravimetrically by drying soil samples in an oven to constant weight. The weight of fresh soil and oven dry weight of same soil sample is expressed as percentage of the difference of moisture content [39]. The water holding capacity (WHC) of the soil samples was measured by using the formula following Jackson [40]. The bulk density (BD) was estimated with the help of a special mental core cylinder of known volume.

The soil pH was measured using a digital soil pH meter (Systronic-μ pH system 361) with ±0.05 accuracy. The soil water suspension was made in the ratio of 1:2. The instrument was calibrated with standard buffer solution of pH 4, 7 and 9.2 before measurement. The soil organic carbon (OC) was determined using the Walkley and Black [41] titration method following Jackson [39]. Nitrogen (N) was estimated using Kjeltec-2300 following the micro-Kjeldahl application of Peach and Tracey [42] and Misra [26]. Available phosphorus (P) was estimated following Olsen et al. [43] and Potassium (K) by Flame Photometer after proper digestion of the samples. The factor of 1.724 was used to convert the OC into soil organic matter (SOM) [26,39]. The value of organic carbon and SOM were determined by multiplying the values of carbon (%) with factors of 1.3 and 1.724, respectively.

$$\text{Total organic carbon (\%)} = \text{Organic carbon estimated} \times 1.32$$

$$\text{Soil organic matter (\%)} = \text{Total carbon (\%)} \times 1.724$$

where 1.724 is the Van Bemmelen factor

2.8. Statistical Analysis

One-way analysis of variance (ANOVA) was used to test the impact of forest types and elevation on soil properties. Pearson's correlation was used to determine significant interrelationships among different environmental variables. Regression analysis was used to find out the association between two variables. Principal component analysis (PCA) was employed to investigate the representation of oak forest communities to physical (Mo, BD, WHC), chemical (C, N, P, K, SOC and SOM) and anthropogenic factors, using PAST software.

3. Results

3.1. Community Structure

Overall, 26 tree species from 21 genera belonging to 16 families were recorded across four oak forest types. Among these, most were angiosperms (92.3%). The four oak species formed climax forests in the study area, viz., Banj oak (1700–2100 m), Rianj oak (1900–2200 m), Moru oak (2300–2600 m) and Kharsu oak (2600–3000 m). The diversity ($F_{3,8} = 7.68$, $p < 0.01$) and richness ($F_{3,8} = 4.32$, $p < 0.05$) were significantly different among all the forest types. In the tree layer, diversity was highest in Moru forest site 1 (M1, 1.86) and lowest in Banj oak forest site 1 (B1, 0.51). The richness ranged from 3 [Kharsu oak site 2 (K2) and Kharsu oak site 3 (K3)] to 10 (M1). In the sapling layer, diversity was highest in Rianj oak forest site 1 (R1, 1.59) and least in Banj oak forest site 2 (B2, 0.90). The sapling richness varied from 3 (B2 and K3) to 6 (M1) across different altitudes. Similarly, in the seedling layer, the highest diversity was recorded in Rianj oak forest site 3 (R3, 1.53) and lowest in Banj oak site 1 (B1), Banj oak site 3 (B3), Rianj oak site 2 (R2), Moru oak site 1, 2, 3 (M1, M2, M3), and Kharsu oak site 1, 2, 3 (K1, K2, K3, 0.00). The seedling richness varied from 1 (B1, B3, R2, M1, M2, M3, K1, K2, K3) to 5 (R3).

Along a gradient of 1700 to 3000 m asl, the maximum basal area (m^2 ha^{-1}) was observed at M2 (74.5) and the minimum at B3 (21.6). Importance value index (IVI) revealed the dominance of a single tree species in all four oak forests. The highest and lowest tree densities (indi. ha^{-1}) were recorded at R3 (1000) and at R2 (450), respectively (Table 3). Likewise, the sapling density was highest at K3 (960) and lowest at M3 (360). The seedling density was highest at R3 (1840), and lowest at K3 (40).

Table 3. Vegetation parameters for trees (T), saplings (Sa) and seedlings (Se) in four oak forests in Gori valley.

Forest Type	Sites	Altitude (m)	Basal Area (m^2 ha^{-1})	Density (indi. ha^{-1})			Diversity (H)			Richness (R)			Regeneration	Disturbance
			T	T	Sa	Se	T	Sa	Se	T	Sa	Se		
Banj oak	B1	1700	34.2	620	400	80	0.51	1.19	0.00	5	4	1	No	High
	B2	1800	46.7	610	400	280	1.36	0.90	0.60	8	3	2	Poor	Moderate
	B3	2100	21.6	650	480	160	1.20	1.24	0.00	4	4	1	No	Moderate
Rianj oak	R1	1900	26.2	910	760	720	1.34	1.59	0.45	4	5	2	Poor	High
	R2	2100	56.0	450	400	80	1.24	1.28	0.00	4	4	1	Poor	High
	R3	2200	46.2	1000	480	1840	1.25	1.29	1.53	5	4	5	Fair	Moderate
Moru oak	M1	2300	40.1	610	640	400	1.86	1.55	0.00	10	6	1	Poor	Moderate
	M2	2400	74.5	660	680	640	1.39	1.18	0.00	7	4	1	Poor	Moderate
	M3	2600	60.2	700	360	240	1.50	1.27	0.00	8	4	1	Poor	Moderate
Kharsu oak	K1	2600	21.9	540	520	40	0.52	1.33	0.00	4	4	1	Poor	Moderate
	K2	2700	71.7	460	800	360	0.86	1.31	0.00	3	4	1	Poor	High
	K3	3000	73.3	460	960	40	0.98	1.05	0.00	3	3	1	Poor	Moderate

B1, B2, B3—B denotes Banj oak; R1, R2, R3- Rianj oak; M1, M2, M3—Moru oak; K1, K2, K3—Kharsu oak and numeric after alphabet denotes site 1, 2 and 3 in each forest type.

3.2. Biomass and Carbon Stock

The mean growing stock volume (GSV), total biomass, and total carbon stock varies significantly across different oak forests ($p < 0.01$). The GSV (m^3 ha^{-1}) ranged from 100.1 (B3) to 731.0 (M2). The maximum total biomass (Table 4) was recorded (Mg ha^{-1}) at M3 (989.1) and the minimum at B3 (263.0). Of the total biomass, the AGB varied between 204.6 (B3) and 787.3 (M3), and BGB between 58.4 (B1) to 201.8 (M3). The dominant species contributed 56–77% of the total tree layer biomass, except in Moru oak forest. The total carbon stock ranged from 118.3 (B3) to 282.4 Mg C ha^{-1} (B2) in Banj oak forest, 177.8 (R1) to 331.3 Mg C ha^{-1} (R2) in Rianj oak forest, 343.3 (M1) to 445.1 Mg C ha^{-1} (M3) in Moru oak forest and 152.5 (K1) to 343.8 Mg C ha^{-1} (K2) in Kharsu oak forest. Among all the forest types, the maximum total carbon stock (Mg C ha^{-1}) was recorded at M3 (445.1) of Moru oak forest and minimum at B3 (118.3) of Banj oak forest. Of the total carbon stock (AGC and BGC) the maximum carbon stock was recorded in the aboveground part, which is 79.64% of the total carbon stock.

Table 4. Growing stock volume (GSV), aboveground biomass (AGB), belowground biomass (BGB), total biomass (TB), litter fall (LF), aboveground carbon stock (AGC), belowground carbon stock (BGC), total carbon stock (TC) along the altitudinal gradient in different oak forests.

Forest Type	Sites	GSV (m^3 ha^{-1})	AGB (Mg ha^{-1})	BGB (Mg ha^{-1})	TB (Mg ha^{-1})	LF (Mg ha^{-1} $year^{-1}$)	AGC (Mg C ha^{-1})	BGC (Mg ha^{-1})	TC (Mg C ha^{-1})
Banj oak	B1	227.6	294.2	77.2	371.4	2.96	132.4	34.7	167.1
	B2	388.1	497.2	130.2	627.5	3.94	223.8	58.6	282.4
	B3	100.1	204.6	58.4	263.0	5.39	92.1	26.3	118.3
Rianj oak	R1	193.6	310.7	84.3	395.0	5.29	139.8	37.9	177.8
	R2	647.1	592.9	143.3	736.2	6.40	266.8	64.5	331.3
	R3	487.0	523.7	131.8	655.5	5.54	235.7	59.3	295.0
Moru oak	M1	335.3	597.4	165.4	762.8	4.44	268.8	74.5	343.3
	M2	731.0	715.4	177.0	892.4	6.10	321.9	79.6	401.6
	M3	649.2	787.3	201.8	989.1	6.28	354.3	90.8	445.1
Kharsu oak	K1	188.5	267.5	71.5	339.0	5.09	120.4	32.2	152.5
	K2	683.7	616.5	147.4	763.9	6.98	277.4	66.3	343.8
	K3	526.2	565.9	139.4	705.2	7.28	254.7	62.7	317.4

B1, B2, B3—B denotes Banj oak; R1, R2, R3—Rianj oak; M1, M2, M3—Moru oak; K1, K2, K3—Kharsu oak and numeric after alphabet denotes site 1, 2 and 3 in each forest type.

The total litter carbon stock of study site was 29.53 Mg C ha^{-1} $year^{-1}$. Litter fall biomass (LF, Mg ha^{-1} $year^{-1}$) was recorded highest at K3 (7.28) followed by K2 (6.98) and R2 (6.40). The litter carbon content followed the order Kharsu > Rianj > Moru > Banj oak forest with the highest value of 3.27 Mg C ha^{-1} $year^{-1}$ for K3 of Kharsu oak forest.

3.3. Anthropogenic Disturbance and Regeneration Pattern

It was recorded that Moru oak (M1, M2) and Kharsu oak (K1, K2) were moderately disturbed forest sites, while Banj oak (B1) and Rianj oak (R1) were the most highly disturbed oak sites in the study area. The PCA primarily reflected different environmental variables on forest communities (Figure 4). The first principal component, which indicated twelve forest sites as the major explanatory variable, explained 52.7% of variance. Livestock grazing, cutting, and lopping resulted in positive loadings (0.58, 0.49 and 0.20, respectively) and fire resulted in negative loading (−0.61). The second principal component explained 28.5% of the original variance and reflected four anthropogenic variables as the dominant explanatory variable. The second PC was associated positively with lopping, cutting, and fire (0.87, 0.22 and 0.03, respectively), but negatively with grazing (−0.45). Different forest sites were highly associated with the environmental variables measured. The highly lopped sites R2 and B1 were positioned to the right of PC1, and B2 and R3 were positioned to the left of the PC1. Sites K1, K2, and M1 were represented by more grazing signs, and sites B2 and R3 by fire, while sites R1 and K1 were represented by tree cutting in the study area.

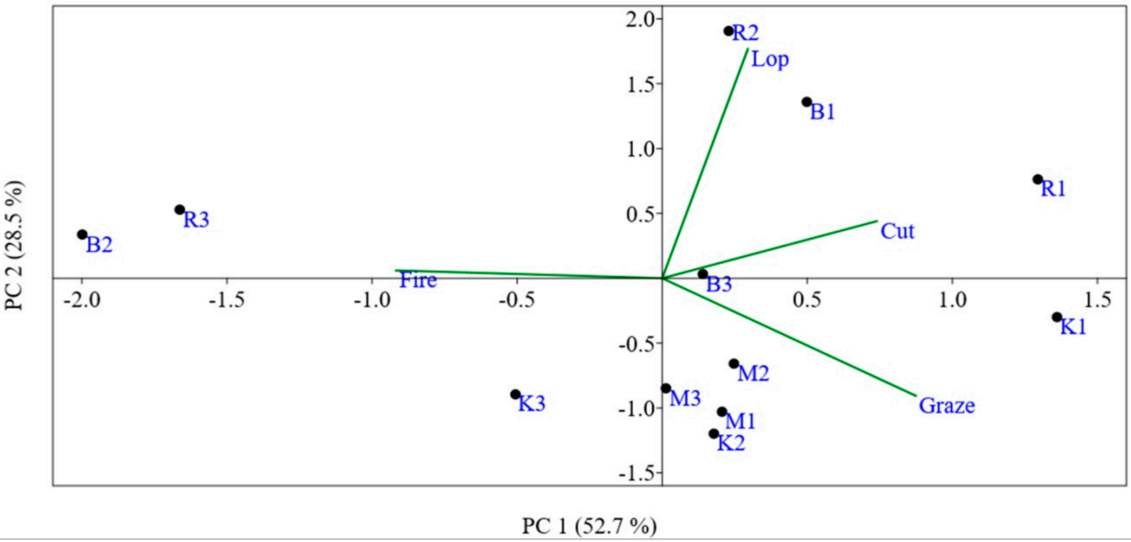

Figure 4. Principal component analysis indicating distribution of anthropogenic variables along first two principal components. The lines in the same direction show similarity whereas; lines in opposite direction indicate dissimilarity. B1, B2, B3- B denotes Banj oak; R1, R2, R3—Rianj oak; M1, M2, M3—Moru oak; K1, K2, K3—Kharsu oak; numeric after letter denotes site 1, 2 and 3 in each forest type.

At the forest level, the highest number of seedlings and saplings were observed in Kharsu oak (65.1%) followed by Rianj oak (64.5%), Moru oak (60.0%) and Banj oak forest (48.9%, Figure 5). In Kharsu oak forest trees were mostly distributed in higher girth class i.e., >121 cm girth classes (13.4%) followed by the 61–90 cm class (9.82%), where *Q. semecarpifolia* contributed in most of the classes (seedling to tree). In Rianj oak forest, about 20.9% of the tree individuals were represented by the 31–60 cm girth class, while other high girth classes were almost similar in occurrence. In Moru oak higher girth class trees were more in number and attained a maximum girth of up to 330–360 cm. In Banj oak forest, the distribution of individuals was highest (19.3%) in the 31–60 cm girth class followed by 61–30 cm girth class, whereas the representation of the higher girth class trees was poor. If we examined the overall regeneration status of the forests, the Rianj oak forest showed good regeneration, whereas Banj, Moru, and Kharsu oak forests displayed fair regeneration. Moreover, the overall regeneration of dominant species in Rianj oak forest was found to be good; however, the regeneration of Moru and Kharsu oak was poor.

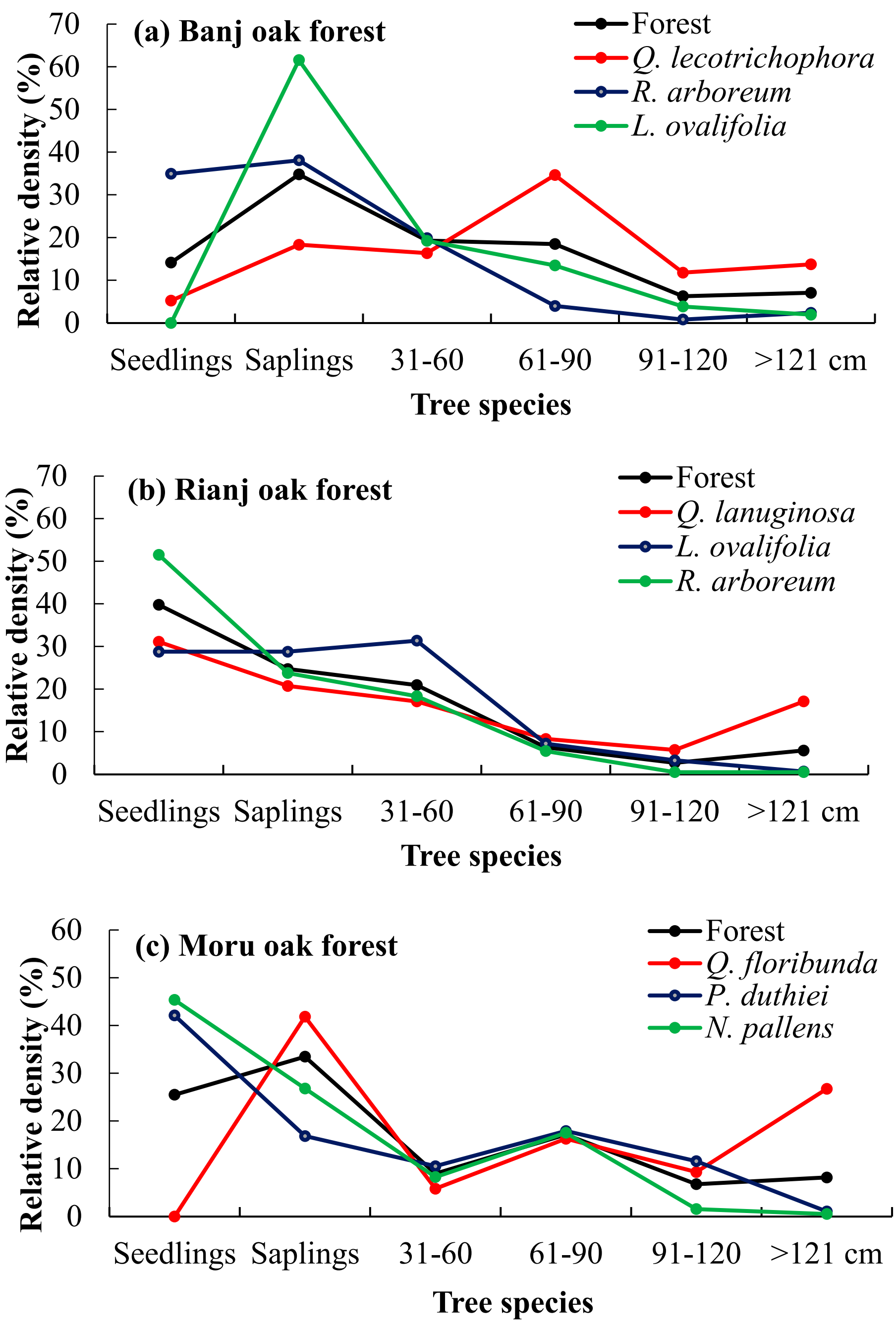

Figure 5. *Cont*.

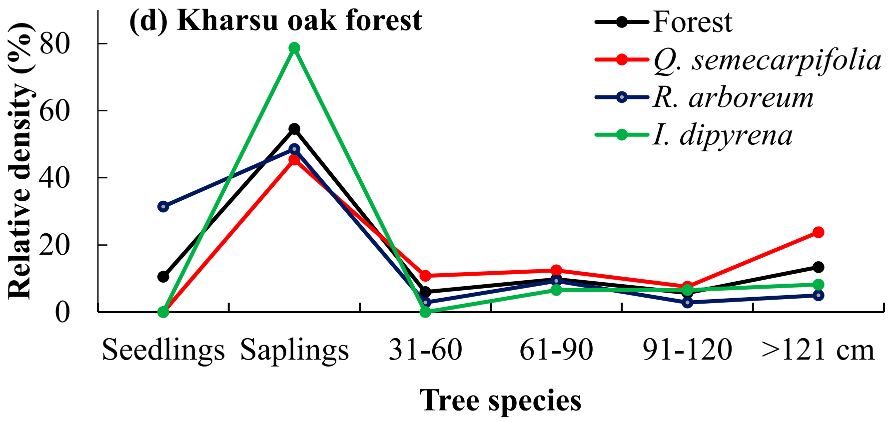

Figure 5. Girth class distribution of entire forest and dominant tree species in oak forest communities.

3.4. Soil Characteristics

The soil moisture ranged from 17.4% (K3) to 30.5% (B1). The maximum WHC was recorded at B1 (41.0%) and minimum (24.0%) at M3. The BD ranged from 0.42 to 0.71 g cm^{-3} at different forest sites. Soil organic content, soil texture, soil mineral density, and their packing patterns all influence bulk density. Among the chemical properties of the soil, pH ranged from 5.70 (R2) to 6.53 (M1). The highest soil nutrients (OC, N and K) were reported in Kharsu oak forest i.e., 3.52%, 0.34%, 324.6 Kg ha^{-1}, respectively while the lowest values were in Banj oak forest (2.62%, 0.19% and 103.6 Kg ha^{-1}, respectively). The value of p was highest at R3 (19.0 Kg ha^{-1}), and was lowest for K1 site (10.5 Kg ha^{-1}). The soil carbon stock (SCS, Mg C ha^{-1}) was highest at K2 (23.6) and lowest at B1 (17.7, Table 5).

Table 5. Soil physico-chemical properties in different oak forest communities.

FT	Sites	Mo (%)	WHC (%)	BD (g cm^{-3})	pH	OC (%)	N (%)	P (Kg ha^{-1})	K (Kg ha^{-1})	SOM (%)	SCS (Mg C ha^{-1})
Banj oak	B1	30.5 ± 1.6	41.0 ± 1.8	0.68 ± 0.06	6.01 ± 0.07	2.62 ± 0.1	0.24 ± 0.03	12.3 ± 1.2	103.6 ± 17.9	3.0 ± 0.3	17.7 ± 1.0
	B2	29.7 ± 2.2	37.7 ± 3.0	0.64 ± 0.05	5.76 ± 0.17	2.92 ± 0.1	0.22 ± 0.02	18.1 ± 1.3	110.1 ± 26.4	3.6 ± 0.3	18.5 ± 1.3
	B3	26.6 ± 1.3	34.5 ± 1.5	0.59 ± 0.08	6.41 ± 0.07	3.12 ± 0.1	0.19 ± 0.01	13.9 ± 1.5	112.0 ± 20.1	3.7 ± 0.2	18.3 ± 1.8
Rianj oak	R1	29.3 ± 1.4	38.5 ± 1.3	0.66 ± 0.06	6.03 ± 0.21	2.70 ± 0.1	0.25 ± 0.02	12.5 ± 1.2	110.0 ± 9.5	4.7 ± 0.1	19.5 ± 0.5
	R2	27.6 ± 2.7	38.0 ± 1.1	0.63 ± 0.06	5.70 ± 0.17	2.95 ± 0.1	0.26 ± 0.02	18.4 ± 1.9	132.5 ± 14.8	5.1 ± 0.1	19.1 ± 1.5
	R3	28.0 ± 1.5	35.6 ± 2.3	0.42 ± 0.06	5.68 ± 0.19	2.87 ± 0.1	0.28 ± 0.02	19.0 ± 0.9	112.0 ± 11.6	4.9 ± 0.2	18.3 ± 1.1
Moru oak	M1	23.8 ± 1.3	36.3 ± 2.3	0.68 ± 0.03	6.53 ± 0.10	2.85 ± 0.1	0.25 ± 0.02	11.0 ± 1.6	146.5 ± 19.7	3.2 ± 0.2	19.2 ± 0.5
	M2	22.9 ± 1.5	33.6 ± 2.0	0.66 ± 0.04	5.89 ± 0.09	2.97 ± 0.1	0.27 ± 0.02	12.5 ± 1.7	180.0 ± 17.8	3.5 ± 0.2	19.4 ± 0.3
	M3	20.2 ± 1.2	24.0 ± 2.3	0.62 ± 0.05	6.24 ± 0.17	3.11 ± 0.2	0.30 ± 0.03	14.4 ± 1.9	203.7 ± 22.0	3.7 ± 0.4	19.1 ± 0.4
Kharsu oak	K1	21.6 ± 0.9	40.6 ± 4.9	0.71 ± 0.04	6.31 ± 0.07	2.83 ± 0.1	0.28 ± 0.02	10.5 ± 0.4	219.8 ± 16.4	3.2 ± 0.2	20.0 ± 0.4
	K2	20.3 ± 1.1	40.2 ± 0.9	0.68 ± 0.05	6.20 ± 0.06	3.51 ± 0.4	0.31 ± 0.02	12.2 ± 1.1	246.8 ± 29.4	4.4 ± 0.7	23.6 ± 1.4
	K3	17.4 ± 1.9	39.1 ± 4.9	0.63 ± 0.05	6.15 ± 0.13	3.52 ± 0.3	0.34 ± 0.01	10.6 ± 1.4	324.6 ± 21.8	4.4 ± 0.5	21.9 ± 1.0

FT—forest type, Mo—moisture, WHC—water holding capacity, BD- bulk density, OC—organic carbon, N—total nitrogen, P—available phosphorus, K—available potassium, SOM—soil organic matter, SCS—soil carbon stock, B1, B2, B3—B denotes Banj oak; R1, R2, R3—Rianj oak; M1, M2, M3—Moru oak; K1, K2, K3—Kharsu oak and numeric after alphabet denotes site 1, 2 and 3 in each forest type.

Physico-chemical properties of soil varied across various forest types. The PCA result reflected the impact of edaphic factors on the quality of different forest communities. It was employed with nine soil attributes which were then reduced based on low eigen value (Figure 6). The first two components explained 65.0% of the overall variation. The PC1 axis explained 40.2% variance and indicated forest sites as the major explanatory variable, while the PC2 axis accounted for 24.8% and reflected soil variables as the dominant explanatory variable. There were two principal components that have an eigen value of more than one. The first component (PC1) with the highest loading values recorded was: PC1 = 0.48 (OC), 0.45 (SOM), 0.49 (K), 0.41 (N), −0.31 (Mo), −0.09 (BD), −0.20 (P), 0.08 (WHC) and 0.07 (pH). The second component (PC2) contributed 24.8% of the total relationship. PC2 = −0.58 (P), 0.56 (BD), 0.40 (pH), 0.21 (WHC), −0.14 (Mo), 0.10 (K), −0.21 (OC), −0.25 (SOM), and 0.04 (N).

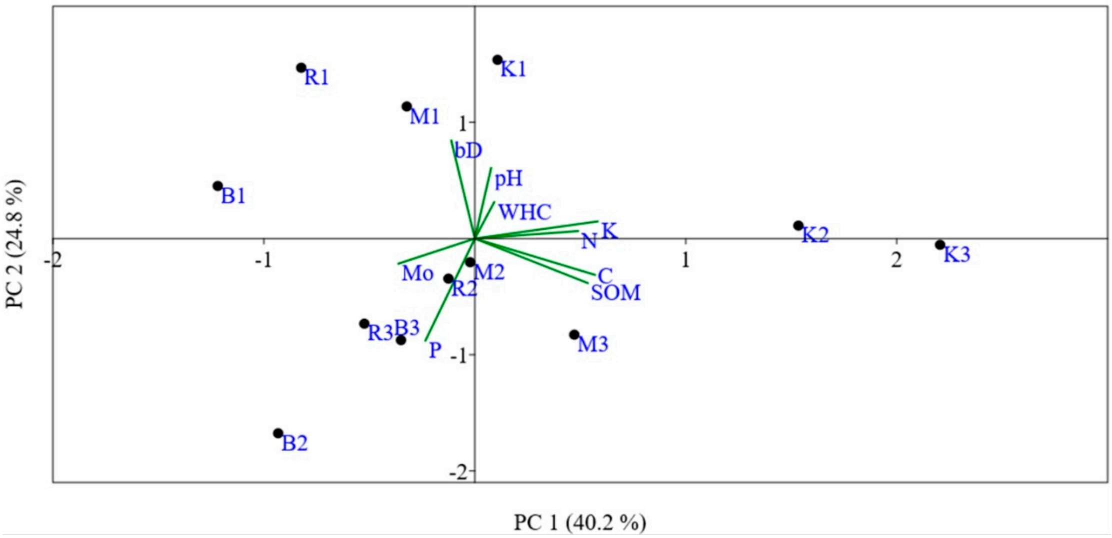

Figure 6. Principal component analysis (PCA) result showing soil physical and chemical properties in four oak forest types. PCA axis 1 expressed 44.4% and axis 2 represented 23.3% for first and second coordinates of sites, respectively. Mo—moisture; WHC—water holding capacity; bD—bulk density; C—carbon; N—nitrogen; P—phosphorus; K—Potassium, SOC—soil organic carbon, SOM— soil organic matter.

3.5. Relationship between Vegetative Parameters, Soil Physico-Chemical Properties, Altitude and Carbon Stock Variables

The basal area was strongly correlated (r = 0.84, $p < 0.01$) with carbon stock across the sampled sites. Tree density of forest species showed a significant negative correlation with N (r = −0.60) and SOM (r = −0.59). Moreover, tree diversity (TH) was negatively correlated with WHC (r = −0.60). OC, N and K were positively correlated with TBA (r = 0.66, r = 0.60 and r = 0.59, respectively). Among the soil parameters, N was positively correlated with OC (r = 0.65), and SOM was positively correlated with K (r = 0.67) and OC (r = 0.97, Table 6).

Table 6. Pearson's correlation matrix for different environmental variables of four oak forests (n = 12).

	Alt	TD	TBA	TH	Mo	WHC	pH	OC	N	P	K	SOM	D	TC
Alt														
TD														
TBA														
TH														
Mo	−0.61 *													
WHC				−0.60 *										
pH														
OC	0.77 *		0.66 *											
N	0.81 *	−0.60 *	0.60 *					0.65 *						
P							−0.61 *							
K	0.94 **		0.59 *		−0.67 *			0.75 *	0.77 *					
SOM	0.66*	−0.59 *	0.68 *					0.97 **			0.67 *			
D			−0.58 *					−0.59 *						
TC			0.84 **					0.40 *					−0.65 *	

** Significant at 0.01 and * at 0.05, empty cells show insignificant correlation, Alt—altitude, TD—tree density, TBA—total basal area, TH—tree diversity, Mo—moisture, WHC—water holding capacity, BD—bulk density, OC—organic carbon, N—nitrogen, P—phosphorus, K—potassium, SOM—soil organic matter, R—regeneration, D—disturbance, TC—Total carbon stock.

The basal area of tree species has a significant positive impact on carbon stock ($R^2 = 0.73$, $p < 0.01$) when tested with linear regression (Figure 7).

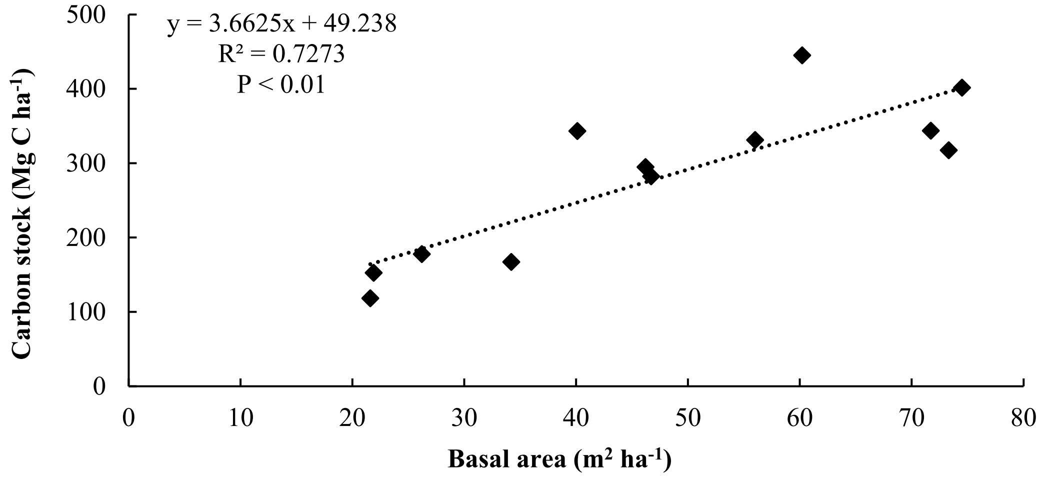

Figure 7. Relationship between basal area and carbon stock of four oak forest communities in the study area (n = 12).

Results from ANOVA indicated that forest type had significant effect ($p < 0.05$) on WHC and tree diversity while it also had significant effect ($p < 0.01$) on species richness, soil moisture, nitrogen and potassium. This study also reported that altitude had significant effect ($p < 0.01$) only on bulk density, while all other parameters do not show any significant difference due to altitude. Our study reported that disturbance had a significant negative impact on basal area, total carbon stock and soil OC. The altitude showed a significant positive effect on OC (r = 0.77), N (r = 0.81), K (r= 0.94) and SOM (r = 0.66), however Mo (r = −0.61) showed negative correlation with altitude.

4. Discussion

All forest types showed a clear pattern in the segregation of total biomass into above- and below-ground components. The contribution of AGB (78.9–80.2%) and BGB (19.8–21.1%) to the total biomass is comparable to the values reported (79.6% AGB and 20.4% BGB) by Kaushal and Baishya [44], (78.5% AGB and 21.5% BGB) by Sharma et al. [45] and (79% AGB and 21% BGB) by Chhabra [46]. We identified relations among vegetation, edaphic factors and biotic factors in our study sites, explaining a large part of the variation in carbon stock. Key factors for understanding the carbon stock are community structure, regeneration, elevation, disturbance, and soil conditions, which influence the growth and development of a forest ecosystem. Since carbon is proportional to biomass, the higher the biomass, the greater the carbon stock.

4.1. Influence of Community Structure on Carbon Stock

The significant positive impact of basal area of tree species on carbon stock suggests the existence of canopy-dominating trees of higher girth classes in the forest sites. Moru oak had higher carbon stock than other oaks due to a greater number of individuals in higher girth classes, which indicates that these forests stored more carbon as compared to other forest types. Species richness and diversity did not correlate with carbon stock [47]. Sharma et al. [21] and Gandhi and Sundarapandian [48] observed a negative correlation between tree diversity and biomass, whereas Behera et al. [45] reported a positive correlation between the two variables. Therefore, such studies are critical on a regional scale for determining forest management and carbon stock improvement.

Tree density showed a significant negative correlation with N and SOM, which might be due to the presence of anthropogenic pressures in these oak forests. This understanding of the impacts of tree species on soil carbon is crucial for the C-cycle and greenhouse gas reduction. The WHC was higher in Kharsu oak forest, indicating that more litter was produced by this forest type, which boosts the capacity of the soil to retain water. BD was highest in the Kharsu oak forest while moisture content was found to be low compared to other forest types, which may possibly be due to the uncontrolled grazing pressure on this forest as grazers promotes soil compaction [49], which leads to high BD and lowers the moisture content [50]. Grazing also reduces the stability of soil by disrupting the soil aggregates [15]. The low density, diversity and species richness on any ecosystem due to highly compact, less moistened soil indicates that soil compactness leads to species loss in that area [51].

Physico-chemical features of soil are connected with several phytosociological indices, suggesting that the species with high nutrient contents may be major driver in the connection between community structure and carbon stock. N showed a positive correlation with TBA, which is supported by Gairola et al. [52]. The N was highest in Kharsu oak forest type, where biomass was also higher. Soil C was highest in Kharsu oak forest, where TBA was also highest. WHC was highest in Banj oak, where TH was the least. Higher concentration of OC and N may have given rise to higher biomass in this forest type. The lowest value of N was recorded in Rianj oak site, where the value of TBA was very low and the highest value of N was observed in Kharsu site, where TBA was at its maximum. The high K contents were recorded under Kharsu oak forest because the oak individuals are related to greater K release [53].

4.2. Influence of Altitude

Altitude is recognized as a key component that governs the vegetation characteristic and the process of soil formation [54] by changing topographic and climatic factors. Its variation among the forest types also played a key role in explaining disparities in carbon stock. Altitude showed a significant effect on the basal area of different forest types. Several authors stated that carbon stocks decline with increasing altitude. According to Singh et al. [55], TB in diverse forest types in the Kumaun Himalaya remained high, up to 2600 m. Similarly, in the Garhwal Himalaya Gairola et al. [47] observed that TB was lower above 2650 m (*Q. semecarpifolia*). We also noticed a substantial drop in TB over 2600 m (*Q. semecarpifolia*).

Altitude showed a significant effect on BD. Bulk density decreased with increasing altitude in all the forests. The distribution of different soil nutrients is influenced by the altitudinal gradient. Soil OC, N, K, and SOM bear a strong significant positive correlation with altitude. The nutrients were especially rich at high elevation sites of Kharsu (K3) and Moru oak (M3) forests. However, Mo showed a negative relationship with altitude, which might be because the high-altitude locations are exposed to direct sunlight for longer time than low altitude sites. The annual accumulation of leaf litter and the slow decomposition of organic wastes at low temperatures account for the increase in SOM with increasing altitude [35]. Tripathi [56] investigated a substantial positive association between OC and altitude (600–2200 m). We also observed that soils under Banj forest (B1) have less carbon than the soils under Kharsu forest.

4.3. Influence of Regeneration and Disturbance

Anthropogenic pressures such as the cutting of trees for fuelwood are responsible for releasing CO_2 into the atmosphere, causing global climate change. Biotic pressures such as livestock grazing, tree lopping, cutting, and wildfires are important factors affecting carbon stock of temperate forests [57]. Our study reported that disturbance has a significant negative impact on TBA, C and carbon stock. The study revealed that B1 and R1 forest sites are poor in soil nutrients comparatively due to the presence of high disturbance. These two oak forests are the most suffered in the study area for their nutrient-rich leaves for cattle feed.

Such disturbances create large gaps in the forest canopy, influencing the future carbon reserves of the forests as a result [17]. The forests with high disturbance (B1, R1) had poor regeneration in Banj and Rianj oak; however, the degree of disturbance might not be the only factor influencing regeneration failure in Moru and Kharsu oak. The abundance of seedlings in the area with the maximum disturbance (Rianj oak forest) suggests that species often reproduce there. This is because disturbance in oak forests reduces understory vegetation, which also makes it feasible for seedlings to establish themselves on the forest floor [58]. In Kharsu and Moru oak forest the dominant species showed a complete absence of seedlings, which indicates poor regeneration status of these species in their respective forest site. The complete absence of seedlings was probably due to the damage to seedling recruits by overgrazing and trampling of grazers; this will result in gradual lowering of its population in the near future [59]. Protecting these two high-altitude oak forests from summer grazing would help in sustaining them in the long term.

As forest sustainability is ensured through successful regeneration, understanding the processes that drive forest regeneration is critical for both forest managers and ecologists. Because anthropogenic disturbance may diminish forest regrowth and carbon stock, these forests require rigorous management practices [17,19]. Furthermore, providing cooking gas (LPG, natural gas) in Himalayan regions might improve the carbon sequestration capacity of these forests by relieving pressures on forest resources.

4.4. Influence of Soil Nutrients

The four oak forests differed significantly in soil physico-chemical properties. According to Paudel and Sah [60], physico-chemical properties of soil vary according to topography, climate, land use, vegetation type, disturbance gradient, and several other living and non-living components of the ecosystem [61,62]. Soil properties frequently change within a very short distance in the Himalayan belt [63,64]. OC, N, K, and SOM were important soil nutrients in the present study, affecting plant structure and consequently influencing the carbon stocks of different forest types.

More nutrient availability promotes tree height and biomass stocks with rising altitude [65]. The value of N was higher in B1 with high disturbance. Moreover, N showed a significant positive relationship with OC and K, which is also observed by Gairola et al. [52]. According to Zhenghu et al. [66], SOMs rich in N have high absorption capacity, which boosts soil fertility. Therefore, a high amount of SOM in site M3 and K3 might also be the reason for more N in these forest types. Thus, the variations in soil nutrients appeared to be driving the differences across forest types.

Nutrient-rich soil generally has a pH range of 5.5 to 7.2, with a significant impact on plant nutrient availability [67]. The majority of the forest sites in our study had soils with a pH greater than 6.0, which could be associated to the high level of disturbance. Padalia et al. [68] reported a positive correlation between OC and BD, while Bargali et al. [14] stated a negative correlation indicating that as OC increases, the BD of the soil drops, which is important for plant growth. In the present study, BD showed a negative correlation with OC, though the values were not significant. K is not influenced by SOM, since it is not a provider of K [69]. In our study, K showed a significant positive relationship with OC and SOM. This was reinforced by the finding of Gairola et al. [52] and Kumar et al. [70] and concluded that a layer of SOM enhances the K retention in the soils considerably. Greater K release is associated with oak individuals, which is the primary explanation for the greater K content in the soils of Moru oak and Kharsu oak forest [53]. The amount of SOM in the soil impacted the dispersion and development of plants [71]. We observed a positive correlation of SOM with OC and K. SOM concentration in fine-textured soils typically ranges from 3–10% by weight [72]. According to Bargali et al. [14], OC is vulnerable to anthropogenic pressure, resulting in depletion of OC. To raise the OC content in the soil, a specific level of soil moisture is necessary for the decomposition of residue [73]. A higher concentration of OC in the soil might facilitate higher biomass in the forest ecosystems. OC in highly disturbed sites B1 and R1 were comparatively lower, which might be because of the litter removal from the forest floor. More litter fall (Rianj and Kharsu oak) leaves more organic matter and improves fertility of the soil (Figure 8).

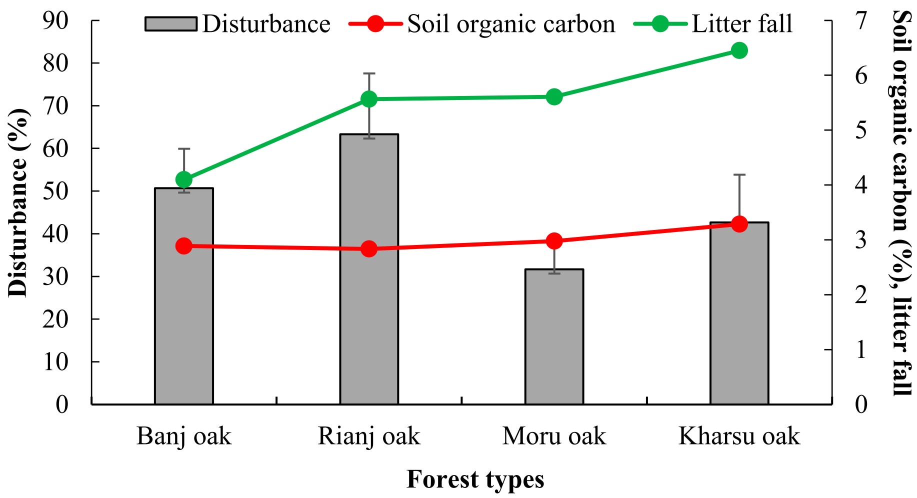

Figure 8. Soil organic carbon, litter fall and anthropogenic disturbance in different forest sites.

4.5. Comparative Study of Biomass, Carbon Stock and Chemical Properties of Soil

Several authors reported total biomass (Mg ha^{-1}) and carbon stock (Mg C ha^{-1}) values for Banj oak forest in the range of 200.1–433.0 and 92.0–194.9, respectively, for Rianj oak forest from 227.2–562 and 107.9–261.8, for Moru oak forest from 292.4–787.0 and 134.5–354.2, and Kharsu oak forest from 279.3–590.2 and 128.5–265.5 in the Uttarakhand Himalaya (Table 7). In the present study, the mean values of biomass (420.6–881.4) and carbon stock (189.3–396.6) fall within the range of earlier studies from Uttarakhand Himalaya for Banj oak forest, whereas the rest of the oak forests fall within the upper range. The maximum mean value of TC (Mg C ha^{-1}) for Moru oak forest in the study area was recorded as 396.6 $\pm$ 29.5 and the least in Banj oak forest (189.3 $\pm$ 48.6). The maximum amount of carbon (obtained by multiplying the mean value of TC with the respective forested area) was stored in Moru oak forest (2454.6 Gg C) and least (525.1 Gg C) in Rianj oak forest (Figure 9). The total carbon stored in the valley was estimated as 5470 Gg C. Our findings showed that soil is the largest pool of forest carbon (43.0–59.7%) followed by AGB (31.5–45.0%), BGB (8.4–11.7%), and litter (0.4–0.5%, Figure 10).

Table 7. Comparative account for biomass carbon stock of similar communities across Uttarakhand Himalaya.

Forest Type	Altitude (m)	TB (Mg ha^{-1})	TC (Mg C ha^{-1})	Reference
Banj oak	1200–2300	391–433	176.0–194.9 *	[9]
	1950	387.3	174.3 *	[74]
	1600–2100	200.1	92.0	[21]
	1500–1650	215.5	107.8	[47]
	1800	317–319	149.0	[75]
	1750–1950	230.12	109.3	[76]
	1750–2200	420.6 ± 108.1	189.3 ± 48.6	Present study
Rianj oak	1800–2400	294–562	132.3–252.9 *	[9]
	2240	285.3	128.4 *	[74]
	2150	557	261.8	[77]
	2050–2250	227.23	107.9	[76]
	1900–2200	595.6 ± 103.0	268.0 ± 46.3	Present study
Moru oak	2100–2700	467–787	210.2–354.2 *	[9]
	2194	458.5	206.3 *	[74]
	2200	782.0	367.5	[77]
	2300–2600	292.4	134.5	[21]
	2550–2650	429.7	214.8	[47]
	2100–2750	588.5	276.6	[35]
	2300–2500	881.4 ± 65.6	396.6 ± 29.5	Present study
Kharsu oak	2650	590.2	265.5 *	[78]
	2500–3000	279.31	128.5	[21]
	2650–2850	389.5	194.7	[47]
	2100–2750	522.34	245.5	[35]
	2600–3000	602.7 ± 132.9	271.2 ± 59.8	Present study.;

* Biomass was converted (45%) using Manhas et al. [38].

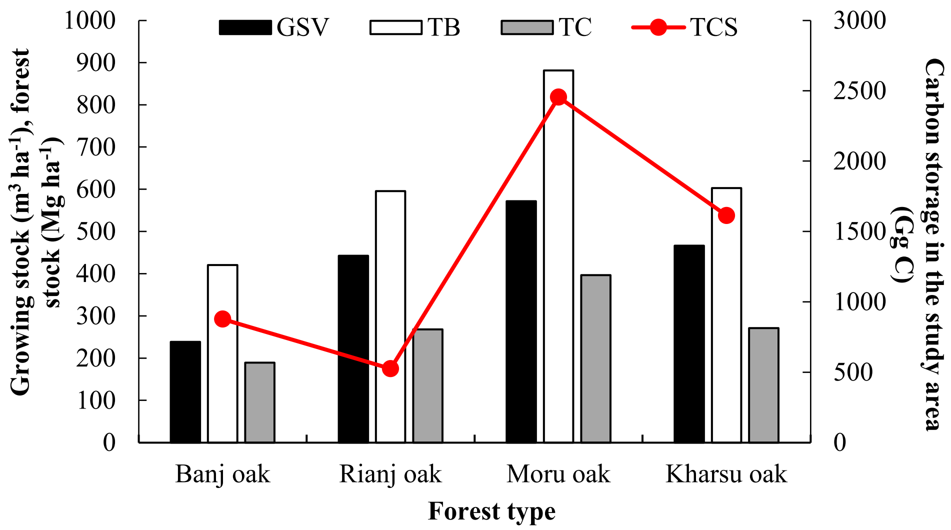

Figure 9. Stock distribution among different forest types along the altitudinal gradient (GSV—growing stock, TB—total biomass stock, TC—total carbon stock, TCS—total carbon storage in the valley).

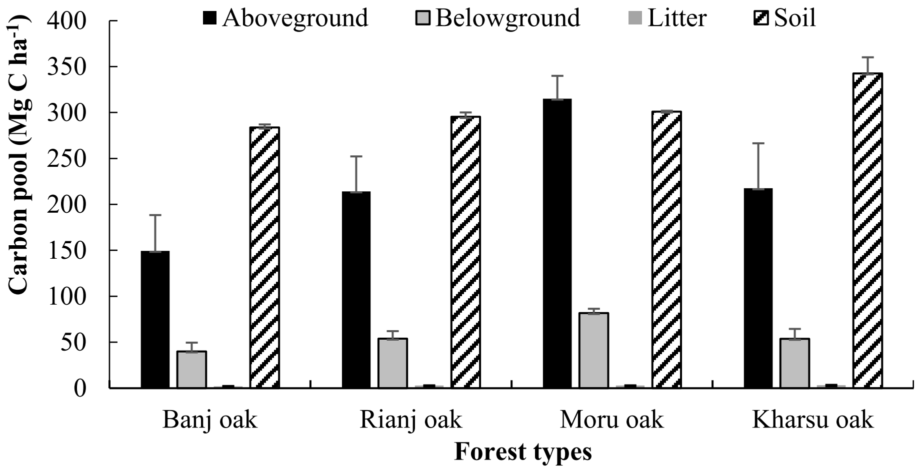

Figure 10. Carbon pool in various oak forest communities in the study area.

The values of OC, N, P, K, and pH for all the oak forest in the present study are 2.62–3.52%, 0.19–0.34%, 10.5–19.0 kg ha^{-1}, 103.6–324.6 kg ha^{-1}, and 5.68–6.53, respectively, which are within the range of values (0.42–6.15%, 0.07–0.34%, 7.2–31.9 kg ha^{-1}, 72.7–712.0 kg ha^{-1}, and 5.4–6.7) recorded by Gairola et al. [52], Sharma et al. [79], Kumar et al. [80], Nazir [81], Semwal [82], and Thadani and Ashton [58] in the Kumaun and Garhwal Himalaya. The value of SOM (3.0–5.1%) in the present study is within the range (0.72–6.15%) recorded by Bargali et al. [14], Gairola et al. [52] and Nazir [82] in the Uttarakhand Himalaya (Table 8).

Table 8. Comparative account for chemical properties of soil of similar communities at different altitudes across Uttarakhand Himalaya.

FT	Altitude (m)	pH	OC (%)	N (%)	P (Kg ha^{-1})	K (Kg ha^{-1})	SOM (%)
Banj oak	1500–1650 [a]	5.50	2.44	0.17	5.75 *	40.67 *	4.12
	1600–2100 [b]	5.81–6.37	0.42–2.31	0.07–0.25	4.11–6.53 *	66.89–139.59 *	0.72–3.99
	1600–2100 [c]	5.5–6.2	1.9–2.5	0.16–0.21	11.5–31.9	86.1–603.8	-
	1700–1850 [d]	5.9–6.3	0.87–1.01	0.08–0.09	13.6–15.5	180.9–215.7	-
	1900–2400 [e]	5.4–5.7	1.3–1.9	0.10–0.20	9.3–12.0	153.2–408.8	-
	Montane [f]	-	1.88–4.00	0.17–0.30	-	-	-
	Up to 2000 [g]	5.37–6.63	2.21–3.58	0.12–0.30	0.02–0.07 **	-	2.93–4.74
	1700–2100 [p]	5.76–6.41	2.62–3.12	0.19–0.24	12.3–18.1	103.6–112.0	2.97–3.71
Rianj oak	1900–2200 [p]	5.68–6.03	2.70–2.95	0.25–0.28	12.5–19.0	110.0–132.5	4.70–5.10
Moru oak	2300–2600 [c]	5.9–6.1	1.6–2.2	0.14–0.17	13.8–23.2	356.7–712.0	-
	2550–2650 [a]	6.13	2.70	0.26	5.30 *	129.17 *	4.65
	2300–2600 [p]	5.89–6.53	2.85–3.11	0.25–0.30	11.0–14.4	146.5–203.7	3.24–3.68
Kharsu oak	2500–3000 [c]	5.8–6.7	2.3–2.6	0.19–0.22	7.2–14.3	72.7–135.1	-
	2650–2850 [a]	6.67	3.56	0.34	8.33 *	261.17 *	6.15
	2600–3000 [p]	6.15–6.31	2.83–3.52	0.28–0.34	10.5–12.2	219.8–324.6	3.20–4.40

* Values in ppm, ** values in percentage, [a] Gairolat et al. [52], [b] Nazir [81], [c] Sharma et al. [79], [d] Semwal [82], [e] Kumar et al. [80], [f] Thadani and Ashton [58], [g] Bargali et al. [14], [p] Present study.

4.6. Sustainable Forest Management Regimes

Plantation of broadleaved trees should be encouraged in the area as these trees increase forest cover, maintains soil fertility, stabilize soil erosion, increase aeration and water infiltration, while adding nutrients to the soil. In wastelands and along agricultural fields, fast-growing fodder species and native grasses should be promoted. Annually, no more than 25–30% of the leaves should be removed, especially if the tree is mature [83], to ensure that the tree's growth and regeneration are not harmed. Trees outside of forests, on the other hand, could be used as a substitute for timber and fuelwood, contributing to carbon sequestration and biodiversity conservation in Himalayan forests. Chir pine needles should be utilized on a commercial scale and forest litter should be collected from the forest floor to minimize wildfire. Rotation of grass cutting in different compartments would aid in the transformation of seedlings to saplings, and to trees. It will ensure the long-term conservation of forests, local biodiversity, and sustained flow of ecosystem services to the local inhabitants and downstream communities. Apart from this, the local agro-pastoral communities in this area should be encouraged to meet their fuelwood and fodder requirements around lower elevations (below 1700 m). Biogas, solar energy, and subsidized supply of LPG will help in minimizing the effects of climate change in the Himalayan region.

5. Conclusions

The study reveals that Moru oak and Kharsu oak forests account for the largest biomass (881.4 $\pm$ 65.6, 602.7 $\pm$ 132.9 Mg ha^{-1}) and carbon stock (396.6 $\pm$ 29.5, 271.2 $\pm$ 59.8 Mg C ha^{-1}) respectively in the study area, with moderate levels of disturbance. Both the natural and man-made disturbances affect the carbon stock of oak forests by altering the micro-climatic condition of that area. This study concludes that the moderate level of disturbance in the forest is suitable for accumulation of a considerable amount of carbon, while the high level of disturbance reduces the regeneration potential of a forest and also disturbs the soil of that forest, making it nutrient deficient. The study reports that Banj and Rianj oak, the highly disturbed forest species, are comparatively poor in soil nutrients and lack regenerating individuals. This prevents these forests from storing a substantial quantity of carbon stock and limits the forest in its capacity to reduce carbon emissions. The present study supports that forest structure, anthropogenic factors, regeneration and edaphic factors contribute substantially to the carbon stock of the area. Considering the significance and the ecological sensitivity of these overexploited oak species, it is recommended to utilize small-girth trees or trees outside forest for timber and fuelwood needs. Natural regeneration and sustainable utilization of these species are crucial since they represent future carbon supply security. Effective land management necessitates the protection of the oak species, which contributes the most to the total carbon stock and potential sequestration in the area. To reduce the strain that human activities place on these natural forests, some fast-growing, high-density tree species or fuelwood plants can be planted in the village corridors. Developing a mechanistic knowledge of how these life-sustaining oak forests adapt and will respond to future manifestations of numerous global change phenomena is crucial. As a result, both the conservation objectives and the sustainable use of these forest resources will be enhanced.

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