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Variation in Productivity, Carbon Sequestration and CO_2 Mitigation of Community Forests in Kumaun Himalaya, India

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ABSTRACT

This research illustrates various aspects related to productivity, carbon content, and the mitigation of community forests in the Kumaun Himalayan forest, India. The bulk density, pH, organic matter and carbon of soil ranged from 0.9–1.1 g cm^{-3}, 5.6–6.5, 1.1–1.3 %, and 0.67–0.78%, respectively. The vegetation layer is ordered by density: Tree, shrub and herb. While the stock of vegetation biomass and NPP of forest varies 177.08±35.83 – 434.75±28.23 mg/ha and 6.72±1.41 – 13.79±1.59 mg/ha/yr. Among these, tree biomass and NPP accounted for 25.20–56.15% and 61.01–83.39%, respectively. The forest floor litter biomass was 2.57±0.45 – 2.75±1.00 mg/ha. The stock of vegetation carbon and sequestration of community forests was between 87.30±17.61 – 209.52±14.16 mg/c/ha, and 3.19±0.67 – 6.55±0.75 mg/c/ha/yr, respectively. However, vegetation's total CO_2 mitigation was 11.71±2.45 – 24.03±2.77 mg CO_2/ha/yr, of which the tree layer contributed 61.01 – 83.39%. Based on the findings, it can be concluded that the studied forest is mitigating a low amount of carbon compared to other previous studies. This is due to unsustainable exploitation of forest resources by rural communities, degraded forest conditions and lack of prudent scientific forest management inputs. Thus, it has indicated that there is an urgent need for scientific inputs in conserving, protecting and managing the existing forest conditions regarding productivity and carbon mitigation.

Keywords Biomass stock, Carbon sequestration, CO_2 mitigation, Kumaun himalaya, Forest productivity.

INTRODUCTION

In the Himalayan region, forests serve as a reservoir of carbon sinks and are a valuable natural resource. Himalayan forests of Uttarakhand are owned and managed by various stakeholders such as the government, community and private people for their economic, social and ecological benefits. However, forests protected and managed by communities, especially in the Himalayan region of Uttarakhand,

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are legally known as Van Panchayat forests or village community forests. Thus, community forestry activities in the region have multiple benefits such as forest products like firewood, fodder, ecological stability, an increase in carbon stock and sequestration, improved livelihoods, and climate change reduction (Charnley and Poe 2007). Resilience and diversity (structural complexity) are strongly positively correlated ; thus, the greater the resilience of an ecosystem, the greater its recovery potential from adverse conditions (Qiao *et al.* 2021, Lian *et al.* 2022, Qiao *et al.* 2023). Regional forests have a global impact on climate change problems (Salunkhe *et al.* 2018). Plants of the forest ecosystem capture and store atmospheric carbon (Borah *et al.* 2015). In addition to the litter accumulation and decomposition processes also stores carbon in the forest soil. The retention capacity of one forest to another varies depending on the site, topography, soil, climate, and the occurrence of species composition. Currently, the forest ecosystem faces many challenges, such as forest fires, loss of biodiversity, habitat alteration, forest fragmentation, and human disturbances, which are further aggravated due to climate change. Due to continuous development and urbanisation, carbon dioxide (CO_2) emissions are constantly increasing, which has complicated conditions like climate change and global warming. Recently, India has been facing huge negative impacts from environmental, social, and economic aspects. Increasingly severe climate events, environmental and human disturbances, forest fires, pests and diseases can destroy forests, thereby reducing forest services. Climate change caused by human influences is negatively affecting forest ecosystem dynamics and resilience to invasive species and diseases, which is likely to have negative impacts on the ecosystem and forest-based livelihoods of local people shortly. Thus, climate change is a combination of changes in temperature, rainfall, drought and floods, which consequently impact on ecosystem's functioning, including the shape and type of the forest, reduction in carbon storage, increase in pests, diseases and forest fires. Which can lead to the extinction of species in particular. However, forests are important in absorbing carbon dioxide from the atmosphere. As a result of climate change, trees' ability to store carbon is declining, which raises the atmospheric concentration of carbon. Hot and dry environments is increasing incidents like forest fires, due to which forests are being destroyed more rapidly, due to which stored carbon is also going into the atmosphere. Climate change is giving more importance to forest pests and diseases, which are affecting biodiversity. As a result, changes in forest ecosystems are reducing the availability of commodities such as fire-wood, litter, fodder, grasses and other minor usufructs, thereby adding to the existing pressure on forest resources by forest-dependent communities. Therefore, understanding and explaining the contribution of forests to climate regulation is essential to develop effective forest management strategies so that forest resources can be used sustainably. In this context, research on the development of forest growing stock is essential so that the existing forest can be maintained from a higher biomass and carbon potential point of view, particularly in those forests utilized by the surrounding communities in any part of the region or elsewhere. However, there is a paucity of data about the potential of community forests of the Himalayan region, especially regarding productivity, carbon sequestration, and CO_2 mitigation potential. Therefore, the present research work was conducted in the community forests, commonly known here as Van Panchayat, in Uttarakhand, India. The study objectives were to explore and assess real-time information on the community forests, including their productivity, carbon stock, sequestration, and mitigation of CO_2 in the Almora District of Kumaun Himalaya. This paper illustrates the various parameters of community forests of the Himalayan region, such as biomass, productivity, forest floor litter biomass, soil carbon storage, carbon stock, carbon sequestration and CO_2 mitigation potential.

MATERIALS AND METHODS

Brief overview of the study area

Research investigation sites were located at (29°52'59.99"N, 79°20'59.99") in the Almora district of Kumaun Himalaya, Uttarakhand, India. Three forest sites in Almora district, namely, Gairar-Barati-Bhainar Community Forest (GCF), Soangaon Community Forest (SCF), and Bhatkot Community Forest (BCF) were selected for the study. These forests are managed by communities known

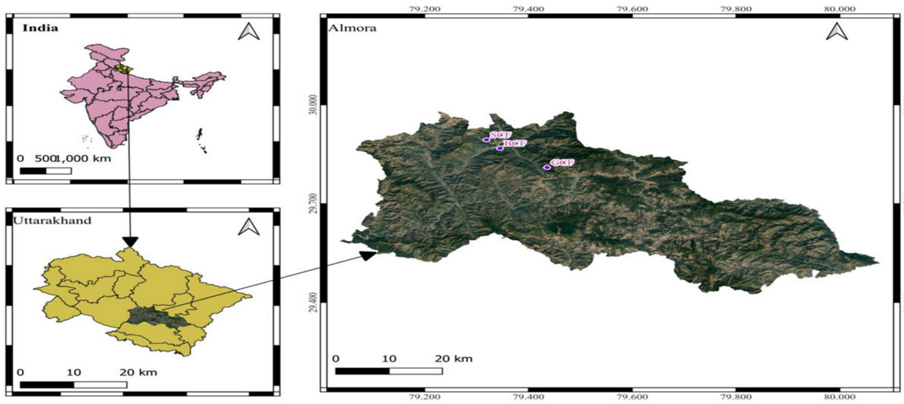

Fig. 1. Map of the study sites.

as Van Panchayats in Uttarakhand. These forests are generally based on community forest management, which was established in 1930 as Van Panchayat forests. In terms of ecology, these forests consist of coniferous trees such as pine (*Pinus roxburghii*) and its allies, as well as broadleaf species such as oak (*Quercus leucotrichophora*) and *Myrica esculenta* and *Rhododendron arboreum*, their associates. Apart from that, there are various other canopy shrubs, herbs and grasses. The soil of these forest sites was found to be of sandy loam and sandy clay type. This type of soil contains a significant amount of clay in the stratum besides gravel and stone particles. The soil's pH was primarily acidic. A comprehensive overview of community forests is depicted in Table 1– Fig. 1.

Methods of sampling techniques

Vegetation analysis

Vegetation analysis was carried out on trees, shrubs, and herbs to assess their density, diversity, and basal area in each community forest of Almora Kumaun Himalaya. The quadrat method was employed to quantitatively analyze the vegetation following Mishra 1968, Saxena and Singh 1982.

Biomass estimation

Tree biomass was quantified using allometric equations of different components as developed (Chaturvedi and Singh 1987, Rawat and Singh 1988). Biomass value was calculated as follows: Average diameter/ Cbh of respective tree species and its tree density, which is placed in the allometric equation of the respective component of tree species of the forest. The gross tree biomass in the community forest was calculated by combining the biomass components of all trees. The biomass of the shrub was estimated using allometric equations of different components, as given for shrub species by Rawat and Singh (1988). The gross stock of shrub biomass was obtained after

Table 1. Description of study area.

Parameters	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)
Latitude	29°48'36.0"N	29°53'38.4"N	29°52'05.3"N
Longitude	79°26'09.6"E	79°19'08.4"E	79°20'42.4"E
Elevation (m)	1613-2149	1049-1282	981-1103
Aspect	West facing	South facing	North East
Forest area (ha.)	112.89	65.56	99.52
Soil type	Loam, silt clay loam and clay loam	Silt loam, clay loam and loam	Clay, silt clay loam and clay loam
Soil pH	6.1	6.5	5.6
Bulk density g./cm^3	0.9	1.2	1.1
Soil moisture %	10.8	3.2	2.8

aggregating the biomass of all shrubs. Herb biomass had been measured in August-September of 2022, when growth was at the highest level. Herbaceous layer samples that had been harvested and exposed to thermal drying at 70°C. The component-wise dry weight of herbs was estimated in the community forest. In each community forest, total vegetation biomass was determined by aggregating the biomass of the tree, shrub and herb layers.

Net primary productivity (NPP) estimation

The NPP of tree species was estimated by allometric equations of different tree components in the forest. For this, the parameters, i.e. annual Cbh was taken at breast height 1.37 cm, and tree density per unit area of the respective tree species was taken. Tree Cbh was measured in the initial period (May 2022) and one year later (May 2023). The overall NPP of tree species in the respective forest site was determined by combining the tree productivity of all species. The NPP of shrubs was determined using allometric equations of different shrub components given by Rawat and Singh (1988). The annual growth diameter/CBH of each shrub species was marked and measured at 15 cm aboveground level in the initial year (May 2022). The component-wise NPP of each shrub species was estimated using the growth and density of the species. Total shrub NPP was determined by summing the NPP of each shrub species in each forest. Herbs are seasonal plants in the forest, their maximum growth occurs during the rainy season. During their period of peak growth (August – September 2022), the biomass previously gained through harvesting was regarded as their productivity. The gross NPP of the forest was calculated by adding the NPP of all vegetation layers.

Forest litter biomass

To estimate forest floor litter biomass, the methods given by (Chaturvedi and Singh 1987, Lodhiyal *et al.* 1995, Lodhiyal *et al.* 2002, Lodhiyal 2012) were used. Forest floor litter biomass was determined by randomly placing 15 quadrats of 1×1 m size in each forest site. The samples of litter were divided into various components, i.e., woody litter, partially decomposed, fresh leaves, and miscellaneous and exposed to thermal drying at 70°C to weigh the material. The dry mass of each component was then aggregated to estimate total litter biomass for each respective forest.

Analysis of soil organic carbon (SOC) and organic matter (SOM)

The Walkley and Black method was used to calculate the SOC (Walkley and Black 1934, Mishra 1968) for 0–30 cm soil depth. In this procedure, 27 soil samples from every forest (3 samples each from soil depths 1–10 cm, 10–20 cm and 20–30 cm, a total 9 samples from the forest sub-site) were gathered. The following formula was used for soil organic matter estimation.

$$\text{Organic matter} = \text{Organic carbon} \times 1.724$$

Carbon analysis of the forest

Carbon stock

The biomass-carbon factor was used to assess the carbon store of forest vegetation (Magnussen and Reed 2004).

$$\text{Carbon stock} = \text{Biomass} \times 0.475$$

Carbon sequestration

The carbon accumulation rate in community forests was determined by using allometric equations, which have already been applied to the biomass estimation method. For the calculation of biomass enhancement after a year, the average diameter/Cbh of tree species after one year of increment (annual increment value measured in May 2023), and Along with the tree species density in the respective forest site was taken.

CO_2 mitigation

CO_2 mitigation was determined using the molecular weight of CO_2 and the carbon sequestration value of each component of each tree species in the respective forest site. Carbon mitigation was estimated separately for each vegetation layer (trees, shrubs and herbs). Total vegetation carbon sequestration for each community forest was obtained by adding these values.

$$CO_2 \text{ mitigation} = \text{carbon sequestration} \times 3.67$$

Statistical observation

The normality of the data was tested for biomass, carbon, productivity and carbon sequestration using the Shapiro-Wilk test. However, the significance level was measured using the Kruskal-Wallis and one-way ANOVA tests in SPSS software. Regression analysis was done using MS Excel, while the PCA was done using RStudio. QGIS software was used to map the study area.

RESULTS AND DISCUSSION

Stand structure and composition

Brief information regarding the species composition and structure in each community forest site is given in Table 2. The tree species that dominated in community forests were *Quercus leucotrichophora* (in GCF site), *Pinus roxburghii* (in SCF site), and *Quercus leucotrichophora* and *Pinus roxburghii* (in BCF site) in the Almora district of Kumaun Himalaya. The tree density was 1200, 373.3 and 633.3 ind/ha, while the basal area was 25.0, 31.9 and 29.4 m^2/ha, reported for GCF, SCF and BCF. The shrub density was 3120, 3789.7 and 1026.7 ind/ha, while the basal areas were 0.2, 0.1 and 0.4 m^2/ha, respectively, for GCF, SCF and BCF. The herb density was 119000, 146000 and 92000 ind/ha (Table 2).

Vegetation biomass

The tree biomass across the community forests varied between 171.0±34.7–429.0±26.8 mg/ha. Of the gross stock of tree biomass, the aboveground biomass ranges between 139.9±28.4 – 317.1±25.2 mg/ha, and belowground biomass observed from 31.1±6.3–111.9±26.8 mg/ha (Table 3). The biomass of trees was 171.0–429.0 mg/ha, which is between 175.5–514.97 mg/ha reported in Indian forests in the country (Rawat and Singh 1988, Sharma *et al.* 2010, Lal and Lodhiyal 2015, Sharma *et al.* 2016, Joshi *et al.* 2021, Pimoli *et al.* 2024, Haq *et al.* 2023, Haq *et al.* 2024, Upadhyay *et al.* 2025). The shrub biomass varied between 0.32±0.27–1.33±1.10 mg/ha. The maximum biomass of the shrub layer was reported as 1.33±1.10 mg ha^{-1} for GCF. Of the total shrub biomass, the aboveground biomass varied between 0.18±0.16 and 0.82±.68 mg/ha and the below ground biomass was 0.13±0.11 – 0.52±0.42 mg/ha (Table 3). The biomass of shrubs 1.31±0.26 – 0.32±0.15 mg/ha was on the lower side of 2.3 – 9.67 mg/ha reported for Indian western Himalayan forests (Haq *et al.* 2023).

Table 2. Briefly describe different important parameters of the studied community forests in Kumaun Himalaya.

Parameters Elevation (m)	Oak forest (GCF) 0981-1103	Pine forest (SCF) 1049-1282	Oak-pine forest (BCF) 1613-2149
Dominant tree species	*Quercus leucotrichophora* A. Camus	*Pinus roxburghii* Sarg.	*Quercus leucotrichophora* A. Camus and *pinus roxburghii* Sarg.
Under canopy vegetation	*Berberis aristata*, *Himalrand tetrasperma* *Rubus ellipticus*, *Ageratina adenophora*, *Asparagus racemosus*, *Themedaanathera*	*Carissa spinarum*, *Woodfordia fruticose*, and *Ziziphus nummularia*, *Evolvulusalsinoides*, *Imperata cylindrica*, *Themeda anathera*, *Lepidagathis incurve*,	*Berberis aristata*, *Himalrandia tetrasperma*, *indigofera cassioidesageratinaadenophora*, *Eulaliopsis binate*, *Anaphalis contorta*,
Tree density ind/ha	1200	373.3	633.3
Tree basal area m^2/ha^{-1}	25.0	31.9	29.4
Tree diversity	1.1	0.1	0.7
Shrub density indi/ha^{-1}	3120	3789.7	1026.7
Shrub basal area m^2/ha^{-1}	0.2	0.1	0.4
Shrub diversity	1.42	1.24	0.39
Herb density ind/ha^{-1}	119000	146000	92000
Herb diversity	1.87	2.45	0.26

Table 3. Component-wise biomass (Mean ± SD in mg./ha) in community forests in Kumaun Himalaya. Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level. AGC- Above ground biomass, BGC- Below ground biomass.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)	Significance
Trees				
Bole	142.8±16.1	106.1±22.5	111.1±30.1	0.20NS
Branches	86.6±6.9	27.8±5.6	55.3±10.7	0.00**
Twigs\cones	39.1±2.3	0.9±0.5	17.7±1.4	0.00**
Foliage	48.6±3.0	5.1±0.7	31.1±4.9	0.00**
AGB	317.1±25.2	139.9±28.4	215.2±47.0	0.00**
Stump root	92.7±5.0	23.9±4.7	52.8±8.6	0.00**
Lateral roots	17.2±1.2	6.6±1.5	10.2±2.0	0.00**
Fine roots	2.0±1.1	0.6±0.1	1.0±0.2	0.00**
BGB	111.9±26.8	31.1±6.3	64.1±10.8	0.00**
Total	429.0±26.8	171.0±34.7	279.2±57.8	0.00**
Shrubs				
Foliage	0.56±0.47	0.47±0.28	0.13±0.11	0.29NS
Stem	0.25±0.21	0.20±0.12	0.06±0.05	0.29NS
AGB	0.82±.68	0.67±0.40	0.18±0.16	0.29NS
Root	0.52±0.42	0.47±0.26	0.13±0.11	0.28NS
BGB	0.52±0.42	0.47±0.26	0.13±0.11	0.28NS
Total	1.33±1.10	1.14±0.66	0.32±0.27	0.29NS
Herbs				
AGB	1.38±0.12	1.53±0.15	1.17±0.07	0.02*
BGB	0.83±0.22	0.94±0.32	0.87±0.12	0.84NS
Total	2.21±0.33	2.47±0.47	2.04±0.17	0.37NS
Forest floor				
Fresh leaf	0.79±0.52	0.69±0.42	0.77±0.46	0.96NS
Partially decomposed	0.71±0.40	0.96±0.29	0.71±0.26	0.57NS
Wood	0.43±0.19	0.53±0.04	0.51±0.17	0.68NS
Miscellaneous	0.84±0.52	0.54±0.10	0.58±0.14	0.49NS
Total	2.75±1.00	2.71±0.17	2.57±0.45	0.93NS

Similarly, stock of carbon of shrub layer (0.62±0.31 mg/ha), the lower side from the findings (8.23±1.01-2.24 ±0.29 mg/c/ha) reported for Western forest of Himalaya (Haq *et al.* 2024). The biomass herbaceous species varies from 2.04±0.17 – 2.47±0.47 mg/ha. The maximum biomass in the herb layer was reported as 2.47±0.47mg/ha for SCF. Of the gross biomass herbaceous species, the aboveground varied between 1.17±0.06 – 1.53±0.15 mg/ha, and belowground was 0.83±0.22 – 0.94±0.31 mg ha^{-1} (Table 3). The total vegetation biomass varied between 176.81±34.64 –432±26.16 mg/ha. The biomass stock of herbs 2.0±0.2–2.5±0.3 mg/ha was on the higher side (0.74 ±0.08–1.42 ±0.24 mg/ha) calculated for Western Himalaya (Rawat and Singh 1988, Haq *et al.* 2024).

Forest floor standing litter biomass

The total forest floor standing litter biomass recorded between 2.57±0.45–2.75±1.00 mg/ha. The maximum forest floor standing biomass of 2.75±1.00 mg/ha was reported for GCF. From these, fresh leaf litter biomass ranges 0.69±0.42–0.79±0.52 mg/ha, partially decomposed litter biomass was 0.71±0.26 – 0.96±0.29 mg/ha, wood litter biomass ranges between 0.43±0.19 – 0.53±0.04 mg ha^{-1}mg/ha and miscellaneous litter biomass varied between 0.54±0.10 and 0.84±0.52 mg/ha (Table 3). The forest floor biomass was 2.6±0.1–2.9±0.2, which comes in between the (0.97 – 9.14 mg/ha) reported for western Himalayan forests (Haq *et al.* 2023). Similarly, in the case of forest floor carbon (1.2±0.1–1.4±0.1), the value comes in between the site (0.48–4.57 mg/c/ha) reported for western Himalayan forests (Haq *et al.* 2023). The value is lower than 6.74 mg/c/ha reported for the central Himalayan forests (Rawat and Singh 1988).

Vegetation NPP

The total NPP of trees observed from 4.1±0.9-11.5±1.2 mg/ha/yr. The maximum net primary

Table 4. Component-wise productivity (Mean ± SD in mg.c/ha/yr) in community forests in Kumaun Himalaya. Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level. AGC- Above ground biomass, BGC- Below ground biomass.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)	Significance
Trees				
Bole	4.5±0.5	2.5±0.6	3.0±1.2	0.06NS
Branches	2.6±0.2	0.8±0.2	1.2±0.3	0.00**
Twigs\cones	0.8±0.1	0.02±0.02	0.2±0.01	0.02**
Foliage	1.4±0.2	0.1±0.02	0.5±0.04	0.00**
AGB	9.2±0.9	3.4±0.7	4.9±1.5	0.00*
Stump root	1.9±0.3	0.5±0.1	0.9±0.2	0.00**
Lateral roots	0.3±0.1	0.2±0.04	0.2±0.1	0.01**
Fine roots	0.02±0.01	0.01±0.00	0.01±0.01	0.05**
BGB	2.3±0.3	0.7±0.2	1.1±0.3	0.00**
Total	11.5±1.2	4.1±0.9	5.9±1.8	0.00**
Shrubs				
Foliage	0.05±0.03	0.07±0.02	0.01±0.01	0.03*
Stem	0.02±0.02	0.04±0.01	0.01±0.005	0.08NS
AGB	0.07±0.05	0.11±0.03	0.02±0.01	0.04*
Root	0.02±0.02	0.04±0.01	0.01±0.005	0.04*
BGB	0.02±0.02	0.04±0.01	0.01±0.005	0.04*
Total	0.08±0.06	0.15±0.04	0.03±0.02	0.03*
Herbs				
AGB	1.38±0.12	1.53±0.15	1.17±0.07	0.02*
BGB	0.83±0.22	0.94±0.32	0.87±0.12	0.84NS
Total	2.21±0.33	2.47±0.47	2.04±0.17	0.37NS

productivity of trees was reported as 11.5±1.2 mg/ha/yr for GCF. The gross NPP, aboveground and belowground, varied from 3.4±0.7–9.2±0.9 mg/ha/yr and 0.7±0.2–11.5±1.2 mg/ha/yr, respectively (Table 4). The productivity of the tree layer ranged between 4.1–11.5 mg/ha/yr, which falls in between the value 6.5–12.8 mg/ha/yr reported for the central Himalayan forests (Gosain *et al.* 2015, Pant and Tewari 2013, Joshi *et al.* 2021). While the value is on the lower side than 16.91 – 20.85 mg/ha/yr reported for the Kumaun Himalayan forests (Lal and Lodhiyal 2016). Variations in tree carbon occurred depending on tree density, girth, species composition, environmental factors, and resource extraction activities such as the felling of trees for fuelwood and timber. The total NPP of shrubs recorded between 0.02±0.02–0.15±0.04 mg/ha/yr. The maximum NPP in the shrub layer was reported as 0.15±0.04 mg/ha/yr for SCF. Of the total NPP of shrubs, aboveground NPP was 0.02±0.01–0.07±0.05 mg/ha/yr, and belowground NPP varied from 0.01±0.005–0.02±0.02 mg/ha/yr. The herb NPP varied between 2.04±0.17–2.47±0.47 mg/ha/yr. The maximum biomass in the herb layer was reported as 2.47±0.47 mg/ha/yr for SCF. Of the total herb biomass, the aboveground reported from 1.17±0.06–1.53±0.15 mg/ha/yr and belowground ranges between 0.83±0.22–0.94±0.31 mg/ha/yr. The total vegetation NPP recorded between 6.16±1.09-14.12±1.17 mg/ha/yr (Table 4).

Vegetation carbon stock

The tree carbon stock ranges 81.2±16.5–203.8±12.7 mg/c/ha. The highest amount of carbon stored in the tree layer was 203.8±12.7 mg/c/ha GCF. Of the total carbon stock, aboveground carbon stock varied from 66.5±13.5–150.6±12.0 mg/c/ha and belowground carbon stock was observed between 14.8±3.0–53.2±3.0 mg/c/ha (Table 5). Tree carbon was (81.2-203.8 mg/ha), the values are somewhat similar to the findings 81.2–143.0 mg/ha documented for Indian central, and Kumaun Himalayan forests (Lal and Lodhiyal 2015, Sharma *et al.* 2016, Singh 2019, Kumar *et al.* 2021, Pimoli *et al.* 2024). However, the present carbon stock value is on the lower side of the findings 91.9–272.5 mg/ha reported for central, western and Garhwal Himalayan forests (Sharma *et al.* 2016, Kaushal and Baishya, 2021, Pimoli *et al.* 2024). Variations in tree

Table 5. Component-wise carbon stock (Mean ± SD in mg c/ha/yr) in community forests in Kumaun Himalaya. Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level. AGC- Above ground carbon, BGC- Below ground carbon.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)	Significance
Trees				
Bole	67.8±7.6	50.4±10.7	52.8±14.3	0.20NS
Branches	41.1±3.3	13.2±2.6	26.3±5.1	0.00**
Twigs\cones	18.6±1.1	0.4±0.2	8.4±0.7	0.00**
Foliage	23.1±1.4	2.4±0.3	14.8±2.3	0.03*
AGC	150.6±12.0	66.5±13.5	102.2±22.3	0.00**
Stump root	44.0±2.4	11.4±2.2	25.1±4.1	0.00**
Lateral roots	8.2±0.6	3.1±0.7	4.9±0.9	0.01*
Fine roots	0.9±0.1	0.3±0.1	0.5±0.1	0.00**
BGC	53.2±3.0	14.8±3.0	30.4±5.1	0.00**
Total	203.8±12.7	81.2±16.5	132.6±27.4	0.01*
Shrubs				
Foliage	0.27±0.22	0.22±0.13	0.06±0.05	0.29NS
Stem	0.12±0.10	0.10±0.06	0.03±0.02	0.29NS
AGC	0.39±0.32	0.32±0.19	0.09±0.07	0.29 NS
Root	0.24±0.20	0.22±0.12	0.06±0.05	0.28 NS
BGC	0.24±0.20	0.22±0.12	0.06±0.05	0.28 NS
Total	0.63±0.52	0.54±0.31	0.15±0.13	0.29 NS
Herbs				
AGC	0.66±0.06	0.73±0.07	0.56±0.03	0.02*
BGC	0.39±0.10	0.45±0.15	0.41±0.06	0.84 NS
Total	1.05±0.15	1.17±0.22	0.97±0.08	0.37 NS
Forest floor				
Fresh leaf	0.38±0.25	0.33±0.20	0.36±0.022	0.96NS
Partially decomposed	0.34±0.19	0.45±0.45	0.34±0.12	0.57NS
Wood	0.20±0.09	0.25±0.02	0.24±0.08	0.68 NS
Miscellaneous	0.40±0.25	0.26±0.05	0.28±0.07	0.49NS
Total	1.31±0.48	1.29±0.08	1.22±0.21	0.93 NS

carbon occurred depending on tree density, girth, species composition, environmental factors, and resource extraction activities such as the felling of trees for fuelwood and timber. The shrub layer carbon stock documented between 0.15±0.13–0.63±0.52 mg/c/ha. The most substantial amount of carbon stored in the shrub layer was reported as 0.63±0.52 mg/c/ha for GCF. Of the total shrub carbon storage, aboveground ranges from 0.09±0.07–0.39±0.32 mg/c/ha and belowground, calculated between 0.06±0.05–0.24±0.20 mg/c/ha (Table 5). Variations in shrub layer carbon and biomass came from persistent anthropogenic pressure and human disturbances such as annual forest fires, which cause a cyclic succession-like state of the shrub layer. The herb layer carbon stock varied from 0.97±0.08–1.17±0.22 mg/c/ha. The highest level of carbon stock in the herb layer was reported as 1.17±0.22 mg/c/ha for SCF. Of the total herb carbon storage in the aboveground recorded between 0.56±0.03–0.73±0.07 mg/c/ha and belowground ranges from 0.41±0.06–0.39±0.10 mg/c/ha (Table 5). Variations in herb biomass and carbon have come from increased grazing pressure and annual forest fires, which are causing a cyclic succession type of activity for the herb layer. The total vegetation carbon stock varied from 83.03 ± 16.45–205.45 ± 12.43 mg/c/ha (Table 5).

Forest floor standing carbon stock

The forest floor standing carbon stock observed from 1.22±0.21–1.31±0.48 mg/c/ha. The maximum forest floor carbon stock of 1.31±0.48 mg/c/ha was reported in GCF. Of the total, the fresh leaf carbon stock varied between 0.33±0.20–0.38±0.25 mg/c/ha, the partially decomposed carbon stock ranges between 0.34±0.12–0.45±0.45 mg/c/ha, wood carbon stock reported between 0.20±0.09 - 0.25±0.02 mg/c/ha, and the miscellaneous litter was 0.26±0.05-0.40±0.25 mg/c/ha (Table 5). forest floor carbon (1.2±0.1-

Table 6. Component-wise carbon sequestration (Mean ± SD in mg.c/ha/yr) in community forests in Kumaun Himalaya Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level. AGC- Above ground carbon, BGC- Below ground carbon.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)	Significance
Trees				
Bole	2.1±0.2	1.2±0.3	1.4±0.6	0.06^{NS}
Branches	1.2±0.1	0.4±0.1	0.6±0.2	0.00**
Twigs\cones	0.4±0.02	0.01±0.01	0.1±0.003	0.02**
Foliage	0.6±0.1	0.04±0.01	0.2±0.02	0.00**
AGC	4.4±0.4	1.6±0.4	2.3±0.7	0.00*
Stump root	0.9±0.1	0.3±0.1	0.4±0.1	0.00**
Lateral roots	0.2±0.02	0.1±0.02	0.1±0.03	0.01**
Fine roots	0.01±0.003	0.005±0.0001	0.006±0.003	0.05**
BGC	1.1±0.2	0.3±0.1	0.5±0.01	0.00**
Total	5.5±0.6	2.0±0.4	2.8±0.9	0.00**
Shrubs				
Foliage	0.022±0.14	0.033±0.008	0.005±0.004	0.03*
Stem	0.010±0.008	0.017±0.003	0.003±0.002	0.08^{NS}
AGB	0.032±0.022	0.051±0.015	0.007±0.006	0.04*
Root	0.010±0.008	0.019±0.005	0.003±0.002	0.04*
BGB	0.010±0.008	0.019±0.005	0.003±0.002	0.04*
Total	0.040±0.027	0.070±0.019	0.011±0.007	0.03*
Herbs				
AGC	0.66±0.06	0.73±0.07	0.56±0.03	0.02*
BGC	0.39±0.10	0.45±0.15	0.41±0.06	0.84^{NS}
Total	1.05±0.15	1.17±0.22	0.97±0.08	0.37^{NS}

1.4±0.1), the value comes in between the site (0.48 –4.57 mg/c/ha) reported for western Himalayan forests (Haq *et al.* 2023). The value is lower than 6.74 mg/c/ha reported for the central Himalayan forests (Rawat and Singh 1988). Variations in forest floor biomass and carbon are due to additional pressures on the forest floor, such as local people using the forest floor for cattle grazing, organic fertilisation of fields, and human disturbances such as forest fires.

Sequestration of vegetation carbon

The sequestration of trees' carbon was documented from 5.5±0.6–2.0±0.4 mg.c./ha/yr. The highest sequestration of carbon in the tree layer was reported as 5.5±0.6 mg/c/ha/yr for GCF. Of the total tree carbon sequestration, the aboveground carbon sequestration was 1.6±0.4 – 4.4±0.4 mg/c/ha/yr, and belowground carbon sequestration varied from 0.3±0.1–1.1±0.2 mg/c/ha/yr (Table 6). The stock of tree carbon was (81.2–203.8 mg/ha), the values are somewhat similar to the findings 81.2–143.0 mg./ha documented for Indian central, and Kumaun Himalayan forests (Lal and Lodhiyal 2015, Sharma *et al.* 2016, Singh 2019, Kumar *et al.* 2021, Pimoli *et al.* 2024). However, the present carbon stock value is on the lower side of the findings 91.9–272.5 mg/ha reported for central, western and Garhwal Himalayan forests (Sharma *et al.* 2016, Kaushal and Baishya 2021, Pimoli *et al.* 2024). Variations in tree carbon occurred depending on tree density, girth, species composition, environmental factors, and resource extraction activities such as the

Table 7. Soil organic carbon (Mean ± SD) of community forests in Kumaun Himalaya. Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine mixed forest (BCF)	Significance
Soil organic carbon (%)	0.78±0.10	0.67±0.04	0.72±0.05	0.14^{NS}
Soil organic carbon (mg C ha^{-1})	21.1±2.7	24.1±1.4	23.8±1.7	0.14^{NS}
Soil organic matter (%)	1.35±0.17	1.16±0.07	1.24±0.08	0.14^{NS}
Soil organic matter ((mg ha^{-1})	36.5±4.6	41.8±2.5	34.2±3.5	0.14^{NS}

Table 8. Component-wise CO_2 mitigation (Mean ± SD in Mg CO_2 ha−1yr-1) of different layers in community forests in Kumaun Himalaya. Note: NS- non-significant, *-significant at 0.05 level, **- significant at 0.01 level.

Component	Oak forest (GCF)	Pine forest (SCF)	Oak-pine forest (BCF)	Significance
Tree	20.1±2.2	7.2±1.5	10.3±3.2	0.00**
Shrub	0.14±0.10	0.26±0.07	0.04±0.02	0.03*
Herb	3.85±0.55	4.29±0.81	3.56±0.29	0.37^{NS}
AGB	18.69±1.77	8.74±1.78	10.52±2.70	0.00**
BGB	5.51±1.03	2.82±0.94	3.35±0.26	0.00**

felling of trees for fuelwood and timber. The sequestration of shrub carbon ranges from 0.011±0.007-0.040±0.027 mg/c/ha/yr. The maximum carbon sequestration in the shrub layer was 0.070±0.019 mg/c/ha/yr reported for SCF. Of the total shrubs' carbon sequestration, aboveground carbon sequestration varies between 0.007±0.006-0.032±0.022 mg/c/ha/yr, and belowground carbon sequestration is reported as 0.003±0.002–0.010±0.008 mg/c/ha/yr. The herb layer carbon sequestration was 0.97±0.08–1.17±0.22 mg/c/ha/yr. The maximum sequestration of carbon in the herb layer was 1.17±0.22 mg/c/ha/yr in SCF. Of the total sequestration of carbon in herbs, the aboveground was from 0.56±0.03–0.73±0.07 mg/c/ha/yr, and belowground varied from 0.41±0.06-0.39±0.10 mg/c/ha/yr. The total vegetation carbon sequestration documented from 2.92±0.51–6.70±0.56 mg/c/ha/yr (Table 6).

SOC and SOM

The soil organic matter was 1.16±0.07-1.35±0.17%. The maximum soil organic matter of 1.35±0.17% was reported for GCF. The soil organic carbon was 0.67±0.04–0.78±0.10%. The maximum soil organic carbon was 0.78±0.10% reported for GCF (Table 7). The study reported 0.67±0.04 - 0.78±0.10 % soil organic carbon, which is less than the 1.36 – 3.24% reported for the Kumaun Himalayan forests (Chaturvedi and Melkania 2013) and 1.04 – 3.31% reported for the Central Himalayan forests (Choudhary and Saxena 2015). Variations in soil organic matter and carbon come from low litter input and surface runoff from the forest due to sparse vegetation. Soil solid carbon (SOC) is an important part of the carbon pool that stores carbon and regulates nutrient cycling and dynamics in ecosystems (Yang *et al.* 2022). The

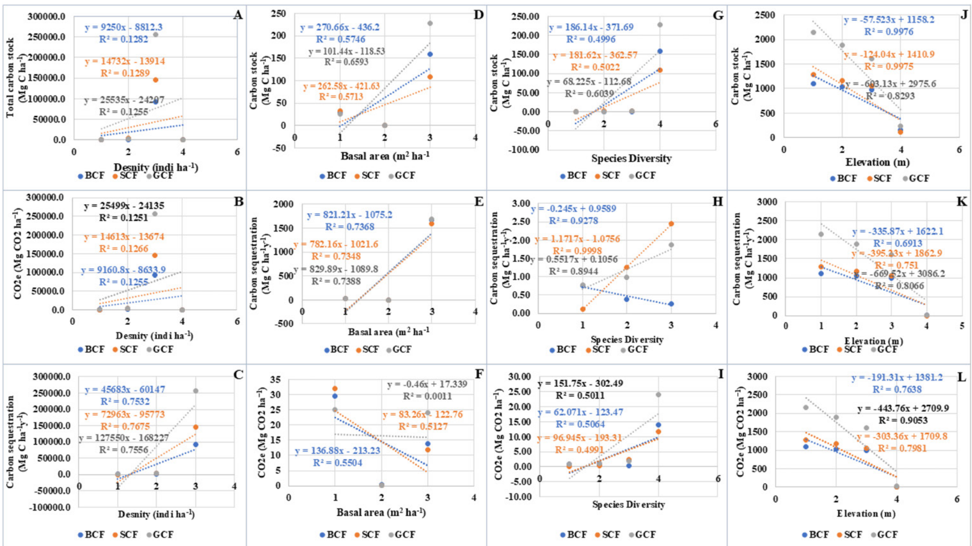

Fig. 2. Regression analysis of different components across the forests.

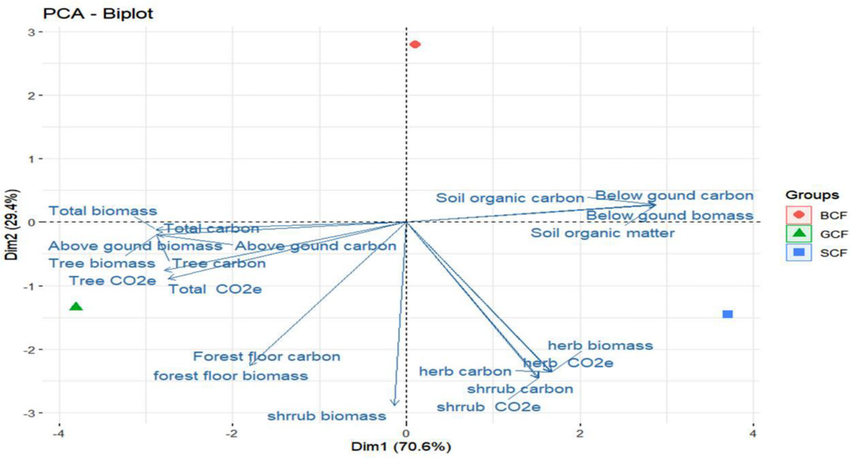

Fig. 3. PCA for carbon and biomass of the community forest.

climate of the mountain hills varies due to variations in topography and vegetation type. The climate of the temperature regions is colder than the climate of sub-tropical places. Since SOM is necessary for forest growth, understanding SOC plays a crucial in maintaining soil quality and its productivity. This is more relevant for the soils of the hill ecosystem.

CO_2 mitigation

The CO_2 mitigation of the tree layer ranges from 7.2±1.5–20.1±2.2 mg CO_2/ha/yr. While in the shrubs, CO_2 mitigation within the range between 0.04±0.02, 0.26±0.07 mg.CO_2/ha/yr. However, the herb layer CO_2 mitigation ranges 3.56±0.29-3.85±0.55 mg.CO_2/ha/yr. Of the total CO_2 mitigation, the aboveground varied from 8.74±1.78–18.69±1.77 mg.CO_2/ha/yr, while the belowground reported between 1.2±0.3–4.0±0.6 mg.CO_2/ha/yr (Table 8).

Regression analysis

The scatter plot (Fig. 2A) illustrates the positive and weak relationship between species density and carbon stock, as well as between species density and carbon mitigation (Fig. 2B). Fig. 2C shows a positive and strong relationship between species density and carbon sequestration. The basal area shows a positive and moderate relation between species basal area and carbon stock (Fig. 2D). It shows a positive and moderate relation with carbon sequestration (Fig. 2E). In contrast, for carbon mitigation, it shows a positive and weak relation for BCF and SCF. However, GCF shows a negative and weak relation (Fig. 2F). The species diversity shows a moderate and positive relation for carbon stock (Fig. 2G), a strong and positive relation with carbon sequestration (Fig. 2H) and a moderate and positive relation with carbon mitigation (Fig. 2I). The elevation shows negative relation with carbon stock, carbon sequestration and carbon mitigation (Fig. 2 J, K, L).

Ordination analysis

For the ordination analysis, the PCA was used. The PCA bi-plot shows that BCF has a relationship with soil organic carbon, belowground biomass and organic matter, whereas GCF shows a relationship with tree and forest floor biomass, carbon and CO_{2e}, while SCF shows a relationship with tree, shrub and herb layer carbon and biomass parameters (Fig. 3, Table 9).

Table 9. Principal component analysis (PCA) summary for different vegetational parameters of biomass and carbon components in the studied forest.

PC	PC1	PC2
Standard deviation	3.7573	2.4255
Proportion of Variance	0.7058	0.2942
Cumulative Proportion	0.7058	1.0000

CONCLUSION

The productivity and carbon content of forests vary from one forest to another, depending on the stand structure, composition, density, age of trees, soil conditions, as well as geographical location and external inputs management. Therefore, different forests have different dry matter and carbon storage potential. Apart from these, the land use change and the extraction pattern of resources also influence the dynamics of the productivity and potential of carbon of the forest. This study concludes, forests were severely affected by many factors, such as (1) grazing, (2) unscientific extraction of fodder, fuel and litter by the villagers, and (3) the site is located in a warm climate and poor rainfall areas. Consequently, these factors result in as poor SOM and SOC. The degradation of forests was caused due to poor participation and poor management of villages. The distribution of carbon content was on higher side due to the high amount of organic matter content present at different soil depths compared to the carbon content distributed in the dry matter of vegetation components. The results showed a variation in different parameters i.e. biomass, carbon sequestration, CO_2 mitigation potential and productivity, of the studied community forests that were depicted based on vegetation structure, elevation, density, basal area, and diversity. Biomass, productivity, carbon sequestration, and CO_2 mitigation were higher in the GCF, followed by the BCF, while it was lowest in the SFC. Moreover, the research also stated that carbon stock and sequestration negatively correlate with elevation in the Himalayan region. The findings of this study indicate that the studied community forest was not in good condition, which is why it needs conservation and management inputs for its sustainability and improvement. This can be concluded that the immediately existing forests must be protected and developed for better growing stock, dry matter and carbon content using more relevant and appropriate methods.

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