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Carbon Dynamics in Community-managed Forests across Altitudinal Gradient in Central Himalaya, India

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Abstract: The present study investigates the variation in carbon stock distribution across different carbon pools along elevational gradients in community-managed forests (Van Panchayats) of the Kumaun Central Himalaya. The forests were categorized into three altitudinal zones: low, mid, and high-elevation sites. Among the various pools, tree biomass carbon accounted for more than 80 percent of the total carbon stock, highlighting its dominant role in carbon sequestration. Soil organic carbon contributed between 14.06 and 17.58 percent, whereas forest floor carbon contributed between 1.19 and 1.81 percent to the total carbon pool. The herb layer biomass carbon showed the least contribution. The strong positive correlation was observed between tree and shrub carbon stocks and elevation ($R^2 > 0.84$), suggesting an elevation-driven pattern in above-ground carbon accumulation. The overall total carbon stock ranged from 169.51 to 185.62 Mg C ha^{-1}. This study emphasizes the necessity of adopting site-specific conservation and management practices to sustain and enhance the carbon stock potential of these forests across elevational gradients.

Keywords: Carbon pools, Community managed forests, Forest floor carbon, Soil organic carbon, Elevational gradient

Forests play a vital role in carbon sequestration, serve as a significant reservoir of biomass, and act as a carbon sink. These forest ecosystems are the largest carbon reservoirs, holding over 80% and 40% of the Earth's terrestrial carbon pools above ground and below ground, respectively (Pan et al., 2011). Plant biomass (both above and below ground), woody debris, litter, and soil are the major carbon pools in forest ecosystems (Sharma et al., 2016). Globally, forests hold more than 650 gigatons of carbon in total. Out of this, around 44 percent is stored in forest biomass, about 11 percent is found in deadwood and litter, and nearly 45 percent is held in the soil. Specifically, forest biomass alone contains nearly 298 gigatons of carbon, showing how vital it is in the global carbon cycle. Carbon stocks have been declining worldwide due to deforestation and land use change (FAO 2020). The estimated carbon stock is 3 billion metric tonnes, accounting for around 40% of the total carbon pool in India's forests (Rawal et al., 2021). The Indian Himalayan forests sequester around 65 million metric tonnes of carbon per year (Tolangay and Moktan 2020). The estimated total forest carbon stock in Uttarakhand across all carbon pools is 378.16 million tonnes.

Based on management, Uttarakhand forests are classified into three categories: Reserve Forests, Community-managed Forests, and Civil Soyam Forests. The community forests, known as Van Panchayat forests and managed by village-level institutions in collaboration with State Forest and Revenue departments (Mukherjee 2004, Nagahama et al., 2022). This decentralized forest governance approach came into existence in 1931 and is a participatory conservation initiative that aids in resource conservation and sustainable utilization while providing livelihoods to rural communities. There are 12,089 Van Panchayats, which are more than 16% (544,964 hectares) of the forest area in Uttarakhand (Agrawal and Ostrom 2008, Negi et al., 2012). These forests not only support the livelihoods of local people but also play an important role in climate change mitigation and biodiversity conservation. As local people and forests are interlinked, they provide a strong incentive for both forest management and conservation efforts (Joshi et al., 2011, Chakraborty et al., 2018). In recent years, global climate change has become a major concern, and forests are considered natural mitigators of climate change as they absorb a significant amount of CO_2 from the atmosphere (Rawat and Singh 2016). These forests offer numerous social, environmental, and economic benefits to the communities residing near forest areas. In community-managed forests, the assessment of carbon stock is crucial to initiate climate change mitigation programs such as Reducing Emissions from Deforestation and Forest Degradation (REDD+), conserving carbon stock, sustainable forest management, and enhancing carbon stock (UNFCCC 2016).

In the past few years, forest ecosystems have been deteriorating due to climatic factors and various human activities (fodder and fuelwood collection, grazing, forest fires, etc. which ameliorate the climate change forces. Several other studies have been conducted on biomass and carbon stock dynamics in the reserved forests in Uttarakhand regions (Gairola et al., 2011, Joshi et al., 2011, Dar et al., 2017). In addition, some research has also been carried out in the community-managed forests of the Kumaun region (Rawat 2012, Vikrant and Chauhan 2014, Bagri et al., 2022, Pimoli et al., 2024). Keeping in view the increasing human interference and poor engagement of community owned forests, the aim of the present study is to assess the variation in carbon pool dynamics along elevational gradients in community-managed forests of the Nainital district in the Central Himalaya.

MATERIAL AND METHODS

The study area is situated between 29°19'19.5"N and 29°25'54.9"N latitudes and 79°27'29.3"E and 79°35'40.1"E longitudes at altitude ranging from 1200 to 2400 m in the central Himalayas (Fig. 1). The mean minimum temperature varied between 0.02°C (January) and 18.7°C (July), while the mean maximum temperature ranged between from 19.3°C (January) and 36.5°C (June). The average monthly rainfall was 0.3 mm (November) and 297.0 mm (September) and the total annual rainfall was 1128.4 mm (Fig. 2). The climate data was taken from the website https://power.larc.nasa.gov in 2022. The study area was selected considering various geographical attributes along with environmental coordinates such as latitude, longitude, altitude using a global positioning system.

The rocks of the study are composed of limestone, pyritic, and carbonaceous. The forest soils are loamy and silty clay (Table 1). The community managed forests include *Quercus leucotrichophora* A. Camus, *Cupressus torulosa* D. Don ex Lamb., *Pyrus pashia* Buch. -Ham. ex D. Don, *Syzygium cumini* (L.) Skeels and *Bauhinia racemosa Lam at* low-elevation VP forest. The mid-elevation VP forest includes *Pinus roxburghii* Sarg., *Quercus leucotrichophora* A. Camus, and *Glochidion velutinum* Wight, while the high-elevation VP forest characterized by *Quercus floribunda* Lindl. ex A. Camus, *Rhododendron arboreum* Sm., *Lyonia ovalifolia* (Wall.) Drude, and *Ilex dipyrena* Wall.

After a thorough reconnaissance of the study area, three community-managed forests (VPFs) were identified at different elevations: Thapalia Mahara Gaon VPF located at low elevation (1200m-1500m), Bhudhalakote VPF at mid-elevation (1500m-1800m), and Satbunaga VPF at high elevation (2100m-2400m). The detailed site characteristics

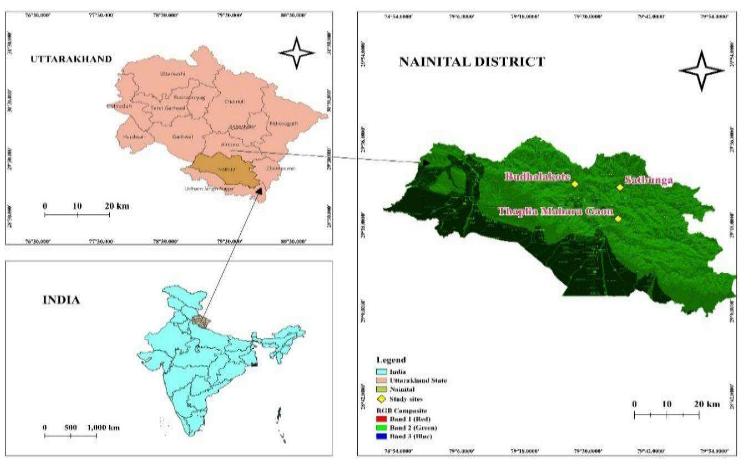
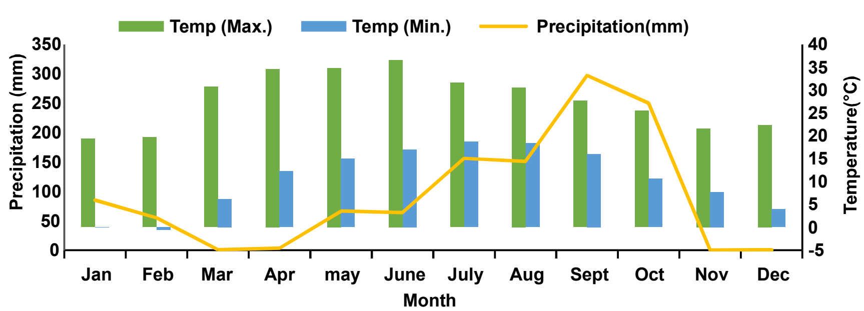


Fig. 1. Location map of the study sites



Source: https://power.larc.nasa.gov.

Max.= maximum; Min.= minimum; temp= temperature

Fig. 2. Mean monthly maximum and minimum temperature (°C) and precipitation (mm)

of these forests are given in Table 1.

In each VPF, three composite random soil samples were collected in three different depths: 0–10 cm, 10–20 cm, and 20–30 cm. Walkley and Black's titration method was used to estimate the SOC content in the collected soil samples (Walkley and Black 1934).

SOC = 0.1 × BD × D × C

Where, SOC: organic carbon storage in the soil horizon (Mg ha^{-1}),

D: depth of soil horizon (cm),BD= Bulk density(cm^{-3}),C= Organic carbon concentration ($g.kg^{-1}$)

Total organic carbon storage in the soil profile was calculated as the sum of the carbon content in each soil horizon. The total carbon stock was estimated by summing the individual carbon pools, following the method of Pearson et al. (2007).

Tree biomass was measured using a non-harvesting method. All individual trees with a circumference greater than 30 cm were recorded, and the circumference was measured at breast height (1.37 m above the ground) in the sampled quadrats. For shrubs, CBH was taken at the collar height. To estimate the biomass of different tree and shrub components (bole, bole bark, branches, twigs, leaves, stump roots, lateral roots, and fine roots) previously established allometric equations,

ln Y = a + b ln X

where Y denotes the dry weight of the component (kg), X is the circumference at breast height (CBH in cm), a is the intercept, b is the slope and ln refers to the natural logarithm, was used. The values of *a* and *b* were adopted from previously established regression models (Rawat 1983, Chaturvedi and Singh 1987, Rawat and Singh 1988, Rana et al., 1989, Adhikari et al., 1995). For herbs, above ground biomass was determined by placing quadrats of 1 x 1 m in each forest. The below ground biomass was collected from the monolith of 25 cm ×25 cm × 30 cm from each harvest plot and washed with fine jat remove all foreign material. The fresh weight was taken in the field and then the samples were placed in perforated paper bags, brought to the laboratory, oven-dried at 60° C till constant weight and weighted.

The biomass carbon stocks for trees, shrubs and herbs were determined following the IPCC guidelines, assuming a carbon content of 47.5% of the above ground and below ground biomass (Magnussen and Reed 2004, IPCC 2006)

C = B ×0.745

Where, C=carbon content and B= biomass

Forest floor litter was collected from 1 m × 1 m permanent quadrats, randomly placed in the forest. Litter from each quadrat was placed in a separate polyethylene bag and brought to the laboratory. The samples were then separated into fresh leaves, partially decomposed leaves, wood, and miscellaneous litter components. These were oven-dried at 60 °C to a constant weight. The dry biomass obtained was multiplied by the corresponding carbon fraction of 47.5%.

Statistical analysis: The collected data in each Van Panchayat forests were analysed using SPSS (version 16), Microsoft Excel 2019, and R-Studio (version 12.1) software. Regression analysis was conducted to assess the relationships between vegetation and soil attributes, while principal component analysis (PCA) was used to explain the variance in these attributes.

RESULTS AND DISCUSSION

More than 80 percent of total carbon was stored in the living biomass of the tree layer across all sites, while the shrub and herb layers made only minor contributions. Soil organic carbon, comprising over 12 percent of total stock, represented the second-largest pool. Both shrub biomass and soil carbon varied significantly with elevation. The relatively higher carbon storage at high elevation may reflect

Table 1. Site characteristics of community-managed forests

Parameter	Low-elevation	Mid-elevation	High-elevation
Van Panchayat	Thapalia Mahara Gaon	Bhudhalakote	Satbunga
Altitude (m)	1200-1500	1500-1800	2100-2400
Latitude	N 29º 19′	N 29º 26′	N 29º 25′
Longitude	E 79º 35′	E 79º 27′	E 79º 36′
Forest area (ha.)	380	44	103
Dominant Tree Species	*Quercus leucotrichophora* A. Camus	*Pinus roxburghii* Sarg. *Quercus leucotrichophora* A. camus	*Quercus floribunda* Lindl. ex A. Camus
pH	6.57	6.5	6.6
SOC %	0.7	0.87	0.81
Soil type	Loam	Loam	Clay loam

SOC= Soil organic carbon

differences in forest structure, stand age, and management practices, consistent with elevational patterns reported in other Himalayan studies (Simegn and Soromessa 2015, Vikrant et al., 2021).

Soil organic carbon (SOC) in the 0–30 cm layer was significantly higher in mid-elevation Van Panchayat forest (VPF) compared to low- and high-elevation sites. The mean SOC stock per hectare, estimated based on soil depth, bulk density, and carbon content, declining trend with increasing depth across all sites.

The highest mean SOC was recorded in mid-elevation VPFs (29.93 Mg ha^{-1}), while the lowest was observed in high-elevation VPFs (26.11 Mg ha^{-1}) (Fig. 3). These SOC values are notably lower than those reported for other Himalayan forest ecosystems, such as the 39.1-91.4 Mg ha^{-1} range observed by Dar and Sundarapandian (2015) and the 47.61–55.20 Mg ha^{-1} by Pawar and Gupta (2013). The comparatively lower SOC in high-elevation VPFs may be attributed to continuous open access for grazing and intensive leaf-litter collection over a three-month period by local communities, which likely disrupts nutrient cycling and reduces organic matter accumulation.

The high-elevation Van Panchayat Forests (VPFs) recorded the greatest total carbon storage (185.62 Mg ha^{-1}), followed by mid-elevation (170.24 Mg ha^{-1}) and low-elevation VPFs (169.51 Mg ha^{-1}) (Table 2). These values lie within the range reported for temperate forests in the Himalaya, such as 107.94-230.12 Mg ha^{-1} (Joshi et al., 2021), 272.52 Mg ha^{-1} (Kaushal and Baishya 2021), and 137.10 Mg ha^{-1} (Sharma et al., 2010).

The tree layer contributed the highest proportion to the vegetation carbon pool, ranging from 80.34 to 82.80 percent, indicating that trees are the dominant component of carbon sequestration across all elevation sites. Tree carbon storage ranged from 136.78 to 153.69 Mg ha^{-1}, with the highest value at the high-elevation Van Panchayat Forest (VPF) and the lowest at the mid-elevation VPF. These values fall within the range documented by Joshi et al. (2021) for temperate Himalayan forests (107.93–274.15 Mg ha^{-1}), yet remain lower than the estimates of 120.23 Mg ha^{-1} and 157.47–203.57 Mg ha^{-1} provided by Mbaabu et al. (2014) and Gwal and Lodhiyal (2019), respectively, for similar forest types. Tree-layer carbon was highest at the high-elevation site, where *Quercus floribunda* dominates, suggesting the presence of dense and mature oak forests capable of accumulating high levels of biomass.

The carbon stock in the shrub layer ranged from 0.95 to 1.98 Mg ha^{-1}, while in the herb layer varied between 0.55 and

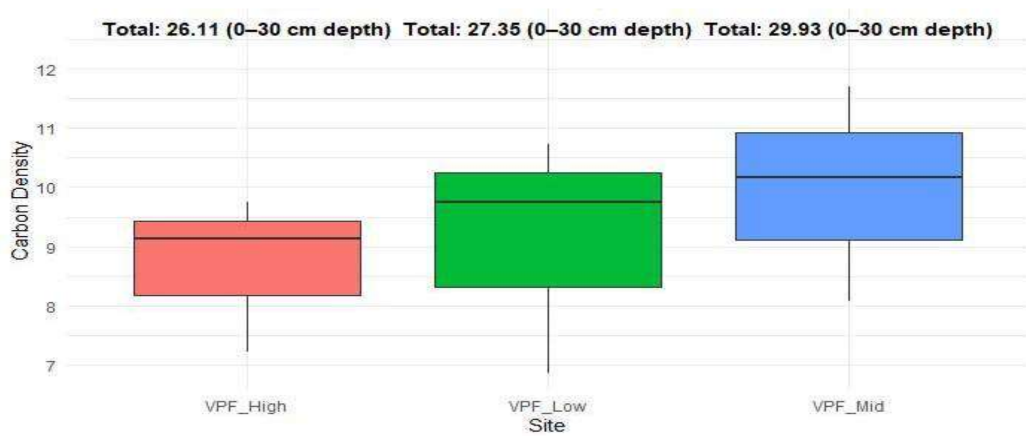


Fig. 3. Soil carbon stock at different elevations in Van Panchayat Forests

Table 2. Carbon pools across elevational gradients in Van panchayat Forests

Parameter	Low-elevation (1200-1500m)	Mid-elevation (1500-1800m)	High-elevation (2100-2400m)
Carbon stock of tree layer (Mg C ha^{-1})	137.22	136.78	153.69
Carbon stock of shrub layer (Mg C ha^{-1})	1.13	0.95	1.98
Carbon stock of herb layer (Mg C ha^{-1})	0.74	0.55	0.71
Total vegetation carbon (Mg C ha^{-1})	182.3	138.28	156.39
Soil organic carbon (Mg C ha^{-1})	27.34	29.93	26.11
Forest floor carbon stock (Mg C ha^{-1})	3.07	2.03	3.11
Total carbon (Mg C ha^{-1})	169.51	170.25	185.62

0.74 Mg ha⁻¹ (Table 2). These are significantly higher for shrubs and significantly higher for herbs compared to those reported by Thakur et al. (2024), recorded 1.31 Mg ha^{-1} and 0.37 Mg ha^{-1}, respectively, in similar temperate forest conditions. In the lower elevation Van Panchayat (VP) forest, dominated by *Quercus leucotrichophora* and characterized by a relatively young forest structure, the higher carbon stock in the herb layer may be attributed to limited extraction of fodder and fuelwood, along with improved regeneration. These factors likely supported enhanced herbaceous growth and soil restoration.

The carbon stock in forest floor litter across Van Panchayat Forests (VPFs) ranged from 2.03 to 3.11 Mg ha^{-1} (Table 2). These were higher than the estimates reported by Krishan et al. (2017), which ranged from 0.84 to 1.44 Mg ha^{-1}. In contrast, these values were lower than the range of 4.21 to 5.97 Mg ha^{-1} reported by Gosain et al. (2015), and the 2.5 to 3.1 Mg ha^{-1} recorded by Dar and Sundarapandian (2015) in temperate Himalayan and tropical dry evergreen forests. The mid-elevation VPF also experiences occasional forest fires, although these are actively suppressed by community members, the combination of fire events and pine needle accumulation likely inhibits understory vegetation growth and reduces litter retention, thereby limiting overall carbon storage. Interestingly, soil organic carbon was found to be highest in this forest, possibly due to the slow decomposition rate of pine needles and minimal disturbance to the forest floor.

Principal component analysis (PCA) correlation variance of carbon stock of tree, shrub, herb, forest floor, and soil organic carbon stock showed PC 1 accounting for 62.6% (Eigen value = 6.26) and Principal Component 2 accounting for 37.4% (Eigen value = 3.74) of the total explained variance in relation to elevation. Variables such as total carbon stock (TCS), tree carbon stock (Tr_c), shrub carbon stock (Sh_c), and herb carbon stock (H_c) showed strong positive associations with PC1. Elevation (Ele) and shrub carbon stock (Sh_c) showed stronger associations with PC2. The high-elevation site (VPF_high) is closely associated with elevation, shrub carbon stock, and tree carbon stock. The mid-elevation site (VPF_mid) shows moderate association with soil and organic carbon properties. The low-elevation site (VPF_low) is located away from major carbon stock vectors, indicating weaker association with total and tree carbon stock (Fig. 4).

The variation in carbon stocks along various elevational gradients is influenced by a number of factors such as forest type, soil, stand structure, and environmental conditions, which determine the carbon storage capacity and ecological dynamics of forest ecosystems. However, elevational changes increase carbon storage and nutrient cycling, which improves ecosystem functioning (Kumar et al., 2013). The variation in carbon storage across different elevational Van Panchayat Forests (VPFs) appears to be influenced not only by altitude and dominant vegetation type but also by forest use patterns and community interactions. However, Singh et al. (2023) observed that carbon stock potential may increase with elevation, depending on site-specific ecological conditions. In contrast, Thakur et al., (2024) reported a peak in carbon stock at mid-altitudes, with a subsequent decline at higher elevations. Among the different carbon pools, tree

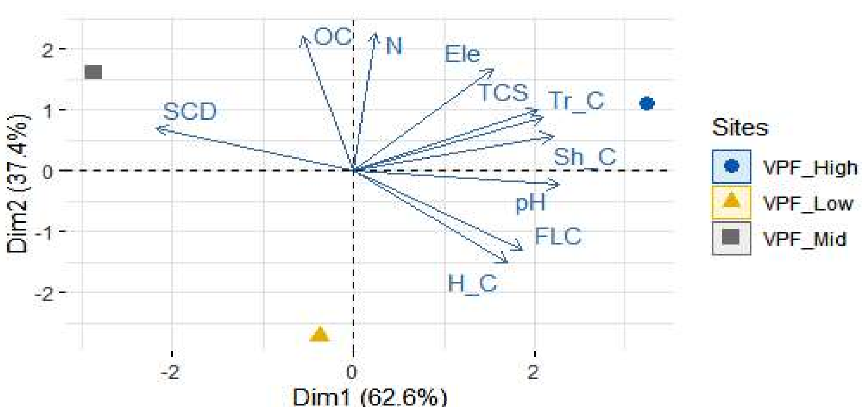


Fig. 4. Principal component analysis correlation (percent variance) diagram based on vegetation biomass, different carbon pools and soil properties in three different elevational community managed forests (where TCS: total carbon stock; Tr_C: tree carbon stock; Sh_C: shrub carbon atock; H_C: herb carbon stock; FLC: floor litter carbon; SCD: soil carbon density; OC: total soil organic carbon percent; N: total nitrogen %; Ele: elevation. Low-elevation VPF site= yellow tringle shape; mid-elevation VPF site = grey square shape; high-elevation VPF site = blue circle shape)

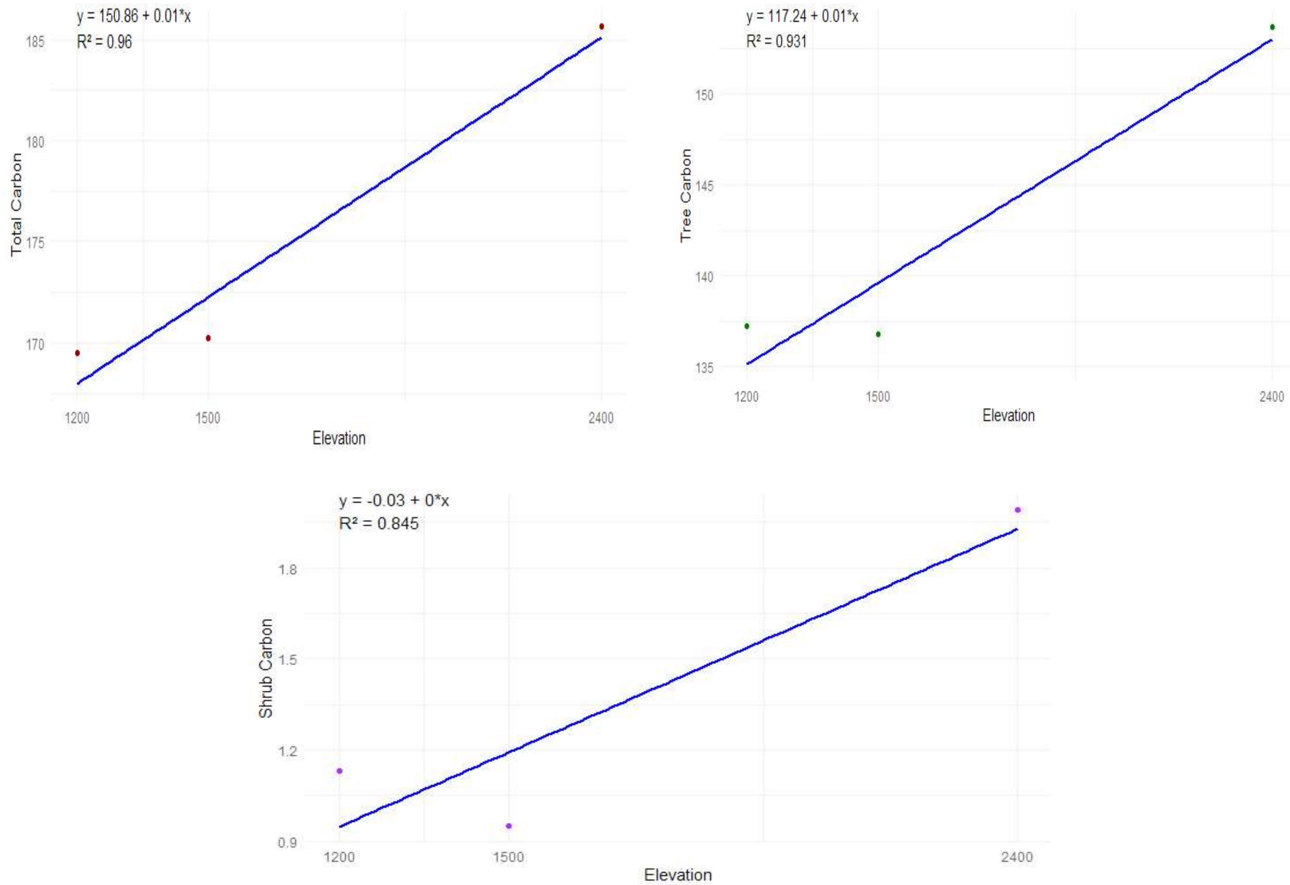


Fig. 5. Relationship Between Carbon Pools (Tree, shrub, and total carbon) and Elevational Gradient in Van Panchayat Forests

carbon, shrub carbon, and total carbon stock exhibited a strong positive correlation with elevation ($R^2 > 0.84$), while soil organic carbon showed a moderately negative correlation ($R^2 = 0.32$). In contrast, forest floor and herb layer carbon stocks demonstrated negligible relationships with elevation ($R^2 < 0.10$) (Fig. 5). These results suggest that elevation influences carbon pools through distinct ecological processes, with aboveground carbon components being more sensitive to altitudinal variation.

CONCLUSION

Community-managed forests are an essential part of the lives of rural people residing in nearby areas. They not only provide livelihoods but also play a crucial role in ecosystem sustainability and carbon sequestration. There is a need to adopt site-specific conservation and management practices to sustain and enhance the carbon stock potential of these forests across different elevation gradients.

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