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Research Note

Carbon Stock Estimation of Bandeshwori Community Forest, Bhaktapur, Nepal

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Abstract

Community forestry in Nepal has contributed to forest conservation, expansion of greenery, and climate mitigation through carbon sequestration. However, the lack of baseline data on carbon stocks has hindered the quantification of the carbon sequestration potential of such forests. This study conducted at Bandeshwori Community Forest, Bhaktapur estimated the total carbon stock of the forest. Standard 23 nested circular plots, each measuring 250 m^2 were established for field sampling. The diameter at breast height (DBH) of trees and saplings was measured, and soil samples were collected at three depth intervals (0-10 cm, 10-20 cm, and 20-30 cm). Above-ground tree carbon stock was calculated using standard allometric equations, while soil organic carbon (SOC) content was determined using the Walkley-Black method. The total carbon stock was estimated as 179.36 ± 14.29 t/ha, equivalent to 12,126.30 tCO_2e/ha. Among the different pools, SOC accounted for the largest share (50.92%) of the total carbon stock and exhibited a consistent decline with depth. The findings suggest that soil constitutes the principal carbon reservoir in community forests, underscoring the role of community forestry in enhancing carbon sequestration and ultimately contributing to climate change mitigation.

Introduction

Climate change, one of the most pressing global challenges, is primarily driven by rising atmospheric concentrations of greenhouse gases (GHGs) such as carbon dioxide (CO_2). Among the contributing factors, forest deforestation and degradation account for up to 20% of global annual CO_2 emissions (IPCC, 2007). Forest ecosystems play a vital role in the carbon cycle, acting both as carbon sinks and sources of emissions depending on their management strategies (Pradhan et al., 2019; FAO, 2020). Approximately 19% of Earth's biospheric carbon is stored in vegetation, and about 81% in the soil (IPCC, 2000). Even a relatively mild disturbance to these terrestrial carbon pools can drastically change atmospheric CO_2 concentrations, thereby intensifying the global warming effect (Kikstra et al., 2022; Sitch et al., 2024). Recognizing this, strategies aimed at reducing deforestation and enhancing forest carbon storage have become critical components of climate change mitigation (FAO, 2020).

Studies have emphasized that curbing deforestation is one of the most economical means of reducing GHG emissions (Stern, 2006). In response, the forestry sector has been heavily emphasized in the United Nations Framework Convention on Climate Change (UNFCCC) negotiations as a tool for climate mitigation. This has led to the development of various forest-based incentive mechanisms, including Reducing Emissions from Deforestation and Forest Degradation (REDD), which also incorporates conservation of carbon stocks, sustainable management of forests and enhancement of carbon pools (Acharya et al., 2009). The 2015 Paris Climate Agreement expanded on these efforts by institutionalizing the Nationally Determined Contributions (NDCs), wherein governments set their own GHG reduction efforts (Sato et al., 2019). Forests are positioned as essential to national and international mitigation goals in many NDCs (Fyson & Jeffery, 2019). These emissions reduction projects are often supported through international climate finance mechanisms. Host nations may be able to access such climate finance through carbon trading, where verified carbon savings are monetized (Austin et al., 2025). However, financial pathways are complicated; ambiguous procedures and limited institutional capacity frequently hinder securing funding (Buchner et al., 2019; Rey Christen et al., 2020).

To effectively participate in such mechanisms, countries must establish robust forest carbon inventories. These inventories not only facilitate accurate reporting and tracking of forest contributions under NDCs but also enhance the legitimacy of claims for obtaining climate finance (Pandey et al., 2014). This requirement is especially crucial for Nepal. The country lost nearly one-fourth (24.5%) of its forest land due to deforestation by the mid-1970s. Back then, research forecasted Nepal could lose all its forest land by 1990 in the absence of management interventions (World Bank, 1979). These alarming forecasts underscored the flaws of then-prevailing state-led forest nationalization, which excluded local communities from resource management (Smith et al., 2023). This governance gap set the stage for a paradigm shift toward community-based forest management, reversing the trend of deforestation and enabling Nepal to nearly double its forest area by 2016 (Smith et al., 2023). Despite its minimal contribution to global GHG emissions, Nepal is one of the pioneer countries implementing forest-based emission reduction programs (Aryal et al., 2024), leading the climate change mitigation movement through its forest carbon sinks.

Nepal institutionalized community forestry through the Forest Act (1993), which provided local communities with legal rights over the forest resources through the community forest user groups (CFUGs) (Luintel et al., 2018; Smith et al., 2023). This participatory approach not only decentralized governance but also empowered CFUGs to manage forest resources sustainably. Since then, the approach has gained international recognition in forest conservation and management (Banskota et al., 2007). Currently, more than 22,000 CFUGs manage approximately 37.5% of the country's total forest area. In addition to preserving livelihoods and biodiversity, these community forests have the potential to sequester carbon and produce quantifiable climate benefits (Newton et al. 2016). Therefore, tracking carbon circulation statistics at the community level provides valuable information for sustainable forest management and improves Nepal's capacity to participate in international climate finance mechanisms. Hence, this study estimates the carbon stock of the Bandeshwori community forest in Bhaktapur, Nepal, as one of such measures.

Methods

Study Area

Bandeshwori community forest (BCF), located in Nangkhel, Bhaktapur is managed by Bandeshwori community forest user group (BCFUG) since 2001 and constitutes 253 households (FOP 2015). The community forest lies under temperate climatic zones and covers an area of 55.36 ha with an altitude ranging from 1500 to 1850 m above sea level. The forest is divided into four sections (Section I: Good, covering an area of 20.25 ha with slope of 35° - 40°; Section II: Good, covering an area of 14.50 ha and slope of 25° - 30°; Section III: Good, covering an area of 10.04 ha and slope of 35° - 40°; and Section IV: Medium, covering an area of 10.57 ha and slope of 25° - 30°) for better management as guided by the forest operational plan (FOP 2015) (Figure 1).

The community forest has both natural and planted forests. *Pinus* species are the planted forest type, while natural forest is dominated by *Alnus nepalensis (*Uttis*), Schima wallichii (*Chilaune*), Castanopsis indica (*Katus*), Rhododendron (*Gurans*), Myrsine capitellata* (Seti-Kath), *Lyonia ovalifolia* (Aangeri), etc. (FOP 2015).

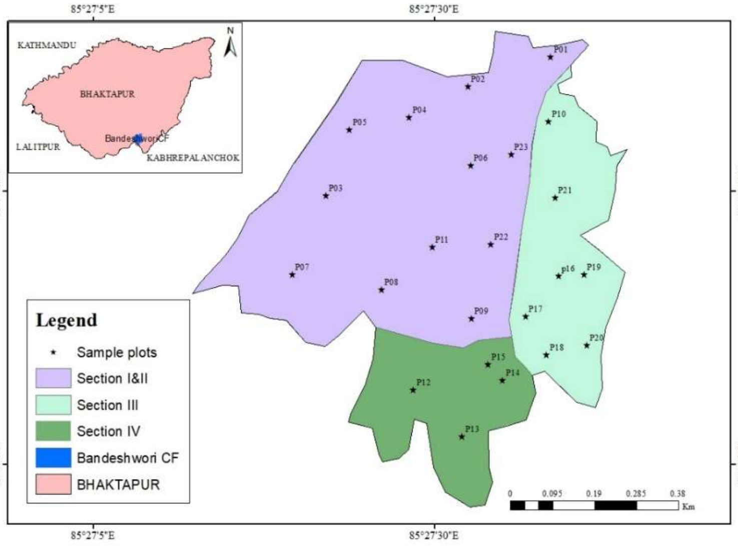

Figure 1. Map showing distribution of sample plots across different forest sections in Bandeshwori Community Forest, Bhaktapur, Nepal.

Forest and Soil Carbon

The forest carbon was estimated using the methodology adopted from Subedi et al. (2010). Firstly, a total of 30 random points were generated over the community forest area using ArcGIS; however, only 23 plots were accessible during the field survey. A field survey was conducted using nested circular plots, each measuring 250 m^2. Each plot included sub-plots for sampling trees (≥ 5 cm DBH), saplings (< 5 cm DBH), and seedlings (Subedi et al., 2010). Soil samples were collected from the inner sub-plots, from three depth intervals (0–10 cm, 10–20 cm, 20–30 cm) with the help of a metal core sampler of diameter 35 mm.

Diameter at breast height (DBH) of all the trees and saplings at 1.3 m height within the plot boundary were measured with the help of D-tape. A clinometer was used to measure tree height, and biomass was estimated using established allometric equations. The Walkley-Black method was used to calculate the organic carbon content of the soil at each depth (Walkey & Black 1958).

Biomass and Carbon Estimation

The above-ground tree biomass (AGTB) was calculated using allometric equations (equation (i)) developed by Chave et al. (2005). The wood density was obtained from Sharma & Pukkala (1990).

$$AGTB = 0.0509\times (\rho D^2H) \text{ --------- (i)}$$

where,
AGTB = above-ground tree biomass (kg)
ρ = wood specific gravity (g/cm^3)
D = tree diameter at breast height (cm) and
H= tree height (m)

To determine the above-ground sapling biomass (AGSB), national allometric regression model (equation (ii)) was used (Tamrakar 2000).

$$\text{Log}\ (AGSB) = a + b \log (D) \text{ ------- (ii)}$$

where,
log = natural log (dimensionless)
AGSB = above-ground sapling biomass (kg)
a = intercept of allometric relationship for saplings (dimensionless)
b = slope allometric relationship for saplings (dimensionless) and
D = over bark diameter at breast height (measured at 1.3 m above ground) (cm)

For estimating below-ground biomass (BGB), equation (iii) developed by MacDicken (1997) was applied, which assumes BGB to be 20% of above-ground tree biomass.

$$BGB = 0.2 \times AGB \text{ -------- (iii)}$$

The biomass stock density is attained in kg/m^2 dividing it by the area of a sampling plot which is converted to t/ha by multiplying it by 10 (Subedi et al., 2010). The carbon content in biomass was calculated as 47% of dry biomass, in line with IPCC (2006).

The soil carbon (%C) was determined using the Walkley-Black method (Walkley & Black 1958), and the soil organic carbon (SOC) stock density was calculated using equation (iv) as described by Pearson et al. (2007).

$$SOC = \rho \times d \times \%C \text{ -------- (iv)}$$

where,
SOC= soil organic carbon content (t/ha)
ρ = bulk density of soil (gm/cm^3)
d= depth of the soil (cm) and
%C= Soil carbon content (%)

The total carbon stock was calculated using equation (v), as the sum of carbon stock densities of the individual carbon pool:

$$C\ (LU) = C\ (AGTB) + C\ (AGSB) + C\ (BB) + SOC \text{ -------- (v)}$$

where,
C (LU) = carbon stock density for land-use category (C/ha)
C (AGTB) = carbon in above-ground tree biomass (C/ha)
C (AGSB) = carbon in above-ground sapling biomass (C/ha)
C (BB) = carbon in below-ground biomass (C/ha)
SOC = soil organic carbon (C/ha)

The total carbon stock was then converted to tons of CO_2 equivalent by multiplying it by 3.67 (Pearson et al., 2007). Data analysis was carried out using MS Excel. A simple descriptive analysis using mean, range and standard error was conducted.

Results

Forest Characteristics

The forest was assessed through three aspects (according to forest section): Section I & II, Section III and Section IV. Sections I & II were dominated by *Alnus nepal*ensis and *Schima wallichii* with scattered *Pinus* species; Section III had a mixed forest type with *A. nepalensis, S. wallichii, Castanopsis indica*, etc. and *Pinus* species at higher altitude; and Section IV was dominated by *Pinus* species and mixed *S. wallichii*. A total of 190 saplings and 36 seedlings were recorded from the 23 sample plots studied.

DBH Class of the Species

In the BCF, the majority of trees (33.11%) were recorded in the 25-30 cm DBH class followed by 15- 20 cm (27.83%) DBH class. The DBH class 5-10 cm also had a substantial portion of trees (20.74%), whereas only 0.15% of trees had DBH greater than 30 cm (Figure 2). In total, 1051 stems with DBH ≥10 cm were recorded, equivalent to 604.32 stems/ha.

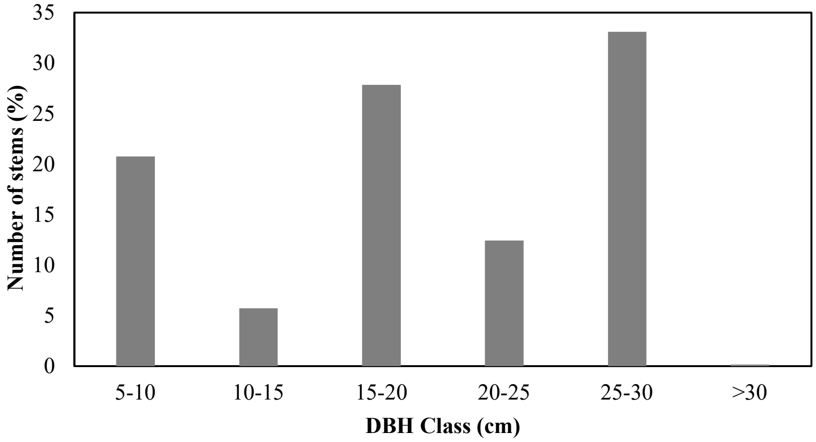

Figure 2. Distribution of tree stems (%) across various diameter at breast height (DBH) classes.

Total Carbon Stock

The total carbon stock ranged between 356.92 t/ha in plot 10 to 82.35 t/ha in plot 3 with average total carbon stock of 179.36 ± 14.29 t/ha (Table 1). The total carbon stock equivalent to carbon-dioxide equivalent was estimated to be 12126.30 tons with mean 657.67 ± 52.40 tons of CO_2 per hectare.

Table 1. Summary statistics of carbon stocks across different pools and contribution of various carbon pools to the total carbon stock

Statistics	C (AGTB) (t/ha)	C (BGTB) (t/ha)	C (AGSB) (t/ha)	Soil Carbon (t/ha)	Total Carbon Stock (t/ha)
Mean	73.13	14.63	0.28	91.33	179.36
Minimum	7.14	1.43	0.00	57.37	82.35
Maximum	219.00	43.80	1.48	135.28	356.92
SD	52.83	10.56	0.33	22.60	68.54
SE	11.01	2.20	0.07	4.71	14.29
Contribution to total carbon stock (%)	40.77	8.15	0.16	50.92	100

The average above-ground tree carbon was obtained to be 73.13 ± 11.01 t/ha. Among the species, *P. roxburghii* contributed the highest (92.89 t/ha), followed by *P. wallichiana* (21.43 t/ha), *S. wallichii* (17.97 t/ha) and *A. nepalensis* (14.97 t/ha), were the major contributor while other species (*Rhododendron* sp., *L. ovalifolia*, *M. capitellata*, etc.) had negligible contribution (Figure 3).

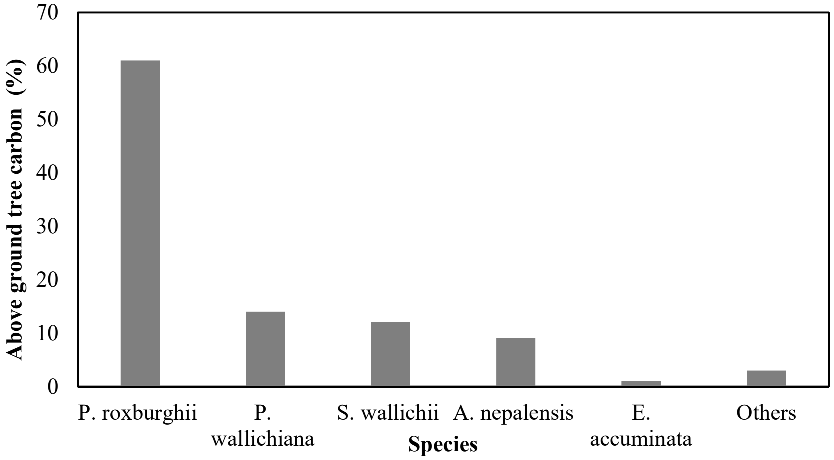

Figure 3. Contribution of different tree species to the total above-ground tree carbon stock.

Similarly, the average below-ground tree carbon and above-ground sapling carbon was obtained to be 14.63 ± 2.20 t/ha and 0.28 ± 0.07 t/ha respectively (Table 1).

Soil Carbon Content

Brownish to blackish color soil was found in the floor of BCF. The soil carbon stock varied between 135.28 t/ha in plot 4 to 57.37 t/ha in plot 7, with mean carbon stock of 91.33 ± 4.71 t/ha (Figure 4).

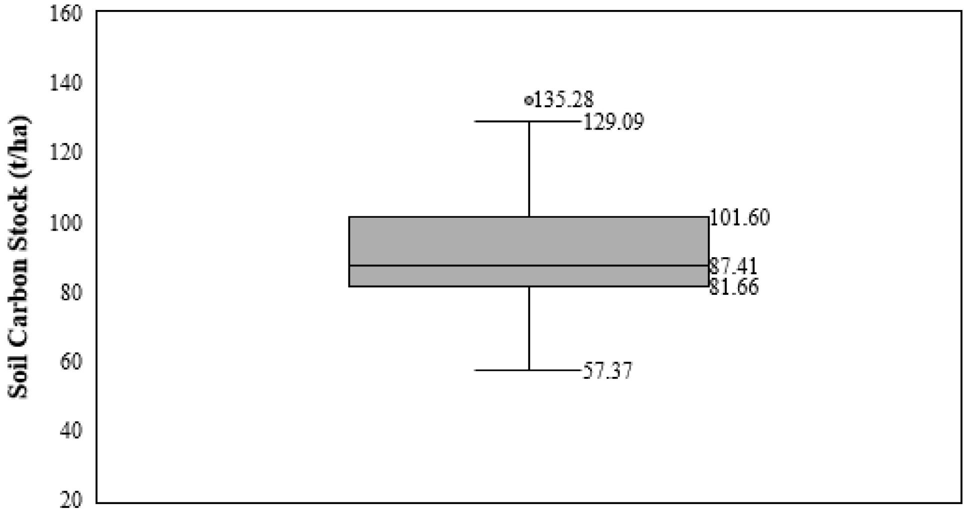

Figure 4. Box plot showing the distribution of soil carbon stock (t/ha). The central box represents the lower (81.66 t/ha) and upper quartiles (101.60 t/ha), along with median (87.41 t/ha); while the whiskers denote the minimum (57.37 t/ha) and maximum (129.09 t/ha) values; and the point (135.28 t/ha) beyond the whiskers represents the outlier.

The soil carbon contributed the highest (50.92%) to the total carbon stock of BCF (Table 1). Furthermore, soil carbon content decreased with the depth of soil layer. The net carbon content of soil was highest for 0-10 cm (81.01 ± 5.90 t/ha), followed by 10-20 cm (65.03 ± 3.97 t/ha) and 20-30 cm depth had the lowest carbon content (48.27 ± 2.85 t/ha).

Carbon Stock within Forest Section

The average carbon stock in Section I & II of the BCF was found to be 160.10 t/ha, while Section III contributed 212.83 t/ha, and Section IV contributed 178.59 t/ha of total carbon stock. Soil carbon contributed the highest carbon stock in all the sections (Table 2).

Table 2. Carbon stock (average) estimates (t/ha) across different forest sections

Forest Sections	C (AGTB) (t/ha)	C (BGTB) (t/ha)	C (AGSB) (t/ha)	Soil Carbon (t/ha)	Total Carbon Stock (t/ha)
I &II	62.05	12.41	0.36	85.29	160.10
III	94.71	18.94	0.17	99.01	212.83
IV	68.64	13.73	0.23	95.99	178.59
Grand Total	73.13	14.63	0.28	91.33	179.36

Discussion

Forest Characteristics

The maximum number of trees (>33%) had DBH ranging from 25 to 30 cm. Only 0.15% of trees had DBH >30 cm, which indicated that the forest had not attained complete maturity, or was indicative of the selective logging practice. Likewise, 20.74% of trees fell under the DBH class of 5-10 cm, indicating that the forest is still young and regenerating. The DBH class distribution was skewed toward mid-sized ranges instead of a typical reverse-J shape, suggesting uneven-aged natural forests (FRTC 2022; Khadka et al., 2024). The skewed DBH class indicated the possibilities of disturbances.

Despite a smaller number of mature trees, a stem density of 604.32 stems/ha was estimated in BCF. This is higher than the national average of 429.93/ha (DFRS, 2015). However, the stem density was below average compared to the middle mountain forests (938.53 per ha) of Nepal (FRTC, 2022). Higher stem density in BCF suggests further growth potential and contribution towards carbon sequestration in the future (Uprety et al., 2025).

Estimated Total Carbon Stock

The total carbon stock for the entire community forest was estimated to be 9929.37 tons. The mean carbon stock of BCF was found to be 179.36 ± 14.29 t/ha, equivalent to 657.67 ± 52.40 tons of CO_2 per hectare. The carbon stock of BCF was found to be higher than the average stock in middle mountain forests (147.13 t/ha) (FRTC, 2022). Studies have shown that community forestry programs have positive effects on the carbon stock (Thapa-Magar & Shrestha, 2015). Bandeshowri CF has been managed by the CFUGs since 2001. Besides, the soil carbon stock of BCF was 91.33 t/ha, which is above average for middle mountain forests (54.33 t/ha) of Nepal (FRTC, 2022), which might be one reason for the higher total carbon stock. The dominance of the planted pine species forest might have contributed to the above-average stock, as previous studies have shown higher carbon stock in planted forests (Chen et al., 2016). However, this is slightly higher than the average carbon stock (176.76 t/ha) of Nepalese forests (FAO 2020). The FAO (2020) also accounted for dead wood stock, as well as the average of the total forest areas of Nepal, which might be the reason for the deviation.

Of the total carbon stock, 50.92% was contributed by soil, 40.93% by above-ground and 8.15% by below-ground, respectively. The above-ground tree stock (73.13 t/ha) of BCF was slightly lower than the average hill forests of Nepal, i.e., 91.15 t/ha (FRTC 2022), and also the national average (83.11 t/ha) (FAO 2020). The contribution of the tree component to the net carbon stock of BCF was found to be lower than the average of mid-mountain forests (61.95%) of Nepal (FTRC 2022), as well as the national average (FAO 2020). As there were very few stems with higher DBH (only 0.15% of trees with DBH>30 cm) in the BCF, this might be one of the reasons. Also, these studies accounted for dead wood stock, while this was not accounted for in our study.

The carbon stock of BCF was found to be the highest (356.92 t/ha) for plot 10 and lowest (82.35 t/ha) for plot 3. The highest carbon stock in plot 10 was due to the dominance of pine trees having the highest average DBH (22.96 cm and 23.67 cm for *P. roxburghii* and *P. wallichiana*). Higher basal area is found to be associated with high carbon stock (Uprety et al., 2025). Likewise, carbon stock varied across the forest management sections. Section III had the highest carbon stock, due to the domination by pine forest in that section. The Pine species had the highest mean DBH and basal area in the BCF. Dahal (2007) estimated the total carbon stock to be higher for pine forest (116.50 ± 16.39 t/ha) than mixed broad leaf forest (25.93 ± 1.03 t/ha). Additionally, the *Pine* species were planted as per FOP (2015), and studies have estimated higher carbon stock in planted forests (Chen et al., 2016). The low carbon stock of Sections I & II is affected by the lower wood density of *A. nepalensis* (Sharma & Pukkala, 1990), one of the dominant tree species in that section.

Soil Carbon

The net carbon content in soil in BCF was estimated to be 91.33 ± 4.71 t/ha. Globally, soil carbon is the largest carbon pool in major terrestrial ecosystems (Scharlemann et al., 2014). In the Nepalese context, several studies have identified soil carbon as the major carbon pool in forest ecosystems. In this study, soil carbon accounted for 50.92% of the total carbon stock, which is consistent with findings from similar regions where soil carbon contributed over 50% of total carbon stock (Lamsal et al., 2023). However, this proportion is higher than the national average (36.92%) reported for middle mountain forests of Nepal (FRTC 2020). Previous studies have emphasized long-term stability and greater carbon sequestration potential of soil, resulting in a higher contribution to total carbon stock (Lal et al., 2015; Berthelin et al., 2022).

Soil Carbon Stock Variation across Soil Depth

Soil carbon content decreased with increased soil depth. Previous studies in the community forests of Nepal have also found maximum soil carbon in the top layer (0-10 cm) compared to subsequent layers (Dahal 2007; Joshi et al., 2021; Lamsal et al., 2023). This difference at various depths is in variation with the microbial activities and availability of decaying materials (You et al., 2014). The top layer has high humus contributed by leaf litter and dead logs over the forest floor, which subsequently increases the microbial activities in the top layer.

Although some studies present contradictory opinions regarding the community forestry program and carbon stocks (Luintel et al., 2018), various studies have reported that community forest management generally contributes as a carbon sink (Banskota et al., 2007; Charmakar et al., 2021). The BCF demonstrates a good potential for carbon sequestration. This assessment of carbon stock would serve as the baseline/reference value for future monitoring to assess the actual carbon reductions from the community-managed BCF and earn potential benefit from the carbon trading mechanisms (Austin et al., 2025). While it is crucial for regular monitoring to understand the temporal changes in carbon statistics, estimate emission reductions, and estimate the rate of carbon sequestration; the integration of advanced tools such as remote sensing, LiDAR, and machine learning is equally necessary for refined carbon estimates as well as scaling across regions and forest types (Singh et al., 2023).

However, this study didn't take into account the leaf-litter and dead wood biomass. Adding these into account in future inventories would provide a more reliable estimate. Additionally, due to resource constraints, only 23 random plots were sampled during this study; a comprehensive spatial coverage of sample plots would contribute to a more generalizable estimation of the overall carbon stock of the BCF.

Conclusion

The Bandeshwori Community Forest (BCF) stores above-average carbon stock compared to the average stock reported for middle mountain forests in Nepal. The dominance of trees with small DBH resulted in lower contributions of above-ground biomass to total carbon stock but also indicates the potential for further growth and carbon sequestration. The soil carbon content, which decreased with depth, represented the largest share of total carbon among various pools in BCF. Continued monitoring to explore temporal changes in carbon pools, particularly SOC, and evaluating carbon emission reduction rate is crucial for any benefit from carbon financing.

CRediT Author Statement

BB: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing- Original Draft, Writing- Review & Editing, Visualization, Project administration; **SA:** Conceptualization, Methodology, Formal analysis, Data Curation, Writing- Review & Editing, Visualization, Supervision

Declaration of competing interest

The authors declare that they have no competing interests.

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