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Carbon secrets: Quantifying biomass and carbon stock potential of Sal (*Shorea robusta* Gaertn.) in a community forest of Makawanpur, Central Nepal

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A R T I C L E I N F O

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A B S T R A C T

In Nepal, carbon sequestration potential of Sal (*Shorea robusta*) in community forests (CFs) is understudied. This study assessed aboveground biomass (AGB) and belowground biomass (BGB) and estimated the carbon stock potential of *Sal* trees in Neureni–Chisapani CF, Makawanpur district, Central Nepal. Data were collected from 16 circular plots of 250 m^2 each, established across four blocks. All *Sal* trees with DBH ≥ 5 cm were measured. The AGB was calculated by using allometric equations and BGB by root–shoot ratios, and the total biomass was converted to carbon stock using the standard carbon fraction. Environmental factors, including altitude, soil pH and rock cover, were recorded to find their relationships with the carbon stock. The forest stored an average of 248.97 t/ha of AGB, 64.72 t/ha of BGB, 313.69 t/ha of total biomass and 146.96 t/ha of carbon. A total of 13.87 m^2/ha of basal area was calculated. Block-level carbon ranged from 137.79 to 158.12 t/ha, though ANOVA showed no significant difference ($p > 0.05$). The carbon stock strongly correlated with DBH, height and basal area; however, Generalized Linear Model showed unimodal and curvilinear relationships with altitude, soil pH and rock cover. Thus, these results confirm CFs as good carbon reservoirs, which helps to develop climate change mitigation strategies and sustainable forest management policies.

INTRODUCTION

The increasing level of atmospheric carbon dioxide (CO_2) is the major cause of global climate change (Kabir et al., 2023). Vegetation and soil are viable sinks of atmospheric carbon (Lal, 2004; Smith, 2004), and the significant role of plants in sequestering carbon into biomass and soil is central to climate change mitigation strategies (Rahman, 2013). The goal of increasing the carbon storage can be accomplished through the protection and conservation of forests, as about 43–50% of the dry biomass of trees is carbon (Malhi, et al. 2002). The capacity of forests in storing carbon varies according to the geographical location, plant species and age of the stand (Ma et al., 2015). Assessment of aboveground biomass (AGB) can help to depict the relationships of biosphere and atmospheric interactions (Anaya et al., 2009), along with the carbon stocks contributed by plants (Ketterings et al., 2001).

AGB and belowground biomass (BGB) can help estimate the total carbon securely stored in forests (Hamburg, 2000). Globally, forests store about 80% of terrestrial aboveground carbon (Houghton, 2005) and over 40% of terrestrial belowground carbon (Pan et al., 2011). In addition, forests and soil, which store carbon, increase biodiversity and also minimize the risk of soil erosion, providing a host of agricultural and environmental benefits (Alemu, 2014). However, the potential of forests in developing countries, like Nepal, is still underexplored due to insufficient localized data and analysis (Lamsal et al., 2018).

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Estimating carbon pools in existing forests provides baseline data of sequestrated carbon over time (Cook-Patton et al., 2020; Shrestha and Singh, 2008), and to quantify the stored carbon in the forest ecosystem, temporal carbon stocks under various forest types must be assessed (Leighty et al., 2006; Thomas Nord-Larsen, 2024). Of the various other emission reduction strategies, biological sequestration of CO_2 by forest is considered the most cost-effective approach (Banskota et al., 2008; Stern, 2007). The tropical forests contribute approximately 40–50% of all terrestrial carbon stocks, although they occupy only 7–10% of the global area (Cuni-Sanchez et al., 2021; Raha et al., 2020). Almost half of Nepal's tropical forests are dominated by *Shorea robusta* (Sapkota et al., 2010) and act as an important sink for the carbon store (Webb and Sah, 2003).

The community forests (CFs) of Nepal are the best known participatory programme (Ghimire and Lamichhane, 2020). They have contributed to a good increment in biodiversity and substantial improvement in forest cover, playing a significant role in carbon sequestration (Ayer et al., 2022; Rawal and Subedi, 2022). Furthermore, they have sufficient capacity to store carbon in the form of biomass (Tripathi et al., 2017) and are considered as the most effective global forest management system (Laudari et al., 2024). Despite this, comprehensive and localized data remain scarce, particularly on central Nepal, where community-managed forests are ecologically diverse and under various scientific management systems.

Numerous studies have highlighted the role of forests in carbon sequestration, both globally (Gorain et al., 2025; Grafton et al., 2021) and regionally (Charmakar et al., 2021; Joshi et al., 2023; Joshi et al., 2021b). Yet, local-scale species-specific assessments remain poorly represented. The carbon dynamics of *Shorea robusta* within community-managed forests under scientific management system have not been adequately quantified. This study links biomass estimates to ecological attributes to advance our understanding of carbon sequestration in tropical CFs, underscoring their role in mitigating the impact of climate change. This research addresses these gaps by providing empirical evidence from Neureni–Chisapani CF in Makawanpur district in central Nepal, thereby contributing to the national carbon database and carbon market initiatives.

This study was conducted to assess the AGB and BGB and estimate the carbon sequestration potential of *Sal* trees in Neureni–Chisapani CF. It aims to (i) quantify AGB and BGB and carbon stock of *Sal* trees, (ii) analyse variations in carbon stock potential among four forest blocks and (iii) evaluate the relationships between carbon stock, structural attribute (DBH, height, basal area) and environmental variables (altitude, soil pH, rock cover).

MATERIALS AND METHODS

Study area

The research was carried out in Neureni–Chisapani CF, located in Hetauda Municipality–07, Makawanpur district, Bagmati province, central Nepal ($27^0 10'$ to $27^0 40'$ N and $84^0 41'$ to $85^0 31'$ E). The district ranges in elevation from 166 metres above sea level (masl) in the south of the Churia hills to 2,584 masl in the north of the Mahabharat hills (Subedi et al., 2019). The Churia range is dominated by the tropical and subtropical climates, while the Mahabharat range is dominated by the temperate climate (Bhattarai et al., 2009). The forest lies within the subtropical belt, at elevations ranging from 466 to 630 masl, with slopes ranging from 5° to 45° with the southern aspect, and covering an area of 71.30 hectares (ha) (CFOP, 2025). The annual rainfall ranges from 1,300 mm to 1,600 mm, the temperature ranges from 15 °C to 32 °C, and soil is predominantly stony, gravelly boulder and red (CFOP, 2025).

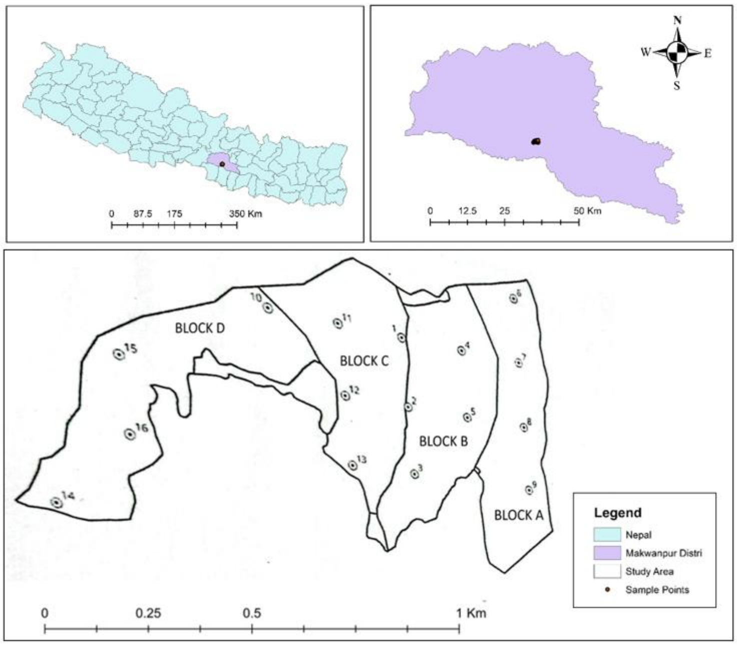

Figure 1: Study area and sample plots in the forest blocks

The forest is dominated by Sal trees (*Shorea robusta*), and the other associated tree species include *Chilaune (Schima wallichi)*, Karma *(Adina cardifolia)*, Asna (*Terminalia elliptica*) and Kangiyo (*Grevillea robusta*). This forest was handed to forest user communities in 2047 B.S. (DFO, 2007) and has been under the scientific forest management programme since 2015. For management purposes, the forest, occupying an area of 71.3 ha, was divided into four blocks, based on physiographic conditions, like creeks, small streams and roads (CFOP, 2025).

Sampling design

The forest was stratified into four management blocks, with approximately equal areas and physiographic conditions (CFOP, 2025), namely block A (17.34 ha), block B (18.43 ha), block C (16.4 ha) and block D (19.13 ha) (CFOP, 2025). The sampling intensity of the area of the forest was calculated, which was 0.5% of the total forest area, which is consistent with the carbon assessment guidelines for community forests (Subedi et al., 2010; Joshi et al., 2021a). We used 0.5% sampling intensity because the forest has the homogeneous stand of *Shorea robusta*, and the estimates was adequated and reliable (Joshi et al., 2021a; Regmi et al., 2021). A total of 16 sampling plots were established using the ArcGIS software, where each block consisted of a total of four concentric circular plots of radius 8.92 m (area = 250m^2) (ANSAB, 2010). All Sal trees with DBH ≥ 5 cm, tree trunks inside the plot but branches outside, and trees in the borderline with at least 50% of the trunks inside the plot were recorded for biomass and carbon stock estimation (ANSAB, 2010).

Field data collection

A survey was carried out during January–June 2025 for obtaining biophysical measurements of individual trees, like diameter at breast height (DBH) and height. DBH was measured using a diameter tape, and tree height with a Suunto clinometer. Other required site details, such as altitude, soil pH and rock cover, were recorded for each plot. Altitude was recorded using GPS. Soil pH was measured using a portable digital pH meter to a depth of 20 cm. Rock cover was visually estimated as a percentage of ground surface. However, slopes less than 10% (5.74^0) were considered insignificant and true horizontal length (Goslee et al., 2016).

Biomass estimation and net carbon content

The biomass of each tree is in different forms, such as stems, branches, leaves and roots. The AGB includes stems, branches and leaves, whereas the BGB includes roots. Biomass was predicted by non-destructive methods. After obtaining the total biomass, the carbon stock was estimated using specific relation as specified by the Intergovernmental Panel on Climate Change (2006).

Aboveground biomass

The total AGB was calculated by using a widely-applied allometric equation (Chave et al., 2005).

$$AGB = 0.0509 \text{ X } \rho D^2H$$

Where,
ρ = Wood-specific gravity (g/cm^3) [0.88 g/cm^3 for Sal trees (Bohara et al., 2021)]
D = tree DBH (cm)
H = tree height (m)

The obtained AGB values for each individual weight (kg) of sampling plot were summed up and divided by the sampling plot area (250 m^2). The biomass stock density value thus obtained in kg/m^2 was then converted to t/ha by multiplying it by 10.

Belowground biomass

BGB was estimated by multiplying AGB 0.26 times (Eggleston et al., 2006).

BGB = 0.26 x AGB (t/ha)

Total biomass

Total biomass of the plant was determined by adding AGB and BGB (Djomo and Chimi, 2017)

Total biomass (TB) = AGB + BGB

Net carbon content

To estimate carbon stock, the total biomass obtained was multiplied by default carbon fraction of 0.47 (Eggleston et al., 2006) as:

Total carbon stock = Total biomass x 0.47

Basal area estimation

The basal area (BA) of the tree was calculated using the basic formula (Rana et al. 2008).

$$\text{Basal area (BA)} = \frac{\pi (DBH)^2}{4}$$

Statistical analysis

The data collected were managed in MS Excel spreadsheet, and R version 4.1.1 (R Development Core Team, 2020) was used for statistical analysis and graphical representation. ANOVA was conducted to compare the differences in the carbon stocks in the different blocks of the forest. A Pearson correlation test was performed to measure the strength of relationship among the key forest structural variables (DBH, tree height and basal area) and carbon stock at 0.05 confidence level. The effect of environmental factors (altitude, soil pH, basal area and rock cover) on carbon stock were calculated through regression analysis. Generalized Linear Model (GLM) (LM: McCullagh & Nelder, 1989; Dobson, 1990) was used to show the relationship between the response (carbon stock) and predictor variables (environmental factors). A quasi-Poisson error distribution with F-test was used to handle the overdispersion of the deviance (Crawley, 2007). The significance of each model was tested against the null model, as well as with each other, up to the third-order polynomials.

RESULTS

Biomass estimation

The estimated average AGB in the forest was 248.97 t/ha. Biomass varied across the four blocks, with block A recording the highest AGB (267.00 t/ha), consecutively followed by block D (247.57 t/ha), block

B (245.40 t/ha) and block C (235.68 t/ha). Similarly, BGB ranged from 60.50 t/ha (block C) to 69.42 t/ha (block A) across the forest. The total average biomass of the forest was estimated at 313.69 t/ha (Figure 2a). Although there was variation of biomass in the blocks, the overall biomass values depict relatively uniform productivity across the forest (F = 0.132, p = 0.86), reflecting a consistent forest structure and management strategy.

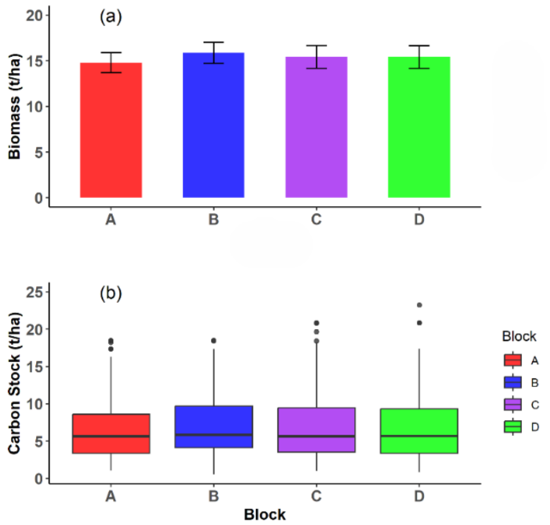

Figure 2: (a) Total biomass (t/ha) in across forest blocks and (b) box plot showing total carbon stock in within forest blocks

Carbon stock estimation and distribution pattern

The average carbon stock of the forest was 146.96 t/ha. The block-level carbon stock estimates ranged from 137.79 t/ha (block A) to 158.12 t/ha (block A), meanwhile block B (145.32 t/ha) and block D (146.61 t/ha) (Table 1). This result indicates that block A contributed higher carbon storage due to the presence of large and tall *Sal* trees, whereas block C constituted relatively small trees and, hence, less carbon storage.

Despite these apparent differences, ANOVA shows no statistical significance within the blocks (F = 0.146, p = 0.932) (Table 2), indicating no large variation in structural and environmental attributes, with homogeneous distribution of carbon. This indicates that the community forest user groups (CFUGs) follow effective forest management strategies

Basal area estimation

The average basal area of the community forest was 13.87 m^2/ha. Among the blocks, the maximum basal area was observed in block B (17.67 m^2/ha), consecutively followed by block D (16.02 m^2/ha) and block C (15.27 m^2/ha). Block A has the lowest basal area (6.58 m^2/ha), although it has the highest biomass and carbon stock. This indicates that that this block has fewer but larger trees, thus having higher biomass contribution (Table 1).

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Table 1: Tree attributes in different eorest blocks

Attributes	Forest Blocks				Total
	A	B	C	D	
AGB (t/ha)	267.00	245.40	235.68	247.57	248.97
BGB (t/ha)	69.42	63.80	60.50	64.31	64.72
Biomass (t/ha)	336.42	309.20	293.18	311.94	313.69
Carbon (t/ha)	158.12	145.32	137.79	146.61	147.43
Basal area (m^2/ha)	6.58	17.67	15.27	16.02	13.87

Table 2: Analysis of Variance between Forest Bocks and Carbon Stock

	Sum of Squares	df	Mean Square	F	P-value
Forest Blocks	11	3	3.63	0.14	0.93
Residuals	8000	322	24.84	-	-

Relationship of carbon stock with structural Attributes

Correlation analysis revealed strong and statistically significant relationships among the four measured structural attributes, like and carbon stock (Figure 3, Table 3). There were strong positive associations between DBH and carbon stock ($r = 0.96$, $p < 0.001$); DBH and height ($r = 0.82$ $p < 0.001$), emphasizing their importance as a reliable predictor for tree-level biomass accumulation. The basal area also showed a positive association with carbon stock ($r = 0.73$, $p < 0.001$), confirming its utility as a stand-level indicator of carbon sequestration capacity. This evidence provides evidence that larger, taller trees with greater basal area contribute to forest biomass and carbon reserves, consistent with the pattern in other tropical Sal-dominated forests.

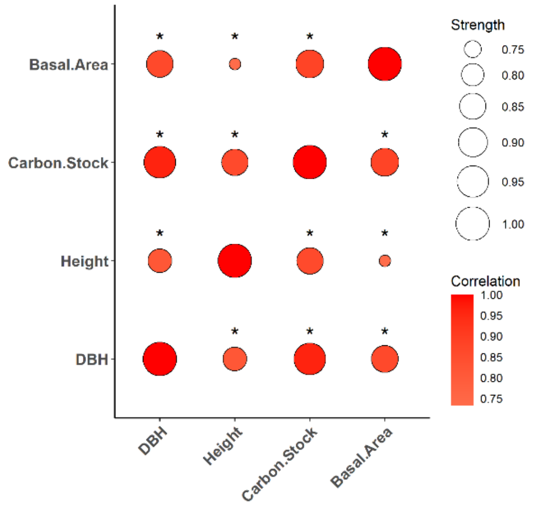

Figure 3: Figure showing pairwise relationships among DBH, height, carbon stock and basal area. Circle size and colour indicate the strength and direction of correlation coefficients respectively, with dark red indicating stronger positive associations.

Table 3: Correlation matrix of measured variables

	DBH	Height	Carbon stock	Basal area
DBH	1			
Height	0.82	1		
Carbon stock	0.96	0.86	1	
Basal area	0.86	0.73	0.88	1

Relationship of carbon stock with environmental variables

The GLMs showed a distinct pattern of carbon distribution in relation to environmental variables (Figure 4). Carbon stock and altitude showed unimodal patterns with humpback shapes, reflecting reduced carbon stock at mid altitude. This suggests that anthropogenic pressures in the intermediate area may reduce tree growth and carbon accumulation. The carbon stock showed a curvilinear response with soil pH, where carbon stock decreased with increasing soil pH, indicating that more acidic soils may support greater carbon storage. Furthermore, it showed a unimodal response with rock cover, suggesting unique patterns in carbon distribution. This reflects that the soil profile determines vegetation distribution, and surface rocks may not be the limiting factor. Similarly, the basal area exhibited unimodal hump-shaped patterns with carbon stock, which provides an interesting relationship where carbon stock was high in the moderate basal area. These trends highlight the combined influence of abiotic and biotic factors on carbon dynamics in the forest ecosystems.

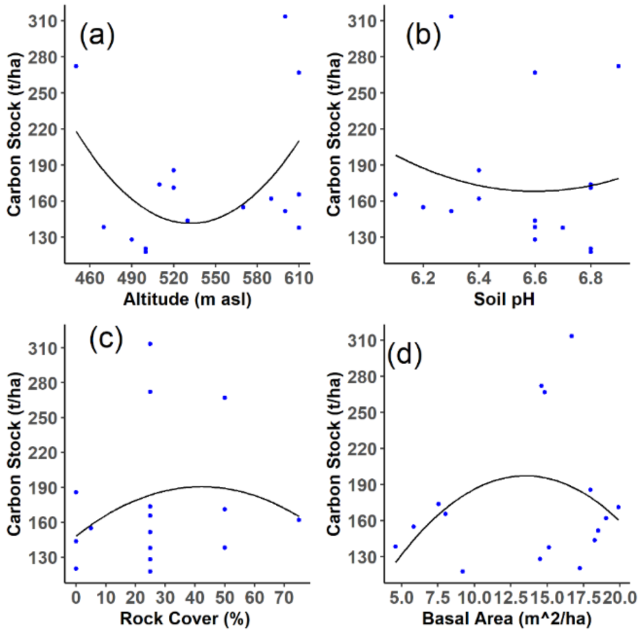

Figure 4: Relationships between the carbon stock (t/ha) and environmental variables: (a) Altitude (m asl), (b) Soil pH, (c) Rock Cover (%) and (d) Basal Area (m^2). Each plot includes observed data points and fitted regression curves.

DISCUSSION

Forest biomass and carbon stock

The present study assessed the average biomass of *Sal* trees as 313.69 t/ha and the carbon stock as 146.96 t/ha in Neureni–Chisapani CF. These values are relatively high compared to several other *Sal*-dominated forests previously reported from Nepal. Pandey et al. (2014) estimated carbon stocks as 89.2 t/ha in sparse stands to 129.0 t/ha in dense stands of the Kayerkhola watershed, Chitwan, while Ghimire (2017) reported 62–65 t/ha in Danphe CF, Dang. The higher carbon stock in the present study likely reflects the presence of mature *Sal* trees with larger DBH and tall trees. It is because the eastern region (Makawanpur) receives more rainfall than the western region (Dang), and high precipitation zones can accelerate growth and hydraulic conductivity compared to dry regions (He et al., 2020). Moreover, the study site is supported by sustained community management practices, favouring recovery and proper growth of trees.

This finding aligns with other tropical forests where carbon storage capacity of the forest is strongly linked to stand maturity and structural attributes, such as basal area and tree height, along with the management strategy (Khan et al., 2020; Fobane et al., 2024). Thus, this forest provides strong evidence that the potential of community forests serves as significant carbon reservoirs within Nepal's tropical belt.

Forest structure and carbon variation

Although biomass and carbon stock varied among the four blocks (highest in block A, lowest in block C), statistical analyses (ANOVA, $p = 0.932$) showed no significant differences between the blocks. This indicates homogeneity in carbon distribution, reflecting consistent physiographic conditions and similar management practices across the blocks. The slight differences in the blocks may be explained by variations in tree size and density. This may be supported by the evidence that block A with lowest basal area (6.58 m^2/ha) has highest carbon stock (158.12 t/ha), suggesting that fewer but larger trees contribute to higher carbon storage.

These patterns highlight that tree size distribution, rather than pure stand density, is the key determinant of carbon sequestration capacity in *Sal* forests. Similar studies were reported from central Nepal by Thapa-Magar & Shrestha (2015), where basal area and carbon storage were strongly correlated, depicting the importance of large mature trees in maintaining carbon pools.

Structural attributes and carbon stock

The strong positive correlation between carbon stock with DBH, tree height and basal area provides strong evidence of tree allometry in biomass accumulation. The strongest relationship was between DBH and carbon stock ($r = 0.96$), supporting DBH as a reliable predictor in biomass estimation models. Height and basal area also showed strong correlation, consistent with the findings from a *Schima–Castanopsis* forest in the mid-hills (Tripathi et al., 2017) and tropical forests in Bangladesh (Saimun et al., 2021).

These results support the ecological principle that larger individuals act as "carbon giants" within forest, contributing to total carbon storage. Silviculture practices that promote the growth and survival of trees through selective harvesting, thinning and regeneration monitoring can significantly enhance long-term carbon sequestration potential.

Carbon stock and environmental variables

Carbon stock exhibited a distinct relationship with the environmental variables. Carbon showed a unimodal pattern with humpback shapes at mid elevations, with higher accumulation at lower and higher elevations. On the other hand, Kumar et al. (2024) reported contrasting trends in Western Ghats, India. The observed result in the study area might be due to illegal anthropogenic pressures, like cutting and felling of trees at mid-altitudes. The curvilinear relationship indicates greater carbon storage at moderately acidic soil. This is consistent with the other results that *Sal* trees grow luxuriantly in slightly acidic soil (Pandey & Bhusal, 2016). As soil becomes more neutral, nutrient limitations may reduce biomass accumulation. The unimodal response of carbon stock with rock cover showed reduced carbon, with increasing rockiness, which highlights the importance of soil profile and rooting space for biomass accumulation. This finding reflects the results from Bohara et al. (2021), who observed slope-dependent carbon variation in a Makawanpur forest. Similarly, the basal area exhibited a unimodal pattern with hump-shaped patterns, confirming that the stand with moderate basal area is favoured by the greater availability of resources like nutrient which favoured the higher basal area and hence carbon stock. This trend is not only in *Sal* forests but also across diverse tropical and subtropical ecosystems (Fobane et al., 2024).

CONCLUSION

The findings of this study show that community-managed forests can maintain stable biomass and carbon levels across the forest area when scientific forest management practices are applied. It further demonstrates that collective management helps to balance forest structure, with mature trees functioning as an effective carbon sink. However, site-specific conditions are important for carbon distribution and should be integrated into management planning. Effective monitoring and adaptive management of community forests at the block level will support sustainable management of forests and enhance their contribution to climate change mitigation.

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AUTHOR CONTRIBUTION

R.K. Gautam: Research design, data collection, data analysis and manuscript finalization; D. P. Dhakal: Research design, data collection, data analysis and manuscript revision; P. Bhattarai: Data analysis, revision of result and manuscript revision

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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