Do Managed Hill Sal (*Shorea robusta)* Community Forests of Nepal Sequester and Conserve More Carbon than Unmanaged Ones?

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ABSTRACT

Nepalese community forests are globally recognized for sustainable forest management and improving the livelihoods of forest-dependent communities, but their contribution to carbon sequestration in trees and soil is rarely studied. This study was performed to understand the effect of management practices on carbon stock of two community forests (CFs) - Taldanda (managed) and Dangdunge (unmanaged) - dominated by Sal (*Shorea robusta*) in the mid-hills of Nepal. Twenty-one concentric sample plots, each of 250 m^2, were laid out in each forest to estimate different carbon pools and a stratified random sampling intensity of 0.5% used to collect data. Results showed significant ($p<0.05$) differences in above and below-ground biomass and carbon sequestration potential between the two CFs. The managed and unmanaged forests had total carbon stock of 269.3±27.4 and 150.0±22.7 ton/ha, respectively, demonstrating 1.79 times higher carbon stock in the former than the latter. The managed forest had significantly ($p<0.05$) greater mean soil organic carbon (SOC) stock than the unmanaged forest. The SOC was highest in the upper soil layer (0-10 cm), with a steady decrease as the soil depth increased. All other measured carbon pools values were higher in managed compared to unmanaged forest. The difference in carbon stock was due to the manipulation of different forest management activities, including thinning, timber extraction, fire control, grazing, and fuel wood/fodder extraction. The study suggests that the implementation of proper forest management would be necessary for enhancing carbon stock in forest trees and soils.

1. INTRODUCTION

Carbon sequestration refers to the removal, capture, or sequestration of carbon dioxide (CO_2) from the atmosphere by condensing and storing it in a sink in a benign manner (Kirschbaum, 2003). It is the prolonged deposition of carbon in soils, plants, oceans, and atmosphere (Selin, 2019). Carbon sequestration in the forest is the process of removing CO_2 from the atmosphere and accumulating it in trees (Jindal et al., 2008). Trees and other plants in a forest absorb CO_2 during photosynthesis and then sequester it as biomass, which comprises standing timber, branches, foliage and roots, as well as all of the plant organisms (Jana et al., 2009). Forest trees and soils account for about 60% of the world's terrestrial carbon (Lal, 2004; Bajracharya et al., 2018); thus, they are the principal carbon pools in the forest ecosystem (Amir et al., 2018). Forests stock up to 70% to 80% of world's carbon and play a crucial role in mitigating greenhouse gas (GHG) emissions and climate change (Batjes, 2014; Vance, 2018). Furthermore, soil organic carbon (SOC) is the most influential carbon pool (Ali et al., 2019; Hou et al., 2019), and its increase has been recognized as a viable strategy for mitigating climate change through increased soil carbon sequestration (Alidoust et al., 2018). Based on the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, IPCC (2003), five terrestrial carbon pools (soil, litter, under-ground and above-ground biomass, and deadwood) and their

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dynamics are considered to estimate carbon stocks. Following the UNFCCC and its subsequent agreements, nations that are required to report on GHG emissions and removals must estimate the amount of carbon sequestration related to forestry, land use changes, and other land use-related activities (Di Cosmo et al., 2022).

In Nepal, forest covers about 45.3% of the total land area (FRTC, 2022) accumulating 1,055 million tons of carbon, which has a substantial contribution to mitigating the adverse consequences of climate change (DFRS, 2015). Forest ecosystems are being spoiled globally by different biotic and abiotic factors such as human encroachment, road constructions, wildfires, community reliance on forests, desertification, and mining (Arnold, 2022). In tropical and subtropical forests, carbon stocks are declining at the rate of 1-2 billion tons/year (Subedi et al., 2014). Based on the degree of disturbances, Nepalese forests are categorized into degraded and non-degraded forests (Jina et al., 2008). Bhattarai et al. (2012) mentioned that forest management practices influence carbon sequestration in both trees and soil. Therefore, effective forest management not only slows down deforestation and forest degradation rates (Nagendra et al., 2008) but also benefits the forest's carbon store and carbon sequestration (Chhatre and Agrawal, 2009; Pandey et al., 2014; Solomon et al., 2017). Presently, 2.4 million ha of forests are being operated by 22,682 local communities across the country as community forests (CFs) (GoN, 2022). These forests are either fully or partially managed or unmanaged by the local communities and have great potential to increase the carbon sequestration and mitigate the climate change. Moreover, agroforestry systems practiced within and outside the CFs also store carbon in trees and soil (Dhakal et al., 2022) and provide a range of ecosystems services (ES) that need to be considered in CF management (Ojha et al., 2022).

In unmanaged forests, occasional large-scale disturbances and frequent small-scale disturbances allow late-successional phases to develop, resulting in a fine-grained mosaic of different developmental phases (Bengtsson et al., 2000). Thus, unmanaged forests display typical features, such as large amounts of dead wood and decaying trees, old and large trees, and pits and mounds around root plates (Spies and Yurner, 1999). On the other hand, managed forest landscapes are characterized by frequent disturbances with low variability in disturbance size and display more homogeneous tree composition, vertical stratification, age structure, and successional dynamics but lack senescent phases (Kuuluvainen et al., 1996; Commarmot et al., 2005). At the local scale, unmanaged forests in general are said to contain more species than managed forests (Okland et al., 2003).

Sal (*Shorea robusta)* forests dominate both in hills and plains of Nepal and are managed by both government and local communities. Sal forests have been heavily exploited either to generate state revenue or to meet the forest product demand of the ever-increasing population (Acharya et al., 2002). Though the role of CFs in improving the livelihoods and ecosystems services have been studied (Dhakal et al., 2022; Ojha et al., 2022), their contribution in terms of carbon sequestration in trees and soil has rarely been reported. Though a few researchers have assessed the carbon stocks for a variety of land-use classes, species, and physiographic regions in CFs, most of them have no records of carbon stocks (Shrestha and Singh, 2008). Moreover, the soil carbon sequestration potential under CFs and agroforestry systems is still underappreciated (Kafle, 2020; Joshi et al., 2021; Dhakal et al., 2022). There is also a knowledge gap on the variation in carbon stock between managed and unmanaged forests in the same geographic region, climate, altitude, and within same species. Thus, this study assesses the above- and below-ground carbon stocks in trees and soil under managed and unmanaged Hill Sal CFs of Nepal. The study also illustrates the influence of management activities on Sal biomass and carbon stock, as well as the association between SOC and bulk density with depth. Additionally, this study offers fundamental knowledge on the association between altitude and carbon stock and provides the baseline information for the carbon sequestration potential of managed and unmanaged Hill Sal CFs of Nepal.

2. METHODOLOGY

2.1 Study area

The study was conducted in a managed Taldanda and an unmanaged Dangdunge CFs of Tanahun District in Nepal's Gandaki Province (27°74′-28°13′ N and 83°94′-84°56′ E) (Figure 1). Taldanda and Dangdunge CFs, with respective land areas of 100.12 ha and 81.98 ha, are both Sal-dominated. These CFs were chosen because they are nearly identical in terms of the growing stock observed 10 years ago (154 m^3/ha), altitude, climatic zone, and aspect, but differ in their management practices.

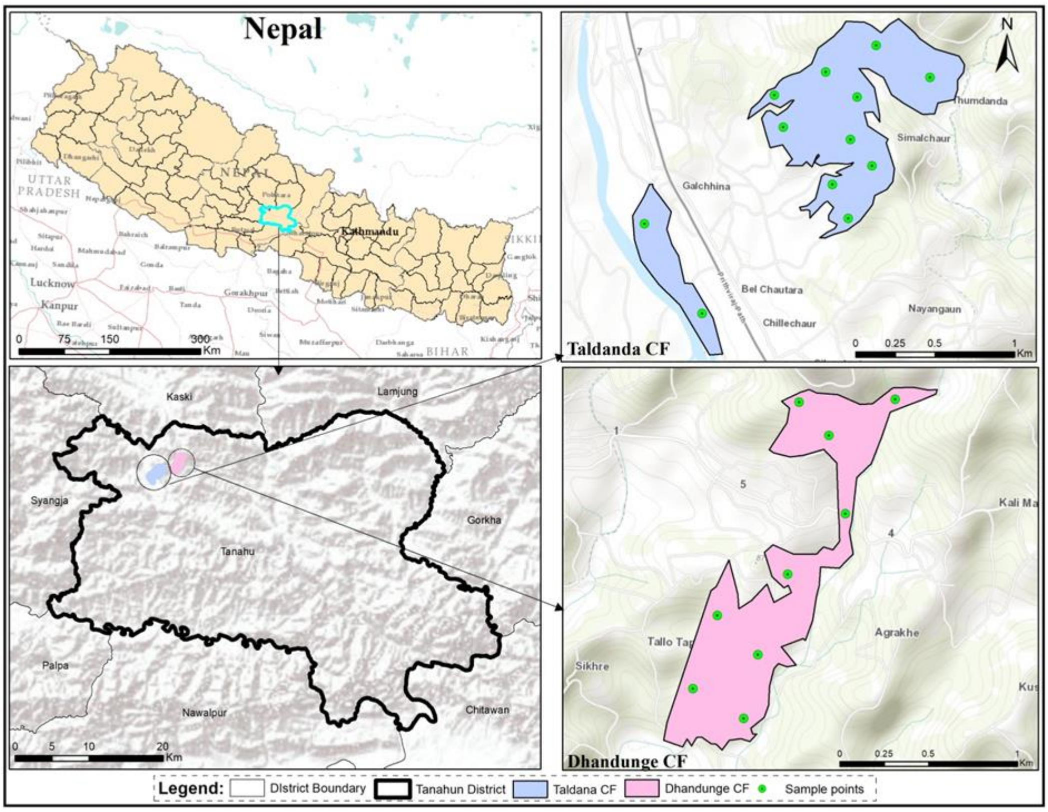

Figure 1. Map of Nepal showing study area with two community forests

2.2 Selection criteria

The criteria for managed and unmanaged CFs are shown in Table 1. Based on these criteria, Taldanda was considered as 'managed CF' and Dangdunge as an 'unmanaged CF'.

2.3 Sampling design and procedure

The majority of the data was gathered through a direct field survey of biophysical measurements. The diameter at breast height (DBH) and height of the tree were measured with a diameter tape (D-tape) and an Abney's level, respectively. A linear tape in the plot was laid out according to the sampling design (Figure 2). According to the guidelines for measuring carbon stocks in CF, 12 and nine sample plots were laid out in Taldanda and Dangdunge CF, respectively (ANSAB, 2010). Due to complex geology and variable altitude, a stratified random sampling method was used for measurements. Based on the Ministry of Forest and Soil Conservation's inventory guidelines, a sampling intensity of 0.5% was used (DoF, 2004).

Due to moderately dense woody vegetation, trees were measured within a circular plot of 250 m^2 with radius of 8.92 m to quantify above ground tree biomass (AGTB) (MacDicken, 1997). The DBH was measured at 1.3 m (DBH≥5 cm was considered as tree) and tree height was measured in each circular plot of 250 m^2 (Figure 2). For sapling measurements, a nested subplot of 100 m^2 with a radius of 5.64 m was established within larger plots (ANSAB, 2010). For assessing regeneration, smaller nested subplots with a 1 m radius were established within the larger nested plots. Saplings with diameters ranging from 1 to 5 cm were measured at 1.3 m above ground level, while saplings with diameter <1 cm were counted as regenerated. The regeneration data were used to observe the quality of regeneration.

The SOC was determined using samples collected from the IPCC (2006) recommended depth of 30 cm. A single 30 cm deep pit was dug at the center of each plot of both managed and unmanaged forests. To calculate bulk density, three soil samples from three depths (0-10 cm, 10-20 cm, and 20-30 cm) of approximately 300 cm^3 were collected from each plot using a standardized 300 cm^3 metal soil sampling core. Likewise, three samples from the same depths were collected to determine the organic carbon concentration in each depth. In addition, secondary data sources like published literature on carbon estimation were also used.

Table 1. Selection criteria of managed and unmanaged CFs

Criteria	Activities	Remarks
Thinning and Timber extraction	• Implementation of guidelines prescribed by respective CF operation plan (OP)	If Yes, Managed If No, Unmanaged
Weeding and cleaning	• Weeding at seedling stage • Cleaning at sapling stage	If Yes, Managed If No, Unmanaged
Fire	• Fire line construction • Controlled or prescribed burning • Legal measures to prevent fire (Sharma et al., 2011; Mathema, 2016)	If Yes, Managed If No, Unmanaged
Grazing	• Hoofmarks and dungs of livestock • Broken tops of seedlings and saplings • Signs of trampling (Joshi et al., 2020)	If Absence, Managed If Presence, Unmanaged
Fuel wood/fodder collection	• Restriction (Jina et al., 2008)	If Yes, Managed If No, Unmanaged

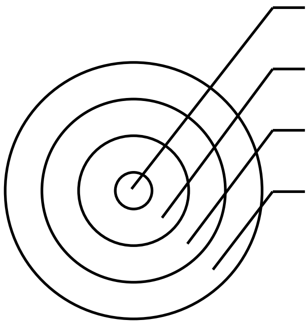

Figure 2. Sampling design of circular plots

2.4 Measurements and data collection

2.4.1 Above ground tree biomass

Above-ground tree biomass (AGTB) was estimated by using the following allometric equation devised by Chave et al. (2005):

$$AGTB = 0.0509 \times \rho D^2 H \quad (1)$$

Where; AGTB=above-ground tree biomass (kg); ρ=wood specific gravity (g/cm^2); D=tree diameter (m); and H=tree height (m).

The biomass stock density (kg/m^2) was calculated by adding the individual tree weight (kg) in the sampling plot and dividing by sampling plot area (250 m^2) and multiplying by 10 to convert to ton/ha. Biomass stock density was then converted to carbon stock density by multiplying by the default carbon fraction of 0.47 (IPCC, 2006).

2.4.2 Above-ground sapling biomass

Above-ground sapling biomass (AGSB) consisted of foliage, branch, and stem. The following regression model was used to calculate the AGSB.

$$\text{Log (AGSB)} = a + b \log (D) \quad (2)$$

Where; log=natural log (dimensionless); 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).

To evaluate the AGSB, national allometric biomass tables was utilized, which was generated by the Department of Forest (DoF), the Department of Forest Research and Survey (DFRS), Tree Improvement and Silviculture Component (TISC) (Tamrakar, 2000). Biomass stock density was then converted to carbon stock density by multiplying by the default carbon fraction of 0.47 (IPCC, 2006).

2.4.3 Below-ground biomass

The below-ground biomass (BGB) included the biomass of all live roots except fine roots with <2 mm diameter (Chavan and Rasal, 2012). The BGB was calculated by multiplying the AGB by 0.26 (constant factor) as per the Good Practice Guidelines of IPCC (2006) and Mandal and Joshi (2015):

$$BGB = AGB \times 0.26 \quad (3)$$

Where; BGB=below-ground biomass and AGB=above-ground biomass.

2.4.4 Deadwood biomass

The deadwood biomass (DWB) was evaluated by adding AGB and BGB and then multiplying by 0.11 (constant factor) as prescribed by IPCC (2006):

$$DWB = (AGB + BGB) \times 0.11 \quad (4)$$

Where; BGB=below-ground biomass and AGB=above-ground biomass.

2.4.5 Soil organic carbon and soil bulk density

Soil samples from 0-10, 10-20, and 20-30 cm depths from two replications were used to calculate bulk density and the carbon content of each plot in the laboratory.

Bulk density: Sixty-three soil samples were taken to the soil lab of the College of Natural Resource Management (CNRM), Puranchaur, Nepal. Samples were oven-dried at 105°C for 24 h and dried soils were passed through a 2 mm sieve. The sieved soils were weighed and the volume of stones was measured by water displacement method for stone correction. The following formula was employed to compute the bulk density (Pearson et al., 2005).

$$\text{Bulk density } (g/cm^3) = \frac{\text{Oven dry mass } (g/cm^3)}{\text{Core volume } (cm^3) - \frac{\text{Mass of coarse fragments } (g)}{\text{Density of rock fragment } (g/cm^3)}} \quad (5)$$

Carbon concentration (%): Sixty-three soil samples from each plot were dried at room temperature for three days and then quantified for carbon measurement by clearing stones and plant residue of >2 mm in size. Then they were taken to the Soil and Fertilizer Testing Laboratory (SAFTL), Gandaki Province, Pokhara where the titrimetric method based on Walkley and Black (1934) was employed for determination of carbon concentration.

Carbon stock density of soil organic carbon was calculated following Pearson (2007):

$$SOC = \rho \times d \times \%C \quad (6)$$

Where; SOC=soil organic carbon stock per unit area (ton/ha); ρ=soil bulk density (g/cm^3); d=soil depth at which the sample was taken (cm); and %C=carbon concentration (%).

2.5 Statistical analysis

To compare the carbon stock density between managed and unmanaged CFs at 5% level of significance, T-tests were performed using SPSS software. Correlation and regression analysis was conducted to establish the relationships between altitude and carbon stock for both managed and unmanaged CFs.

3. RESULTS AND DISCUSSION

3.1 Properties of forest stand

The mean diameter and height of trees was 29.28 cm and 18.36 m, respectively, in Taldanda CF, while they were 16.71 cm and 7.95 m respectively in Dandunge CF. Similarly, the mean diameter (dbh) of saplings was 2.63 cm and 1.89 cm respectively in Taldanda and Dangdunge CFs. On the other hand, tree and sapling density CF were 366 and 1,151 per ha, respectively in Taldanda, while they were 662 and 1,649 per ha, respectively, in Dangdunge CF. The results demonstrate that diameter, dbh, and height of the tree were higher in the managed CF while tree and sapling densities were higher in unmanaged CF. Managed CF had also more regeneration (10,896 per ha) than unmanaged CF (6,719 per ha) (Table 2). Dominant tree species in managed and unmanaged CFs are presented in Table 3.

Table 2. Properties of forest stand under the managed and unmanaged CFs in Nepal

CF	No. of plots	Tree							Sapling				Regeneration
		dbh (cm)			height (m)			trees /ha	dbh (cm)			Saplings/ ha	Seedlings/ha
		Min	Max	Mean	Min	Max	Mean		Min	Max	Mean		
Taldanda CF	12	5.5	55.8	29.28	5.3	27.5	18.36	366	1.3	4.9	2.63	1,151	10,896
Dangdunge CF	9	5.3	46.1	16.71	1.3	21.1	7.95	662	1.1	4.6	1.89	1,649	6,719

Table 3. Dominant tree species in managed and unmanaged CFs

Dangdunge CF	Taldanda CF
Shorea robusta	*Shorea robusta*
Schima wallichii	*Schima wallichii*
Castanopsis indica	*Dalbergia sissoo*
Lagerstroemia parviflora	*Acacia catechu*
Wrightia arborea	*Melastoma malabathricum*
Photinia integrifolia	*Colebrookea oppositifolia*

3.2 Vegetative biomass and carbon stock

The above-ground tree biomass (AGTB) and carbon stock in Taldanda CF were 294.17 ton/ha and 138.26±19.47 ton/ha, respectively, compared to 145.37 ton/ha and 68.33±16.88 ton/ha in Dangdunge CF. Similarly, the above-ground sapling biomass (AGSB) and carbon stock in Taldanda CF were 18.65 ton/ha and 8.77±0.83 ton/ha, respectively, compared to 4.65 ton/ha and 2.18±0.39 ton/ha in Dangdunge CF. The below-ground biomass (BGB) and carbon stock in Taldanda CF were 81.33 ton/ha and 38.22±5.03 ton/ha, respectively, compared to 39.00 ton/ha and 18.33±4.37 ton/ha, respectively, in Dangdunge CF. Likewise, the deadwood biomass (DWB) and carbon stock in Taldanda CF were 43.35 ton/ha and 20.37±2.68 ton/ha, respectively, compared to 20.79 ton/ha and 9.77±2.33 ton/ha, respectively, in Dandunge CF. The data reveal that all biomass and carbon parameters had higher values for managed CF compared to unmanaged CF.

3.3 Soil organic carbon stock

Taldanda CF had higher mean SOC than Dangdunge CF, with 63.72±5.11 ton/ha and 51.38± 4.76 ton/ha, respectively. The maximum SOC was in the upper layer (0-10 cm) in both managed and unmanaged CFs and gradually decreased with increasing soil depth. In both CFs, as the soil depth increased, SOC decreased (Figure 3(a)) but bulk density increased (Figure 3(b)). Taldanda CF also had a higher bulk density than Dangdunge CF on average.

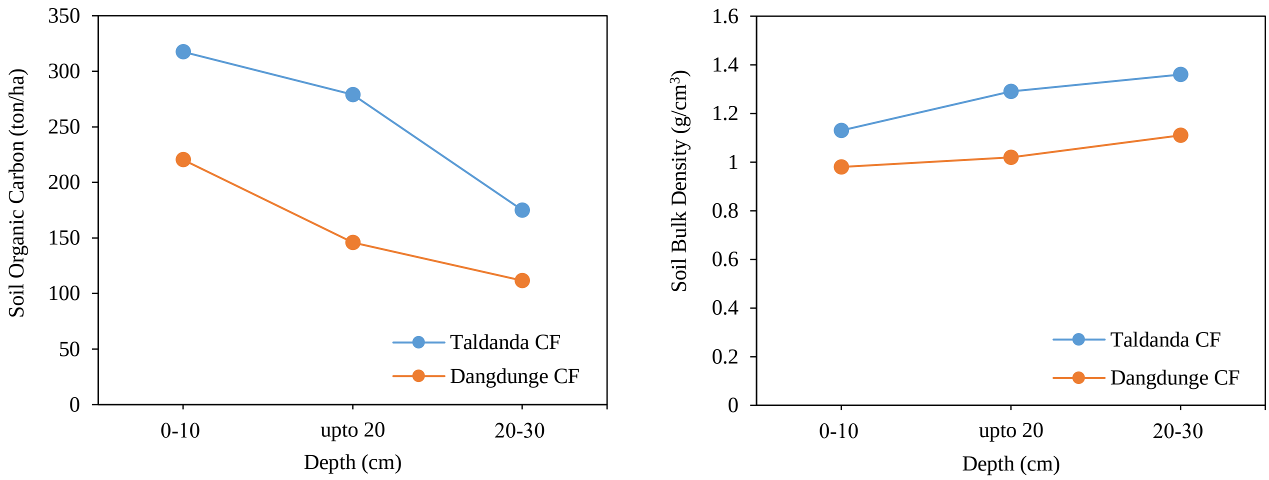

Figure 3. Amount and trend of (a) soil organic carbon stock (b) soil bulk density in each soil depth

3.4 Total biomass and carbon stock

The total carbon stock density was computed by summing the carbon stock density of the individual carbon pools (Table 4). The Taldanda CF had a total carbon stock of 269.34±27.44 ton/ha compared to only 149.98±22.69 ton/ha in Dangdunge CF (Table 4). In Taldanda CF, the total C stock partitioned to 51% in above-ground trees, 3% in above-ground saplings, 14% in below-ground biomass, 8% in the deadwood, and 24% in the soil. In Dangdunge CF, it partitioned to 45% in above-ground tree, 2% in above-ground saplings, 12% in below-ground biomass, 7% in deadwood and 34% in soil. The data reveal that partitioning of total C in Taldanda was higher in plant biomass while in Dandunge it was higher in soil biomass.

3.5 Altitude, aspect and carbon stock

In both managed and unmanaged CFs, plots were allotted without consideration of aspect, so the majority of the plots were located in south facing slope (29%) followed by east (28%), north (24%), and west (19%) facing slopes. Altogether, the altitude ranged from 473 m to 1,090 m from the mean sea level. There were negative correlations between altitude and total C and aspect and total C, suggesting that the carbon stock density decreases with an increase in altitude or aspect (Figure 4).

Table 4. Carbon pools and total carbon stock in Taldanda and Dangdunge CFs

Carbon pools	Carbon stock (ton/ha)		p-value
	Taldanda CF	Dangdunge CF	
Above ground tree carbon	138.26±19.47	68.33±16.88	0.0253
Above ground sapling carbon	8.77±0.83	2.18±0.39	0.0168
Below ground carbon	38.22±5.03	18.33±4.37	0.0498
Deadwood carbon	20.37±2.68	9.77±2.33	0.0012
Soil organic carbon	63.72±5.11	51.37±4.76	0.0327
Total	269.34±27.44	149.98±22.69	0.0287

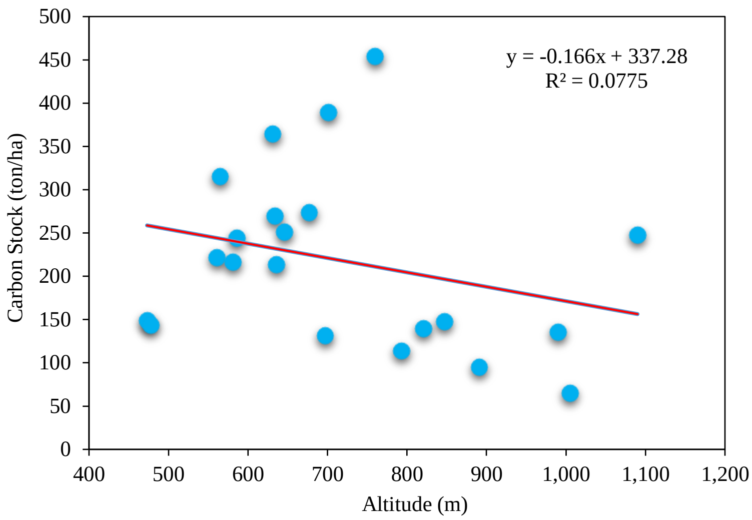

Figure 4. Altitude vs. carbon stock in both managed and unmanaged forests

4. DISCUSSION

Total carbon stock and tree biomass were significantly higher for the Taldanda CF than Dangdunge CF (Table 4) due to the absence of disturbances, including grazing, fuel wood/fodder collection, and timber harvesting (Joshi et al., 2020). Agro-forestry practices, grazing management, restoration of degraded land, mixing fertilizers, and inclusion of grass species are the best strategies for carbon storage under the fodder production system (Prasad et al., 2018). Also, the differences in above-ground carbon stock in the two CFs might be due to variations in forest age, plant species, and local factors (Bohara et al., 2021). The proper management activities lead to more effective stand productivity, and greater increment and assemblage of biomass (Jati, 2012). Joshi et al. (2020) also mentioned both the tree and sapling carbon stock were higher in non-degraded (managed) forests. Furthermore, there was better decomposition of leaf, litter, and tree branches, and below ground fine roots in Taldanda CF due to the protection of the forest from fire, grazing, and fodder/fodder extraction restriction. In contrast, due to lack of such protections, such advantages were not observed in Dangdunge CF which might have affected the BGB and carbon stock (Singh et al., 1987). Kafle et al. (2019) found a deadwood biomass of 22.39 ton/ha and deadwood carbon of 10.74 ton/ha in Parsa National Park, Nepal. Site parameters such as stand establishment and quantity, grade, age, and management activities may affect the deadwood carbon stock in the forest. Our study found a deadwood carbon stock value of 20.37±2.68 in Taldanda and 9.77±2.33 in Dangdunge CF, which was much less than other estimates, e.g., 0 to >600 ton/ha (Bastienne and Pablo, 2008).

Higher SOC in the managed CF was a result of the prevention of forest fires and livestock grazing. The presence of decomposable organic matter from branches and litter fall can boost the soil carbon in forests (Jati, 2012; Bhatta et al., 2021). Such boosting can occur significantly in the managed forest. However, in an unmanaged forest, forest fire always imbibes aboveground biomass and forest floor carbon, and based on the extent of the fire, belowground roots and soil carbon may be adversely impacted (Joshi et al., 2020). Tarus and Nadir (2020) predicted that when exposed to excessive fire, the carbon retained in the forest floor litter and branches undergoes prompt oxidation, permitting it to transfer to a gaseous phase. Forest management practices affect the rate as well as the intensity of carbon stock and SOC (Mandal et al., 2013).

There were differences in the average bulk density of the two forests -1.26 g/cm^3 in Taldanda CF and 1.03 g/cm^3 in Dangdunge CF (Figure 3(b)). Higher soil compaction in Taldanda CF could be due to management activities like thinning, weeding, and cleaning. On the other hand, intensive grazing, movement of local people to the forest for livestock grazing and leaf, litter, fuel wood and fodder collection might be the causes for soil compaction in Dangdunge CF. Animal trampling can cause changes in bulk density, infiltration rate, soil moisture, and soil mechanical properties (Chaichi et al., 2005; Dunne et al., 2011). Grazing influences the soil nutrient release and availability, degradation of leaf litter and roots, and the organic matter (Cornwell et al., 2008; He et al., 2012). Hence, forest management activities have an impact on soil carbon sequestration and emissions (Jandl et al., 2007). Finally, in agreement with findings of this study, Thong et al. (2020) mentioned that soil carbon sequestration can be significantly affected by aspect and altitude.

5. CONCLUSION

Taldanda CF had a total carbon stock of 269.3±27.4 ton/ha and a CO_2 sequestration of 987.6 ton/ha, whereas Dangdunge CF had a total carbon stock of 145.0±22.7 ton/ha with CO_2 sequestration of 549.9 ton/ha. SOC constituted 24% of total C stock in managed forest, while 34% in unmanaged forest. The SOC decreased gradually as soil depth increased, whereas bulk density increased in both CFs. Furthermore, carbon density had a negative correlation with altitude and aspect in both CFs. This study shows that managed CFs have a higher capacity to store CO_2 in forest biomass than unmanaged forests but soil C sequestration is higher in unmanaged CF. The study suggests that the implementation of proper forest management activities is of utmost important not only for the enhancement of carbon stock in tree and soil but also for sustainable forest management and mitigating climate change. The study recommends that the growing biomass stock and carbon stock need to be estimated and updated on a regular basis nation-wide to ensure accurate estimates of carbon emissions and carbon sequestrations necessary for reporting requirements and meeting the net zero target.

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