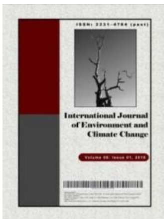

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Effect of Harvesting and Non-Harvested Forest Management on Carbon Stocks

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Authors' contributions

This work was carried out in collaboration between all authors. Author BS designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors KRT and DBG managed the analyses of the study. Authors RMB and BKS managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Forest management is an important strategy which can significantly contribute to climate change mitigation through appropriate care of forest resources. This study was carried out to evaluate two systems of carbon stock accumulation; a harvested forest verses a non-harvested forest. Both the above-ground and below-ground cabon stocks were assessed. Biomass of standing trees, poles and ground vegetation was measured for carbon determination in defined areas using an allometric relationship. Soil (core and composite) samples were collected from 0 –20, 20 – 40 cm and below 40 cm depths, assessed for density, carbon concentration, and profiles C-stocks were estimated. ANOVA and t-tests were performed to compare the effects of forest management on total carbon stocks. The results showed that the total above ground timber carbon (AGTC) was higher in non-harvested forest (220±154 t/ha^{-1}) than in harvested forest (128.6±86.1 t/ha^{-1}). The overall mean carbon stock was higher in the non-harvested forest (357±179) than in the harvested forest (257.4±93.1), which was statistically significant (p=0.031, >0.05). However, the soil organic carbon (SOC) pool was observed to be higher in the harvested forest (101.5±36.1) than in non-harvested forest (89.6±26.5).

Keywords: Above ground timber carbon; below ground biomass; carbon pools; soil organic carbon; altitudinal range.

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1. INTRODUCTION

Forest management can significantly contribute to climate change mitigation. Forests store about twice the amount of carbon present in the atmosphere. It is estimated that 15% of CO_2 emissions can be reduced by appropriate management of forests [1-3]. Forest biomass consists of major terrestrial carbon pools; namely, above and below ground, dead organic matter, and soil carbon. Estimation of these current and future pools is dependent upon changes in tree density, as well as, the age and species composition of the forest. Removing atmospheric carbon dioxide and storing it in different carbon pools leads to changes in biomass, soil, dead organic matter, litter, which can impact the course of climate change [1,2]. Proper forest management and improved technologies offering cost-effective ways to both reduce emissions and sequester carbon, are urgently required to mitigate climate change for the survival of our environment and our planet [4].

According to Rodger [5,6] 86% of the terrestrial above-ground carbon and 73% of the earth's soil carbon are stored in forests. Critical aspects of carbon loss are contained in major carbon pools in undisturbed forests; in order to assess the impact of deforestation and re-growth rates, it is necessary to know the stocks of carbon in biomass per unit area [7]. In order to calculate this, the aboveground tree biomass and belowground soil carbon need to be measured for representative areas of a forest [8]. Allometric equations have commonly been used to estimate the aboveground biomass. However, soil organic carbon (SOC) shows considerable variability, both horizontally and vertically within the soil profile, and generally decreases with depth without consideration of vegetation type and soil texture [9]. Therefore, different forest management approaches are needed, to study the carbon pool at the forest management level, first to estimate carbon pools in vegetation (above and belowground) and secondly to estimate carbon pool in the soil.

Bhutan being one of the most successful countries in the world in terms of environmental and forest conservation, maintains more than 70% of land area under forests by constitutionally making it mandatory to maintain and protect at least 60% of its forests [10]. Bhutan has 51.55% of its area under protected forests, which is one of the key strategies to maintain forest cover and protect wildlife species [11]. Vegetation is diverse, due to the wide variation in elevation, which ranges from 100 m above sea level (masl) to about 7500 masl within a distance of 150 km from south to north. Bhutan's forest ecological zones may be subjected to specific types of management systems which change forest biomass, affecting carbon sequestration [12,13]. Therefore, it is vital to know how management systems in Bhutan are contributing to climate change mitigation through carbon sequestration.

Forest conservation and management plays an important role in the livelihoods of the rural communities in Bhutan. Besides timber harvest for local consumption, forest resources are utilized in rural farming with more than 60% of the population depending on agriculture and livestock for earning cash income [11]. These activities remove forest resources and have an impact on carbon stock. However, the impact of the use of forest resources by farmers on forest biomass and carbon sequestration has not been quantitatively ascertained [14]. Additionally, no prior study on different forest management practices in relation to carbon stocks has been done in Bhutan. Therefore, the objective of this study was to assess the effect of different forest management practices on total carbon stocks. It was hypothesized that forest management affects the size of total carbon stocks and that harvesting leads to a reduction in the stock.

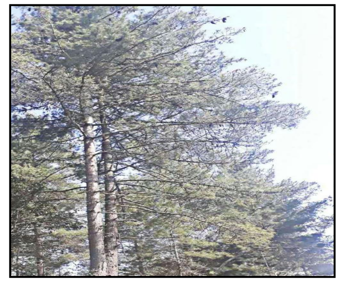
2. METHODS

2.1 Study Area

Khotokha, located in central Bhutan, has a broad valley at mid-altitudes with surrounding hills rising in moderate slopes, with occasional steep areas in some parts. The elevation of the area ranges from 1900 m at the bottom of the valley to 3785 m at the ridge top. Nearly 70% of the land area of Khotokha has less than 35% slopes (Fig. 2). The forest of Khotokha is dominated by mixed conifer such as *Abies densa* Griff, *Tsuga dumosa* (D.Don) Eichler, *Pinus wallichiana* A. B. Jacks with sparsely distributed associated species like *Quercus semecarpifolia* Sm, *Betula alnoides* Buch.-Ham. ex D.Don and *rhododendron* species [15]. Table 1 shows the total number of species found in each of the study sites.

Acer campbellii

Betula alnoides



Pinus wallichiana

Tsuga dumosa

Quercus semecarpifolia

Rhododendron

Fig. 1. Photos of species present in the study

Table 1. Species present in harvested and non-harvested forest sites of the study area

Harvested	Non-harvested
Acer campbellii	*Acer campbellii*
Betula alnoides	-
Pinus wallichiana	*Pinus wallichiana*
Tsuga dumosa	*Tsuga dumosa*
*Q. semecarpifolia**	*Q. semecarpifolia*
Rhododendron	*Rhododendron*

**Quercus semecarpifolia, - Non-availability*

The entire population in the study area depends on farming as the main source of livelihood [15]. It was also observed that the sale of potatoes contributes to nearly 90% of the household income, and the sales of livestock products and vegetables contribute the rest. People in the area also depend heavily on forest resources for timber, cattle bedding and non-wood forest products (NWFP) to support their livelihood. More than 50% of the households are illiterate. However, every household has children going to school at present [16].

2.2 Sampling Design, Sample Layout and Data Collection

2.2.1 Sampling

For the sampling of biomass and soil carbon, random sampling was carried out in two sites which are designated as harvested (H) and non-harvested (NH) forests. Based on the forest management systems, plots were laid out within the same agro-ecological region along an altitudinal gradient (at <2700m, 2700-2899m and >2899m asl). On each altitudinal range 7 sample plots were selected randomly using GIS software. The biomass and soil sampling was done from October to December 2015 and subsequent carbon stock calculations were done using standard methods.

After deciding on the total number of samples to be enumerated in the whole forest, the sample plots were distributed randomly on the map using Arc GIS. The coordinates of the plots were recorded on the map and entered into the GPS. The plots on the ground were established with the help of GPS. For tree stratum, 20m x 25m sample plots were laid out and nested plots for poles (10m x 10m), seedling (5m x 2m); and litter, herbs and grasses (1m x 1m) were laid out simultaneously [17].

2.2.2 Measurements and data collection

Diameter at breast height was estimated using a diameter tape, while the height of trees and poles was estimated using a clinometer. Saplings and seedlings were counted manually. The total fresh weights of litter, herbs and grasses were determined on the site using portable balance.

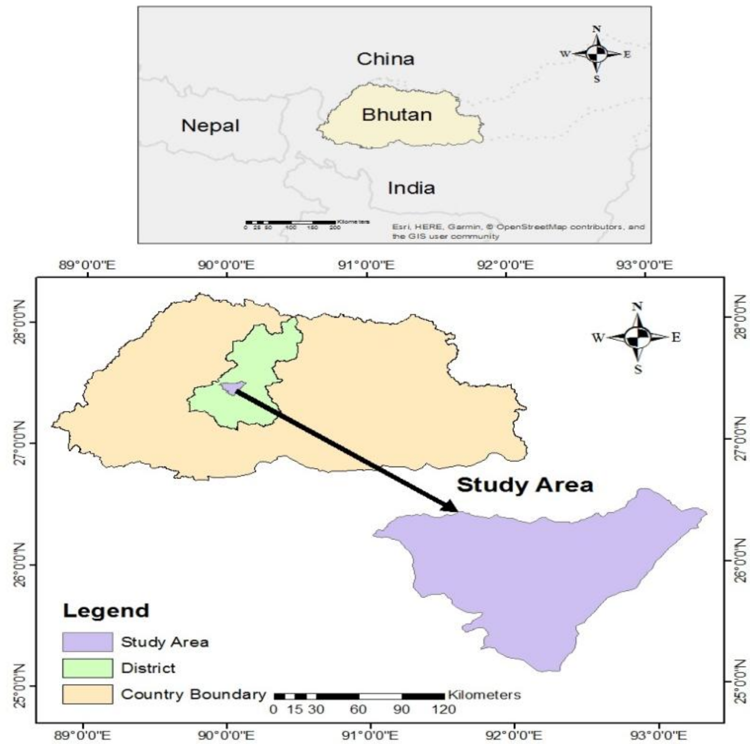


Fig. 2. Study area

The samples of litter, herbs and grasses were transported to the laboratory for dry matter estimation. The samples of soil and litter were dried in a forced-air oven at 105°C and 75°C until constant weights were obtained.

Soil samples from three different depths (0- 20 cm, 20-40 cm, and >40 cm) were collected from the center of each plot using a metal soil corer of known volume for estimation of the carbon stock density in soil. The soil samples collected were placed into labeled sample bags for determining organic carbon contents in the laboratory. Only 40 of the 42 plots were sampled as 2 plots were not accessible for sampling.

2.3 Above Ground Tree Biomass (AGTB)

The values of AGTB were obtained by using the relation, AGTB= 0.0509 * $\rho D^2 H$ [18], for plants having dbh> 5cm. Where ρ is wood density (g/cc), D is the diameter at breast height (cm), H is the height of the tree (m). The carbon content in AGTB and LHGB (litter, herbs and grasses biomass) was calculated by multiplying total biomass amount by the IPCC [19] default carbon fraction of 0.47.

2.4 Leaf-litter, Herbs and Grass Biomass

For the herb, grass and litter components, the amount of biomass per unit area was calculated by using the Good Practice Guidance developed by IPCC [19] shown below.

$$\mathrm{LHG} = \frac{W_{field}}{A} - \frac{W_{subsample,dry}}{W_{subsample,wet}} \mathrm{X} \frac{1}{10000}$$

Where;

LHG = biomass of Leaf Litter, Herb, and Grass [t ha^{-1}];
W_{field} = Fresh field weight [kg] of leaf Litter, herb, and grass, destructively sampled within an area of size A.
$W_{sub\ sample\ dry}$ = weight of the oven-dry sub-sample of leaf litter, herb, and grass taken to the laboratory to determine moisture content [g]; and
$W_{sub\ sample\ wet}$ = weight of the fresh sub-sample of leaf litter, herb, and grass taken to the laboratory to determine moisture content [g].

2.5 Below-ground Biomass (BB)

One of the most common descriptors of the relationship between root (below-ground) and shoot (above-ground) biomass is the root-to-shoot ratio, which has become the standard method for estimating root biomass from the more easily measured shoot biomass. Below ground biomass estimation is much more difficult and time consuming than estimating above ground biomass. Measurements of root biomass are indeed highly uncertain, and the lack of empirical values for this type of biomass has for decades been a major weakness in ecosystem models [20]. To simplify the process for estimating below-ground biomass, it has been recommended to use root-to-shoot ratio value of 1:5 to estimate below-ground biomass as 20% of above-ground tree biomass [21].

2.6 Soil Organic Carbon (SOC)

The carbon stock density of soil organic carbon was calculated by using formula given below [22]:

$$SOC = \delta \times d \times \%C$$

Where:

SOC = soil organic carbon stock per unit area [t ha^{-1}];

δ = soil bulk density [gcm^{-3}];

d = the total depth at which the sample was taken [cm]; and % C = Organic carbon content

Soil Bulk Density, δ (g/cc) = oven dry weight of soil/volume of soil in the core

2.7 Lab Analysis

The wet samples of litter, herb, shrubs, and grasses collected from the sites were brought back to lab and dried in a force-air oven at 75^{o}c until constant weight was obtained. Similarly, soil samples from three layers collected were brought to lab for determining its carbon content using the Walkley-Black Method [23].

Total above ground carbon= *C(AGTB)* + *C(AGSB)* + *C(LHG)*

Total belowground carbon= *C(BGB)* + *C(LHG)* + *SOC*

Total carbon content = *C(AGTB)* + *C(AGSB)* + *C(BGB)* + *C(LHG)* + *SOC*

C(AGTB) = Carbon in aboveground tree biomass; [tC ha^{-1}] =AGTB*0.47

C(BGTB) = Carbon in belowground tree biomass (root); [tC ha^{-1}] =AGSB*0.47

C(LHG) = Carbon in litter, herb & grass; [tC ha^{-1}] =LHG*0.47

SOC = Soil organic carbon; [tC ha^{-1}]

2.8 Data Analysis

The entire dataset was analyzed using SPSS and Minitab software programs. The t-test and Anova were performed to compare the results between two forest management systems and the three altitudinal ranges, respectively.

3. RESULTS AND DISCUSSION

3.1 Forest Biomass and Carbon

Biomass estimation is important for evaluating the productivity and sustainability of forest ecosystems. It also enables the determination of the amount of carbon that can be sequestered from the atmosphere by forests. Also, the potential amount of carbon emitted in the form of carbon dioxide when forests are harvested or cleared can be estimated [6]. Thus, knowledge of the sequestration capacity of the forest and emission levels enable planning for more effective forest resource management to support economic as well as climate change mitigation goals.

The diameter distribution class of the sampled forest sites indicated that the tree stand density in the non-harvested area (1,234) was less than that of the harvested area (1,919). However, the diameter class of less than 10 cm was found to be higher in the harvested area (1,543) forest site than that of the non-harvested forest area (580) (Table 2). This was most likely because the larger diameter (older) trees had already been harvested. Moreover, the natural regeneration was higher in the harvested than in the non-harvested area since openings were created promoting natural regeneration. Natural regeneration was profuse in the openings created during harvest allowing the sunlight for better germination. On the other hand, in the non-harvested forest area the canopy was noted to be very dense, which did not allow rapid regeneration to take place; hence there were larger numbers of plants below 10 cm diameter class in the harvested forest. Table 2 also shows that, except for the diameter class below 10 cm, there was higher number of trees in all other classes of the non-harvested forest compared to the harvested forest. This was mainly due greater relative age and protection of the forest for the better growth of the stand in this area.

The DBH distribution (Table 2) class showed that most of the trees in both forest management systems were young with only a few old (large) trees. Many primary forests, especially very old forests, are considered as low carbon sinks. This is because, their carbon exchange is found to be low and younger trees grow faster thereby accumulating more carbon than older ones. Therefore, alteration of the forest from old trees to new younger ones with rapid growth is considered to be beneficial in enhancing carbon sequestration levels [24-27]. Studies have supported the conclusion that a young forest sequesters relatively large volumes of additional carbon proportionate to the forest's growth in biomass, while an old forest may not sequester much additional carbon. An old forest, however, has the capability to retain large amounts of carbon [28]. As the forests in this study are young, there is a high capacity to enhance forest carbon stock. Additionally, maintaining the proportion of old and young trees in a managed forest offers opportunity to optimize the forest growth rate allowing for continuous carbon sequestration.

3.2 Carbon Stocks in Harvested and Non-harvested Forest

The estimated average values for AGTC (above ground timber carbon) of harvested forest (H) and non-harvested forest (NH) were 128.6 t ha^{-1} (86.1 SD) and 220 t ha^{-1} (154 SD), respectively, with 95% CI for difference from -169.6 to -12.2. The parametric test of hypothesis based on two independent sample t-tests showed that there was a statistically significant difference in the average values of AGTC between H forest and NH forest (df=31, t=2.36, p=0.025<0.05). Furthermore, the average value of AGTC on NH forest was found to be considerably higher (Table 3) than that of the harvested forest.

The difference in total above ground carbon stocks was mainly attributed to the presence of more trees of large size in the non-harvested forest compared to the harvested forest. Other similar studies pointed out that mature trees contain a maximum growing stock compared to those of younger stage hence more carbon [29]. The estimated average value for BGTC (below ground timber carbon) (BGTC was taken for roots as 20% of the AGTC) was 27.7 ton/ha^{-1} (17.2 SD) and 43.9 t ha^{-1} (30.9 SD) for H and NH forests, respectively. The average LHG carbon and SOC (soil organic carbon) of H forest and

Table 2. Diameter distribution class of the forest sites

Dia class	Harvested forest			Non-harvested forest		
	Frequency	Percent	Cumulative percent	Frequency	Percent	Cumulative percent
<10 cm	1543	80.40	80.40	580	46.66	46.66
10-19.9	130	6.77	87.18	260	20.91	67.57
20-29.9	170	8.85	96.03	265	21.31	88.89
30-39.9	21	1.09	97.13	65	5.22	94.12
40-49.9	22	1.146	98.28	24	1.93	96.05
50-59.9	14	0.72	99.00	10	0.80	96.86
>60	19	0.99	100	39	3.13	100
Total	**1919**	**100**		**1243**	**100**	

Table 3. Comparison of carbon between harvested and non-harvested forest

Variables	Harvested	Non-Harvested	*t*-value	*p*-value
	Average±SD	Average±SD		
AGTC	128.6±86.1	220±154	2.36	0.025*
BGTC	25.7±17.2	43.9±30.9	2.36	0.025*
LHG	1.53±0.90	3.58±0.93	7.21	0.000*
SOC	101.5±36.1	89.6±26.5	1.22	0.229^{ns}
Total	**257.4±93.1**	**357±179**	**2.26**	**0.031***

** Significant at p < .05; ns non-significant at p < .05*

AGTC=Above ground timber carbon, BGTC= Below ground timber carbon - refers to the root carbon which is 20% of the AGTC, LHG=Litter, herb and grass carbon and SOC=Soil organic carbon

NH forest was observed to be 1.53±0.909 and 3.59±0.932, 101.5±36.1 and 89.6±26.5, respectively with 95% CI for the difference from -33.93, -2.45, -2.622, -1.473, -7.88, 31.80 except for SOC. The parametric test of hypothesis based on two independent sample t-test indicated that there was a statistically significant difference in the average values of BGTC and LHG between H forest and NH forest (df=31, t=2.36, p=0.025 and df=39, t=7.9, p≤0.001). No statistically significant difference was seen for the average SOC values between H forest and NH forest ((df=36, t=1.22, p=0.229). However, the total carbon stock for all components combined showed a significant difference in the average values between H and NH forests ((df=30, t=2.26, p=0.031) (Table 2). The reason for the variation in C between the Harvested and Non-harvested forest is likely due to the undisturbed natural forest ecosystems compared to the younger harvested forest [30]. Undisturbed in this context refers to the absence of human exploitation of forest resources and absence of cattle grazing, free of pest and diseases. Usually, such forests are thought to be in a climax state and at equilibrium [30].

3.3 Carbon Stock at Different Altitudinal Ranges

The mean carbon for AGTC for both the harvested and non-harvested forests were observed to be lower at lower elevations (<2700 m), slightly higher at mid-altitudes (2700 -2899 m), and significantly increased above 2899 m (Table 4). This could be due to the dominance of old growth characterized by trees with large dbh at higher altitudes. Also, cold conditions at high elevation causes slow growth and decomposition of organic matter, this leading to higher carbon accumulation. The results also indicated that, the higher dbh classes of timber occurred at high altitudes.

Increase in total AGTC is closely related with increasing dbh because as the latter is an important predictive parameter of biomass [18]. Similarly, a study conducted in Thailand [26] showed that larger tree size has greater amount of biomass and correspondingly greater amounts of carbon stock. It is also likely that the forests at the higher altitudes are more remote, and therefore, are less impacted by anthropogenic activities, leading to higher AGB densities.

However, this does not imply that other forest types with smaller biomass are not important. They have the potential to attain large size and stand density in the near future leading to more carbon sequestration and storage, provided the forests are enhanced under appropriate management without human disturbance. Some studies showed patterns of decreasing aboveground biomass/carbon with increase in altitude [31]. However, it was also reported that the mean AGTB/C is significantly lower in the lower altitude due to greater susceptible to timber extraction, litter collection, and agricultural expansion [31]. This is because of better accessibility and typical land allocation where such activities are practiced. In the present study area, the lower altitude areas have more settlements and human activity; hence the forests are subject to disturbance, either by local people or from commercial extraction. In fact, wood is the principal source of energy in the rural households and more than 90% of the population in the study area use wood for cooking and heating, as well as, construction purposes.

The mean carbon stock for the LHG was found to be slightly more in the lower altitude range on the both harvested and non-harvested forest. This could be due to higher temperatures leading to higher plant growth rates at these elevations compared to the higher altitude ranges. However, it was not statistically significantly different according to altitude range (p = 0.218). Similar results have been reported whereby the litter fall at the lowest elevation site was significantly higher than at the highest site [32]. The annual litter fall decreased with elevation. Similarly, the mean carbon increases as altitude decreases. However, statistically the increase of C as altitude decreased was observed to be non-significant (p=0.386, <0.05 (Table 4)). Other researchers also noted an increase in soil C with the rise in temperature, meaning that, there is an increase of soil C at lower altitude [33,34]. The reason for the decrease of carbon content with increase in altitude could be the colder climate, sparse vegetation and slow growth rates at higher altitude with low temperature and less rainfall. Several studies [35-37] have shown that SOM decomposition and soil C accumulation in terrestrial ecosystems is greater under the warmer climatic condition, possibly due to high plant growth rates and dense vegetation. However, it is debated that the temperature influence on SOM decomposition is arguable [38-40].

Table 4. Comparison of carbon between H and NH at different altitudinal range

Variables	Harvested Average±SD			*p*-value	Non-Harvested Average±SD			*p*-value
	<2700	**2700-2899**	**>2899**		**<2700**	**2700-2899**	**>2899**	
AGTC	103.2±59.3	146.8±97.1	272.1±159	0.001*	90.45±58.31	200.56±114.11	374.51±142.64	0.001*
BGTC	20.63±11.85	29.37±19.43	54.42±31.80	0.001*	20.63±3.17	29.34±5.19	54.42±8.50	0.001*
LC	2.789±1.69	2.488±1.161	2.404±1.30	0.784^{ns}	4.10±1.12	3.26±.81	3.39±.77	0.218^{ns}
SOC	103.62±35.39	107.81±31.26	75.26±17.39	0.010*	44.60±17.01	49.38±11.72	38.99±8.78	0.386^{ns}
TOTAL	230.2±67.1	286.5±111.0	404.2±191.3	0.005*	159.78±79.61	282.54±131.83	471.31±224.05	0.005*

** Significant at p < 0.05; ns non-significant at p < 0.05*

3.4 Carbon Stock Estimation According to Management Type and Altitude

Results (Table 5) showed that AGTC varies significantly in relation to altitude and different forest management systems (p = 0.002, 0.006). Similarly, BGTC showed significant difference with altitude and forest management (p = 0.002, 0.006). However, litter/herb/grass carbon did not differ significantly with altitude range (p = 0.73) and SOC did not differ with management practice (p = 0.143). Conversely, litter/herb/grass carbon showed a significant difference with management practices, while SOC differed significantly in relation to altitude ($p \leq 0.001$, 0.028), respectively.

Table 5. Two-way Anova for testing different variables by altitude and forest management

Source	df	mss	*f*-value	*p*-value
Above Ground Timber Carbon				
Altitude	3	67235.84	5.870	0.002*
Management	1	97833.60	8.542	0.006*
Error	37	11453.60		
Total	42			
Below Ground Timber Carbon				
Altitude	3	2689.43	5.87	0.002*
Management	1	3913.34	8.54	0.006*
Error	37	458.14		
Total	42			
Litter, Herb & Grass Carbon				
Altitude	3	.384	0.43	0.730 ^{ns}
Management	1	43.726	49.34	0.000*
Error	37	.885		
Total	42			
Soil Organic Carbon				
Altitude	3	2887.15	3.38	0.028*
Management	1	1920.82	2.25	0.142^{ns}
Error	37	852.23		
Total	42			

LSD post hoc test revealed that there was no significant difference between any of the soil layers (0-20 and 20 -40 cm and >40 cm depth). The reason for the non-significant result for the SOC by management could be the presence of the same tree species and location in the same ecological zone. However, variation in SOC with altitude could be due to the presence of different tree species at different altitudes along with change in climatic factors affecting plant growth and decomposition. Lower altitude areas were comprised of Blue Pine (*Pinus wallichiana*), middle altitudes consisted mainly of Hemlock (*Tsuga dumosa*), and the higher altitude range was dominated by Fir (*Abies densa*). Previous studies explained that carbon stock in forest vegetation varies based on geographical location, plant species and age of the forest [40]. The soil carbon also depends on the amount of leaf litter fall and decomposition rate [41]. As such, assessment of the plant diversity and floral composition can provide additional information about carbon accumulation and stocks [42].

3.5 Soil Organic Carbon (SOC)

The purpose of studying soil organic carbon (SOC) content has changed with time. In the past, it was studied mainly to evaluate the soil quality [43-45]. However, at present, carbon dynamics in soil is studied in the context of green house gases emission assessment and sequestration potential in the soil and plants [46,47].

The t-test between H and NH indicated that there was a significant difference (p = 0.036) at a depth of 40-60 cm. One-way ANOVA was conducted to examine whether differences occurred in the average SOC contents with respect to soil depth or layers. The results showed that there was a significant difference in the average SOC (p < 0.05). This means averages SOC content of at least one pair of soil layer differed significantly. To identify the significant pairs, LSD post hoc test was used, which revealed that a significant difference in average SOC contents existed only between the 1st and 2nd layers (p =0.03<.05) (Table 6). However, there was no significant difference between the other layers at 0-20 and 20 -40 cm depth (p = 0.66 and .55), respectively.

There was an increase in the carbon accumulation from the top layer to the second depth and a decline from the 2nd to the 3rd layer.

Table 6. Summary of soil organic carbon (SOC) (t ha^{-1})

Soil depth (cm)	Harvested area		Non-Harvested area		*t*	*p*-value
	N	Mean±(SE)	N	Mean±SE		
0-20	20	13.41±1.49	20	12.39±1.79	0.43	0.66
20-40	20	20.62±2.80	20	18.59±1.87	0.60	0.55
40-60	20	16.37±2.23	20	14.03±1.23	0.91	0.036
Total	**20**	**50.39±4.13**	**20**	**45.01±3.03**	0.43	0.03

Thus, higher carbon content was observed in the middle layer (20 - 40 cm). A study carried out by Larson and Pierce [47] also found an increase in soil organic carbon (SOC) with increased soil depths in *Pinus roxburghii* forest, where organic carbon was highest in the top layer (0–20 cm) and lowest in middle depth (20–40 cm)and increased again below the middle depth (below 40 cm). Several studies have shown that there is a decrease in density of carbon with increasing soil depth [48]. It was also noted that accumulation of carbon increased more in the harvested area (50.39±4.13 t ha^{-1}) than in the non-harvested (45.01±3.03 t $ha\text{-}^{1}$). This could be because of the presence of dead organic matter such as leaf litter and dead branches and wood left after harvesting of timber. Several studies show that about 50% of the soil carbon is stored in forests [49], which include dead organic matter and soil organic matter [19]. Harvesting activity can cause severe soil disturbance [50] mixing the forest soil into the mineral soils. Exposure of soil increases losses due to soil erosion [51], and leaching of dissolved organic carbon (DOC) [52]. Decomposition rates of surface litter usually decrease after clear cutting because of the low biotic activity and decrease in soil moisture content [52]. Some studies indicated an increase in forest floor carbon several years after harvest [53-56]. If forest harvesting is done with adequate care, there could be a minimum or no effect on SOC stock. Additionally, less biomass input may be compensated by large amount of harvest residues left behind [57-60].

Although C is preferentially accumulated at shallower depths, deeper soils store substantial amounts of C stocks and there is a need for considering sub-soil for accurate estimation of the C stocks in forests [61]. The reason for the maximum SOC in the middle layer could be because of DOC. Other research reported that 25% of the total carbon in the soil can infiltrate as DOC [62] and conifer forests are characterized by a greater flux of DOC into the soil [62]. As conifers dominated the area in the present study, the greater C in deeper soil horizons may have been influenced by DOC infiltration [63]. The total carbon stock from 0 to 5m depth may vary from 47% to 77%, which shows that, there can be a large amount of carbon in the deeper soil layers [64].

3.6 Carbon Stocks and Climate Change

The present study along with previous research and evidences indicate that forests and soil can also play an important role in storing carbon. As many studies in the past few decades have shown, the flux of carbon dioxide, methane and other greenhouse gases from deforestation, forest and land degradation, agriculture, industry, vehicular emissions and power generation, is leading to climate change [1]. Aside from reducing emissions of greenhouse gases through improved technologies, capturing and sequestering C in terrestrial ecosystems offers a viable and important approach to mitigating climate change. Simultaneous efforts to reduce emissions on one hand and enhancing carbon accumulation on the other will be required to effectively tackle anthropogenic climate change. Considering this role, proper management of forests and soil would prove to be an effective means to enhance the terrestrial carbon sink.

4. CONCLUSION

Carbon content in the forest vegetation varied significantly depending on forest type and management. The total vegetation carbon pool in the study area was higher in the non-harvested forest than in the harvested forest. Similarly, the litter/herb/grass pool was also highest in non-harvested forest compared to harvested forest area. However, the soil organic carbon (SOC) pool was observed to be higher in the harvested forest (101.5±36.1) than in the non-harvested forest (89.6±26.5). Improved management of forest resources has the potential to enhance both the vegetation and soil carbon pools in the context of changing climate.

Forests are the largest terrestrial carbon pool on Earth. They serve as major sources and sinks of carbon in nature. They have an important role in the mitigation of global warming and adaptation to climate change. Estimation of the forest carbon stocks enables us to assess the amount of carbon loss during harvest and estimate the amount of carbon that a forest can store when such forests are regenerated and managed wisely. There have ben numerous studies carried out to estimate forest biomass and carbon stocks. However, there is still a need to further develop methods to accurately quantify the biomass of all forest components and carbon stocks more efficiently.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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