*Article*

# Spatial Distribution of Soil Organic Carbon in the Forests of Nepal

Rajesh Malla [1] and Prem Raj Neupane [2,*]

[1]  Forest Research and Training Centre (FRTC), Pokhara 33700, Nepal; raj_malla@yahoo.com
[2]  Center for Earth Systems Research and Sustainability (CEN) &World Forestry, University of Hamburg, D-21031 Hamburg, Germany
*   Correspondence: prem.raj.neupane@uni-hamburg.de

**Abstract:** Soil organic carbon (SOC) is the major constituent of the soil organic matter. SOC stocks are determined by several factors such as altitude, slope, aspect, canopy cover, and vegetation type. Using the Third National Forest Inventory (2010–2014) data of Nepal, we assessed SOC status in forests at a national scale for the better understanding of the SOC distribution within Nepal. In this study, we estimated SOC against different factors and tested the spatial distribution of SOC using analysis of variance (ANOVA). The results showed that the forests located at a higher altitude have higher SOC accumulation. In particular, broadleaved forests exhibit a higher amount of carbon stock compared to other forest types. Moreover, forests with a larger canopy cover, located on a higher slope, and with a cooler aspect are associated with a higher accumulation of SOC. The SOC stock in the forest varies according to altitude, slope, aspect, canopy cover, and forest type, which might be attributed to the change in the microclimate of the area. The significant increase in SOC amount with the increase in slope, altitude, and crown cover helps to understand the extent of SOC distribution in forests. Broadleaved forests with a larger canopy cover in the higher altitude region have a higher SOC retention potential, which is likely to contribute to mitigating the impacts of climate change by sinking more carbon into the soil.

**Keywords:** forest types; soil organic carbon; altitude; canopy cover; slope; aspect

## 1. Introduction

Forest ecosystems are globally very important carbon reservoirs, storing 46% of the total terrestrial carbon [1]. Forest soils act as carbon sinks due to their higher organic matter content [2], which contains roughly 55–60% of soil organic carbon (SOC) [3]. Forest soil retains more than 40% of the organic carbon of the terrestrial ecosystem globally [4,5]. Thus, the soil is considered one of the most crucial carbon pools in the terrestrial system, and organic carbon in the soil is a highly important natural resource that needs to be restored, enhanced, and improved [6] as it improves the physical, chemical, biological, and ecological properties of the soil [3,7].

According to Global Forest Resource Assessment 2020, while 192 countries and territories (99 percent of the world's forests) reported on biomass estimation, only 76 countries and territories (representing 66 percent of the world's forests) reported information on forest carbon [8]. SOC dynamics and its storage in tropical forests persistently exhibit uncertainty in the global carbon cycle [9]. Understanding the dynamics and distribution of SOC in forest soils is essential to better predict the forest SOC [10]. However, the dynamics of the SOC stock are poorly quantified, largely due to a lack of direct field measurements [11]. The estimations presented in this study provide a baseline for estimating future changes in soil C stocks in Nepal, and for assessing their vulnerability to key global change drivers, thereby informing future actions aimed at the conservation and management of C stocks [12].

Maintaining higher levels of SOC is an indicator of good soil health [13] that increases soil fertility [14], whereas the loss of SOC contributes to soil and land degradation [15,16], global

warming [17], and negative effects on soil functions [15]. Therefore, SOC is considered a key environmental indicator for several global environmental issues, including land degradation, and food security [18,19]. However, SOC is in a declining trend worldwide. Asia is the most affected region, losing 33.5% of the world's SOC, and Nepal also shows a similar trend [18].

SOC stocks are the functions of several factors including the amount of above ground litter fall and root turnover, forest types, tree species diversity, canopy cover, soil conditions and vegetative cover, soil properties and moisture, soil depth, altitude, slope, aspect, and climate [20–32]. These predictor variables affect SOC stocks either positively or negatively. In particular, altitude has a positive relation with SOC stocks [33–35] while slope, warmer aspect, and crown cover have a negative relation [24,28,36]. The relationships between SOC stocks and these variables are not always consistent. Some studies reported a negative relation of SOC with altitude, e.g., [37,38], while others revealed a positive relation with slope, e.g., [24,39,40].

Vegetation—a source of organic matter—has a strong effect on accumulation of SOC stocks [41]. More than 41%ent of the land of Nepal is covered by forests [42], holding 37.8% carbon as SOC [43]. The forests distributed throughout the country, with considerable topographic and climatic variations, are expected to retain a different amount of SOC. Several studies have assessed SOC in the different forest types of Nepal; however, they are limited to a small area with lesser climatic and altitudinal variation [18,28,29].

Thus, a better understanding of the status of SOC under different forest types at the national scale is lacking. Only the third national level forest resource assessment (2010–2014) of Nepal has assessed SOC from the permanent sample plots so far. This study, using the nationwide SOC data, aims to answer the following questions. (1) How do altitude, aspect, slope, and canopy cover affect SOC stock distribution in the forests of Nepal? (2) Does the SOC stock vary among forest types in Nepal? The SOC status in forests located in various physiographic conditions will provide a better understanding of the distribution of SOC in the different types and will be supportive to adopt the appropriate forest management strategies to store more SOC in forests in the future.

## 2. Materials and Methods

### 2.1. Study Area

The study covers the entire forest area of Nepal (Figure 1). Of the total land area of the country, 86% is covered by hills and high mountains, and the remaining 14% is a flat- and lowland, located at less than 300 m altitude. Wide altitudinal variations and diverse climatic conditions have created four main physiographic zones, i.e., *Terai* (lowlands), mid hills, high mountains, and high *Himal* [44], and have also influenced the composition of flora and fauna [45]. Stainton [46] classified 35 forest types in Nepal, which are further broadly categorized into 10 major groups based on the altitudinal range [45].
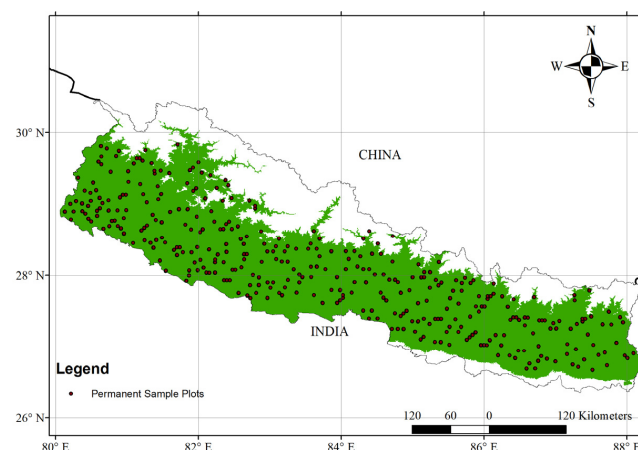


**Figure 1.** Study area map showing permanent sample plots distributed throughout the forests of Nepal. Green color on the map indicated forest cover in Nepal.

*2.2. Forest Types*

In Nepal, there are three categories of classification of forest type based on species composition, structure, and altitude. This study included forest types mentioned by the Department of Forest Research and Survey, Nepal (DFRS), and Shrestha [43,47] as Group I and Group II, respectively. Group I includes 15 different forest types classified by the DFRS [43] based on tree species composition. They are (1) *Shorea robusta* forest (S), (2) Terai mixed hardwood forest (TMH), (3) lower mixed hardwood forest (LMH), (4) *Pinus roxburghi* forest (Pr), (5) *Pinus wallichiana* forest (Pw), (6) *Quercus* forest (Q), (7) upper mixed hardwood forest (UMH), (8) *Abies* forest (A), (9) *Cedrus deodara* forest (Ce), (10) *Betula utilis* forest (Bu), (11) *Picea smithiana* forest (Ps), (12) *Cupressus torulosa* forest(Ct), (13) *Tsuga dumusa* forest (Td), (14) *Juglans wallichiana* forest (Jw), and (15) *Acacia catechu/Dalbergia sisso* forest (AC/DS). Group II includes broadleaved forest, mixed forest, and coniferous forest, as classified by Shrestha [47] based on structural features. Table 1 shows the forest types included in this study, together with location attributes (altitude, aspect, and slope) and canopy cover for each of the forest types. Out of 15 forest types in Group I, only 7 forest types were included in the study (Table 1).

**Table 1.** Forest types included in the study, and corresponding locality factors (altitude, aspect, and slope) and canopy cover of each of the forest types. TMH: Terai mixed hardwood forest; LMH: lower mixed hardwood forest; S: *Shorea robusta* forest; Pr: *Pinus roxburghi* forest; Pw: *Pinus wallichiana* forest (Pw); UMH = upper mixed hardwood forest; and Q: *Quercus* forest.

| Group | Forest Types | Altitude (m) | | | Canopy Cover (%) | | | Aspect (Degree) | | | Slope (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max |
| I | TMH | 98 | 466.5 | 1215 | 5 | 63.29 | 96 | 0 | 139.9 | 358 | 0 | 31.4 | 100 |
| | LMH | 214 | 1421 | 1990 | 11 | 64.25 | 99 | 1 | 170.3 | 360 | 5 | 61.4 | 100 |
| | S | 90 | 429.8 | 1337 | 9 | 68.33 | 98 | 0 | 122.3 | 360 | 0 | 33.6 | 100 |
| | Pr | 869 | 1363 | 2361 | 9 | 52.11 | 81 | 1 | 154.5 | 360 | 10 | 54.9 | 90 |
| | Pw | 1836 | 2605 | 3445 | 16 | 60.33 | 92 | 10 | 175.5 | 355 | 20 | 52.8 | 90 |
| | UMH | 1288 | 2532 | 3993 | 4 | 63.56 | 99 | 1 | 164.3 | 360 | 10 | 62.4 | 100 |
| | Q | 1430 | 2346 | 3669 | 20 | 66.37 | 99 | 20 | 161.7 | 350 | 8 | 62.9 | 100 |
| II | Broadleaved | 88 | 1061 | 3993 | 4 | 64.7 | 99 | 0 | 145.6 | 360 | 0 | 45.9 | 100 |
| | Mixed | 657 | 1892 | 3510 | 11 | 63.5 | 97 | 10 | 174.5 | 355 | 10 | 59.5 | 98 |
| | Coniferous | 869 | 1923 | 3600 | 9 | 57.1 | 92 | 1 | 166.1 | 360 | 10 | 56.1 | 95 |

*2.3. Data Collection*

The primary data used in this study were acquired from the third national forest inventory (NFI) conducted during 2010–2014. The NFI adopted a two-phase systematic sampling design, composed of 450 clusters containing 1553 Permanent Sample Plots (PSPs) allocated systematically in the entire forest area. Data were collected only from the accessible sample plots (slope up to 100% or 45°). This is the first NFI in Nepal that collected soil samples to analyze the soil organic carbon of the forests. Four soil pits were established in the four cardinal directions in each PSP to collect soil samples. In each cardinal direction, soil pits of appropriate size within a 2 m × 2 m area were dug at a 21 m distance from the PSP center. Soil samples were collected from three different horizons (1–10 cm, 10–20 cm, and 20–30 cm) from each soil plot dug outside the peripheries of the PSPs [48]. A study reported that about 53% of the SOC stock over 1 m depth was held in the top soils, i.e., up to 30 cm depth [22].

*2.4. Soil Organic Carbon (SOC) Analysis*

For SOC analysis, four soil samples of the same horizon of the subplots were mixed. Each PSP had 3 soil samples taken from three different soil horizons. The Walkley–Black wet combustion method [49] together with titration was applied in the soil laboratory of the DFRS in Nepal to analyze soil organic carbon. The method is based on wet oxidation where

the organic carbon in the soil is determined via oxidation with a mixture of potassium dichromate and sulfuric acid [50]. In addition, dry combustion and a LECO CHN Analyzer were used in the Metla Soil Laboratory, Finland, to assure the quality of the laboratory test. The soil organic carbon analyzed in the soil laboratory was later estimated on a per hectare basis [48].

Due to the inappropriateness of sites for soil collection, soil samples were not collected from all of the clusters and PSPs during the NFI. This study used only 1059 PSPs out of 1553 after eliminating non-soil PSPs and outlier PSPs for SOC analysis in different forest types. The lack of a full representation of the SOC samples in the study may cause some bias in the results.

### 2.5. Data Analysis

Based on the findings of previous studies [29–31,36,51,52], forest types, altitude, aspect, slope, and canopy cover were selected to assess SOC variation in the forests of Nepal. To analyze the variables, altitude was divided into four groups (<1000, 1000–2000, 2000–3000, and 3000–4000 m), slope into four groups (<8.5°, 8.5–19°, 19–31°, and 31–45°) and forest canopy cover into three groups (<40, 40–69, and ≥70%). The category of altitude is based on the forest types including tropical forests, sub-tropical forests, temperate forests, etc., [45], whereas the categories of slope and canopy cover are based on the forest resource assessment of Nepal [48,53].

An ANOVA test was employed for data analysis. Before applying the ANOVA test, the SOC data were transformed using "BoxCoxTransformation" function in R-package (version 4.3.1) "e1071" [54] to normalize their distribution. The transformation method is used on a non-normal dependent variable to convert it into normal distribution for the statistical test. After the ANOVA test, Tukey's post hoc test (pairwise test) was applied to see the significant difference between the two variables. All data were analyzed in the R program [55]. Due to the unequal number of subplots in a cluster, the mean per hectare of SOC and standard error were analyzed using Equations (1)–(3).

$$Mean\ soc\ (\overline{x}) = \frac{\sum_{i=1}^{n} tc_i}{n} \tag{1}$$

$$Standard\ deviation\ (SD) = \sqrt{\sum_{i=1}^{N} (ms_i - \overline{x})^2 \frac{1}{N-1}} \tag{2}$$

$$Standard\ error\ (SE) = \frac{SD}{\sqrt{N}} \tag{3}$$

where:

$tc_i$ = total SOC in a ith cluster;
$n$ = number of sub plots;
$N$ = number of cluster plots;
Mc = mean cluster size = $n/N$;
$ms_i$ = mean SOC in the ith cluster, i.e., $tc_i/Mc$.

The distribution of SOC based on forest types, altitude, aspect, slope, and canopy cover is depicted in the figures for visual interpretation using the "ggplot2" package in R. Although there were 15 forest types under Group I, we used only 7 forest types (see Table 1). The excluded 8 forest types contained ≤6 cluster plots and were considered to have an insufficient sample size.

## 3. Results

### 3.1. Distribution of SOC along the Altitude of the Forests

The distribution of SOC along the altitudinal ranges varied. The highest SOC concentration was found in the altitude ranging from 3000 to 4000 m (mean = 112.63 ton/ha, SE ± 14.15), followed by 2000–3000 m (mean = 109.69 ton/ha, SE ± 7.20), and 1000–2000 m

(mean = 66.15 ton/ha, SE ± 4.34), while the lowest was found in forests with an altitude below 1000 m (mean = 35.03 ton/ha, SE ± 1.70). The result shows that an increase in altitude helps accumulate a substantial amount of SOC in forests (Figure 2). The ANOVA test showed that there was significant difference in SOC stocks along the altitudinal gradient in the forest (Table 2). Further, Tukey's test (pairwise comparison) showed that the distribution of SOC in the altitudinal ranges 3000–4000 m and 2000–3000 m ($p = 0.99$) was not significantly different. Compared to the two lower altitudinal ranges (<1000 m and 1000–2000 m), both of them exhibited a significantly higher amount of SOC.
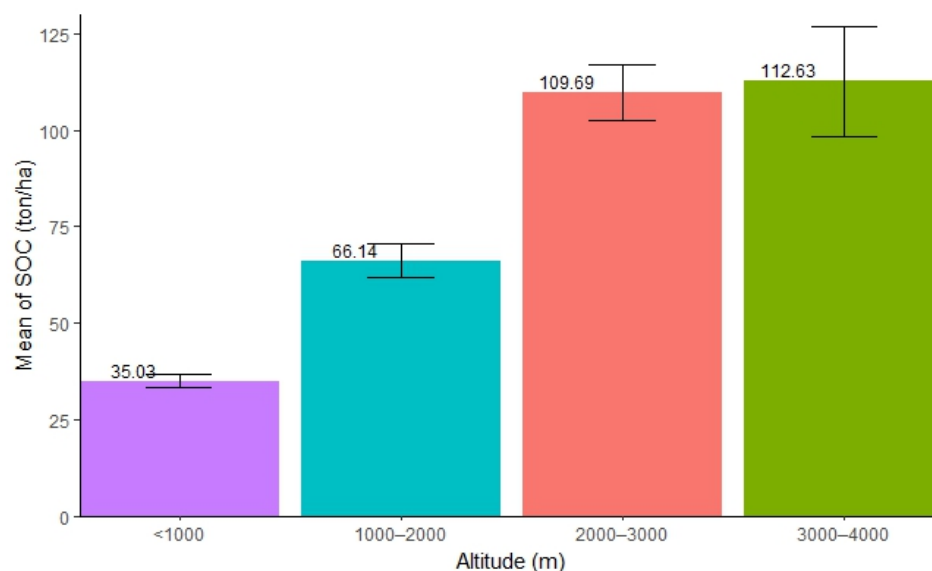


**Figure 2.** Mean distribution of SOC along different altitudinal ranges.

**Table 2.** ANOVA table for the SOC of different altitudinal ranges in forests.

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 3 | 99.6 | 33.2 | 71.41 | $<2 \times 10^{-16}$ *** |
| Within groups | 390 | 181.3 | 0.46 | ---- | ---- |
| Total | 393 | 280.9 | ---- | ---- | ---- |

Note: *** represents *p*-value < 0.001 for ANOVA statistical test.

### 3.2. Distribution of SOC along the Slope of the Forests

The distribution of SOC with varied slopes was found to be significantly different. The highest SOC concentration was observed in the slope range of 31–45° (mean = 73.95 ton/ha, SE ± 3.21), followed by 19–31° (mean = 60.52 ton/ha, SE ± 3.29), and 8.5–19° (mean = 49.17 ton/ha, SE ± 4.05), while the lowest was observed in forests with a slope below 8.5° (mean = 32.4 ton/ha, SE ± 2.71). The result shows that an increase in slope significantly contributes to the accumulation of SOC in forests (Figure 3). The ANOVA test showed that there was significant difference in SOC stocks along the slopes in the forest (Table 3). Further, the pairwise tests revealed that all pairs of slopes exhibited significant differences in SOC stocks ($p < 0.05$), except for the pairs (8.5°–19° and 19°–31°) and (19°–31° and 31°–45°).

**Table 3.** ANOVA table for the SOC of different slope ranges.

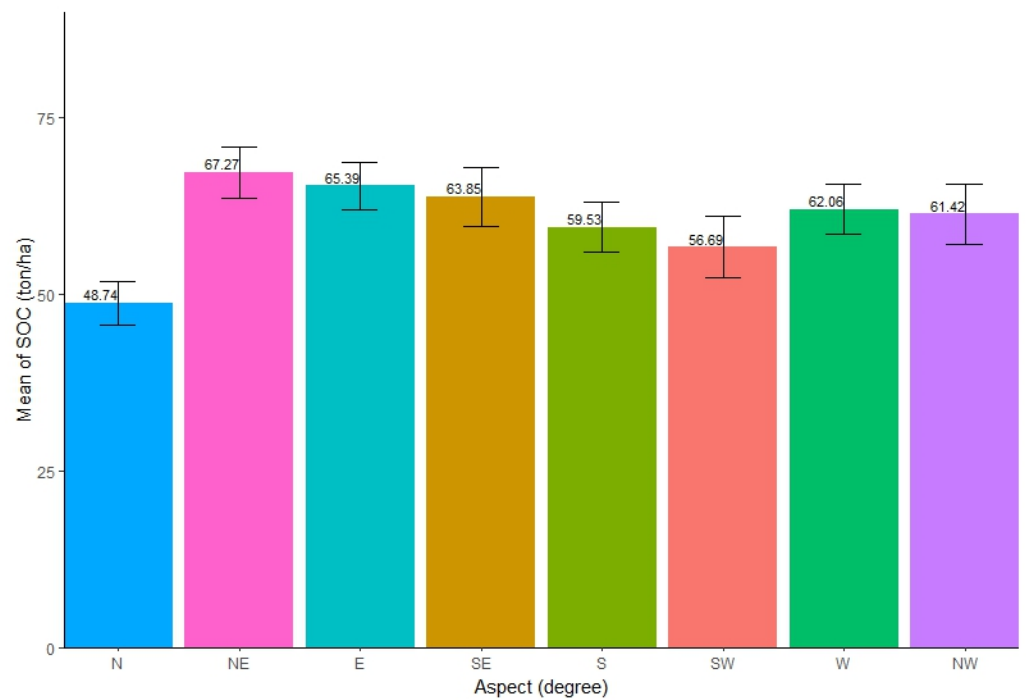| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 3 | 36.3 | 12.11 | 21 | $6.25 \times 10^{-13}$ *** |
| Within groups | 583 | 336.3 | 0.57 | ---- | ---- |
| Total | 586 | 372.6 | ---- | ---- | ---- |

Note: *** represents *p*-value < 0.001 for ANOVA statistical test.
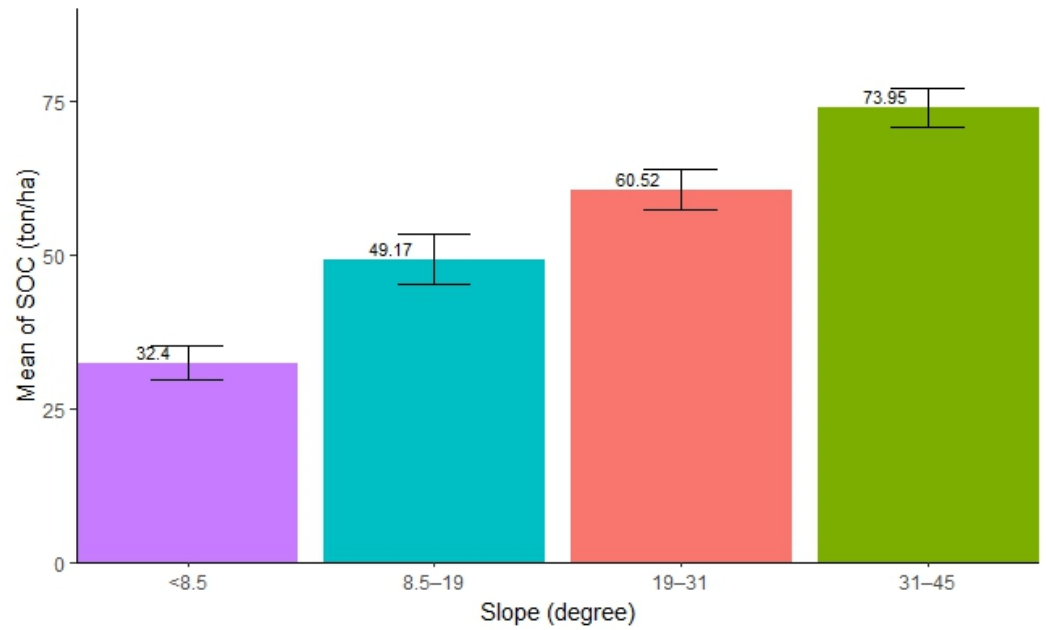
**Figure 3.** Mean distribution of SOC along different slope ranges.

### 3.3. Distribution of SOC along the Aspect of the Forests

The distribution of SOC across varied aspects was found to be slightly different. The highest SOC (mean = 67.27 ton/ha, SE ± 3.58) concentration was found in the northeast (NE) aspect of the forests, while the north (N) aspect had the lowest SOC (mean = 48.74 ton/ha, SE ± 3.04). The SOC stocks among eight different aspects showed similar distribution (Figure 4). The ANOVA test showed that there was significant difference in SOC stocks among the different aspects in forests (Table 4). Further, Tukey's pairwise tests showed that only the pair of N and E aspect and the pair of N and NE aspect had insignificant differences in SOC stocks ($p < 0.05$).



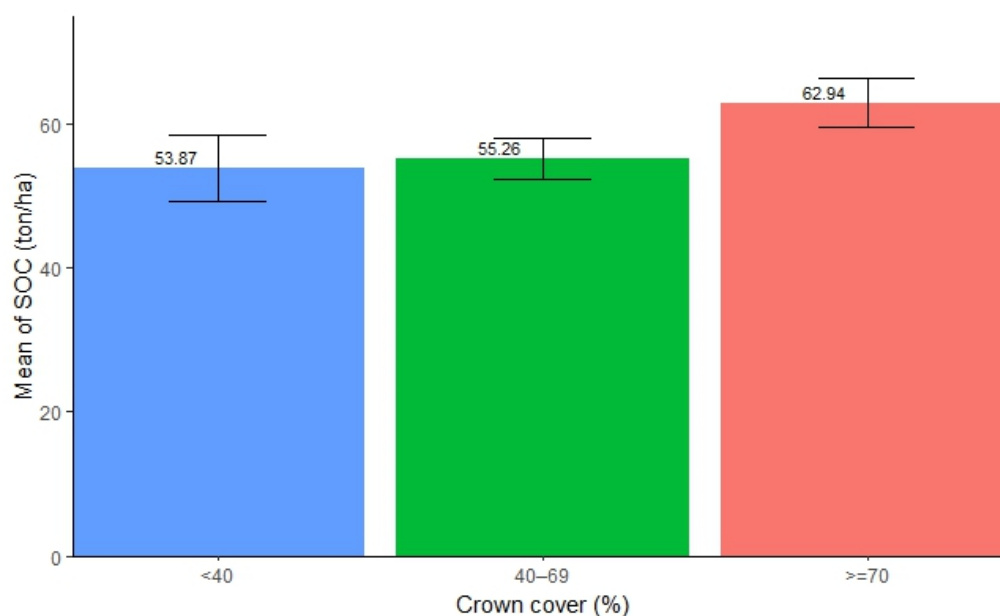**Figure 4.** Mean distribution of SOC along different aspects.

**Table 4.** ANOVA table for the SOC of different aspects.

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 7 | 8.7 | 1.23 | 2.206 | 0.031 * |
| Within groups | 726 | 406.9 | 0.56 | ---- | ---- |
| Total | 733 | 415.6 | ---- | ---- | ---- |

Note: * represents *p*-value < 0.05 for ANOVA statistical test.

### 3.4. Distribution of SOC along the Canopy Cover of the Forests

The SOC in forests with different canopy cover was found to be significantly different. The highest SOC concentration was found in the canopy cover exceeding 70% (mean = 62.94 ton/ha, SE ± 3.35), followed by 40–69% (mean = 55.26 ton/ha, SE ± 2.88), while the lowest was found in the canopy cover below 40% (mean = 53.87 ton/ha, SE ± 4.66). The result shows that an increase in canopy cover contributes to a higher accumulation of SOC in forests (Figure 5). However, the ANOVA test showed no significant difference in SOC stocks among the different canopy covers in forests (Table 5). Further, pairwise tests showed that none of the pairs displayed significant differences in SOC stocks (*p* > 0.05).



**Figure 5.** Mean distribution of SOC along different canopy covers.

**Table 5.** ANOVA table for the SOC of different canopy covers.

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 2 | 1.3 | 0.636 | 1.03 | 0.357 |
| Within groups | 573 | 353.4 | 0.616 | ---- | ---- |
| Total | 576 | 354.7 | ---- | ---- | ---- |

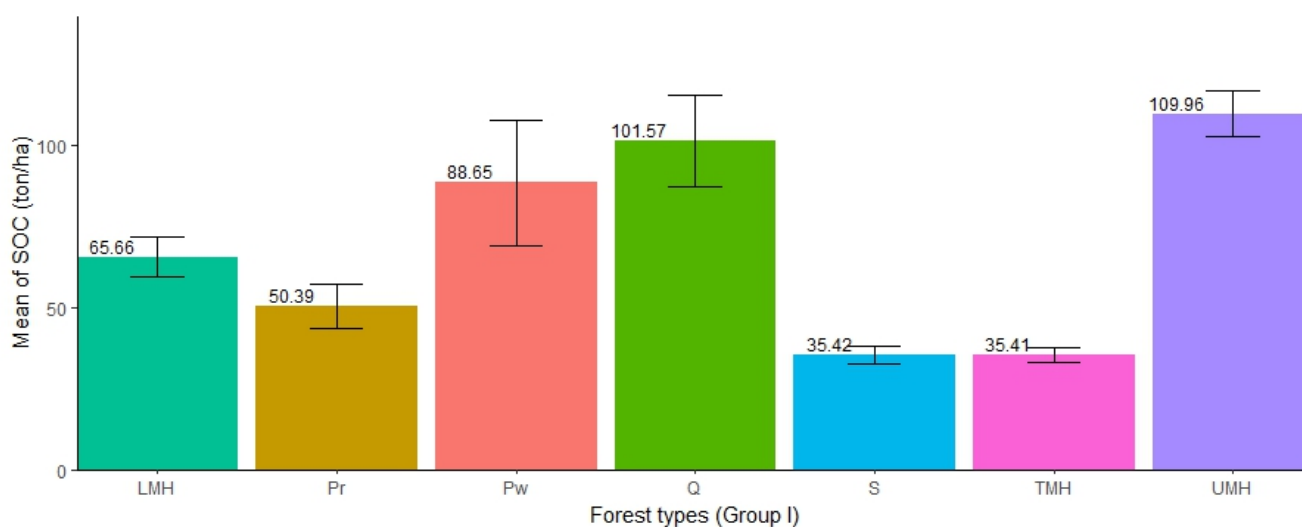### 3.5. Distribution of SOC in the Forest Types (Group I)

The distribution of SOC in the seven forest types was found to be different except for TMH and S forests, which had approximately the same amount of SOC (35.41 and 35.42 ton/ha). The highest mean SOC concentration was found in UMH forests (mean = 109.96 ton/ha, SE ± 6.96), followed by Q (mean = 101.57 ton/ha, SE ± 14.06), Pw (mean = 88.65 ton/ha, SE ± 19.5), LMH (65.66 ton/ha, SE ± 6.09), Pr (mean = 50.39 ton/ha, SE ± 6.91), TMH (mean = 35.41 ton/ha, SE ± 2.30), while the lowest was found in S (mean = 35.42 ton/ha, SE ± 2.64). The SOC stocks in UMH forests are three times higher than those in S forests. The ANOVA test showed that there was significant difference

in SOC stocks among the forest types (Table 6). Furthermore, the pairwise test showed that out of 21 pairs of forest types, SOC stocks were significantly different in 12 pairs of forests (i.e., Q-LMH, S-LMH, TMH-LMH, UMH-LMH, Q-Pr, UMH-Pr, S-Pw, TMH-Pw, S-Q, TMH-Q, UMH-S, and UMH-TMH). The ANOVA result showed significant differences in SOC accumulation in different forest types (Figure 6).

**Table 6.** ANOVA table for the SOC of different forest types (Group I).

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 6 | 108.7 | 18.12 | 34.76 | $<2 \times 10^{-16}$ *** |
| Within groups | 449 | 234.1 | 0.52 | ---- | ---- |
| Total | 455 | 342.8 | ---- | ---- | ---- |

Note: *** represents *p*-value < 0.001 for ANOVA statistical test.



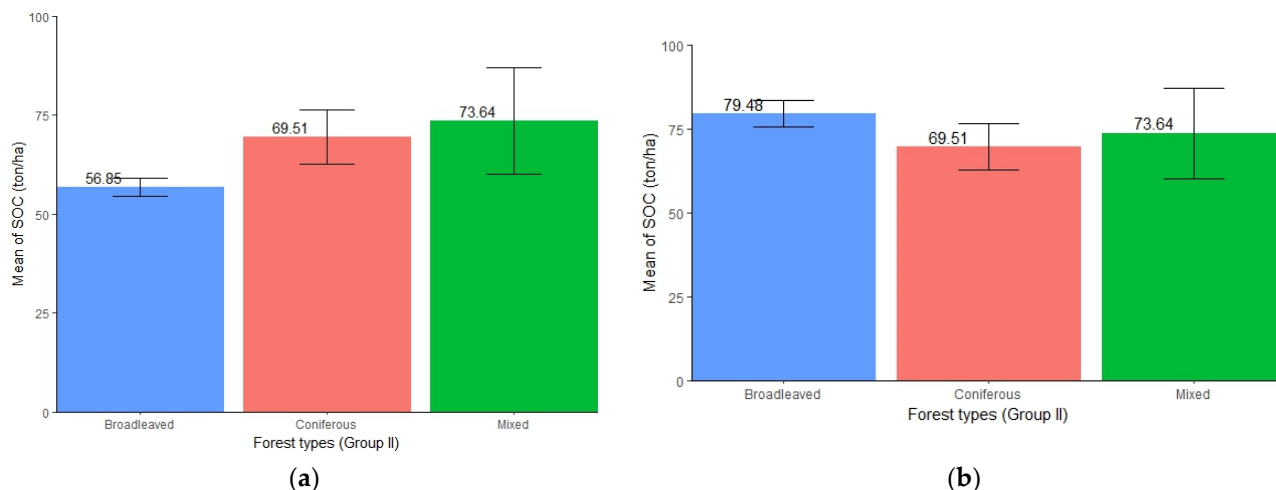**Figure 6.** Distribution of SOC in different forest types (Group I).

*3.6. Distribution of SOC in the Forest Types (Group II)*

The three different forest types exhibited varied amount of SOC accumulation. When considering all of the altitudinal ranges of the study area, mixed forests (mean = 73.64 ton/ha, SE ± 13.42) were found to store the highest amount of SOC followed by coniferous forests (mean = 69.51 ton/ha, SE ± 6.89) and broadleaved forests (mean = 56.85 ton/ha, SE ± 2.31) (Figure 7a). While assessing SOC above 657 m altitude (the range of both broadleaved and coniferous forests), a higher concentration of SOC was found in broadleaved forest (mean = 79.48 ton/ha, SE ± 4.01) followed by mixed and coniferous forests (Figure 7b). However, the ANOVA test showed no significant differences in SOC stocks among the three forest types (*p* > 0.05) in either case (Tables 7 and 8).

**Table 7.** ANOVA table for the SOC of different forest types (Group II).

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 2 | 12.8 | 6.39 | 2.32 | 0.098 |
| Within groups | 399 | 1095 | 2.74 | ---- | ---- |
| Total | 401 | 1107.8 | ---- | ---- | ---- |

**Figure 7.** (**a**) Distribution of SOC in different forest types (Group II) representing all altitudinal ranges. (**b**) Distribution of SOC in different forest types (Group II) representing altitude > 657 m, i.e., where the presence of coniferous forests is seen.

**Table 8.** ANOVA table for the SOC of different forest types (Group II, alt > 657 m).

| Source | Degree of Freedom (df) | Sum of Squares (SS) | Mean Squares (MS) | F-Stat | *p*-Value |
|---|---|---|---|---|---|
| Between groups | 2 | 3.8 | 1.90 | 0.602 | 0.548 |
| Within groups | 280 | 883.7 | 3.15 | ---- | ---- |
| Total | 282 | 887.5 | ---- | ---- | ---- |

## 4. Discussion

### 4.1. Effects of Altitude, Slope, Aspect, and Canopy Cover to SOC Stocks in Forests

Our study shows a positive relation between altitude and SOC stocks. Several studies have also reported a similar positive correlation [33–35,56–59]. However, it is important to note that this relationship is found to be case-specific. Contrastingly, some studies reported that the stabilization of SOC increases at lower altitude compared to higher [37,38]. Along with altitude, several other factors such as topography, exposure, climate, parent material, and vegetation influence soil carbon stocks [20,60–62]. In particular, altitude is an important factor for regulating soil organic matter decomposition [51], resulting in an impact on SOC stocks. It does not directly affect the ecosystem, but is an indicator of climatic functions [63]. SOC distribution depends on the altitude-induced variation in climatic variables (temperature and precipitation). SOC stocks increase with altitude due to slow soil organic matter decomposition at the higher elevation sites [25,64]. In Nepal, temperature decreases by 6 °C for every 1000 m increase in elevation [65], which supports our result that a lower temperature at a higher altitude contributes to the higher SOC stocks.

Likewise, slope is an important predictor variable for estimating SOC [66]. Our result shows the effect of slope on SOC stocks. SOC accumulation in the forest soil increases with an increase in slope. Other previous studies [24,39,40] reported the same positive relation between slope and SOC. However, an inverse relationship between SOC and slope has also been reported [36,67], which could be attributed to the erosive down-hill transport of leaf litter and soil debris. It is also reported that the differences in climatic variables (temperature and moisture), aspects, and plant species affect SOC distribution regardless of slope [68]. Our result is supported by the fact that land surface temperature decreases with the increase in slope, influencing the incidence angle and reflectivity of solar radiation [69]. This leads to a lower rate of decomposition due to a decrease in temperature, contributing to more SOC retention [23].

The aspect of the forest is also one of the variables affecting SOC stocks due to a difference in temperature depending on the duration of the sun light received. North-

facing slopes are generally cooler, more moist, and densely vegetated than other aspects, and thus accumulate a higher amount of SOC [36,70]. Our result shows a similar trend to previous studies except in the N aspect. Contrary to other studies [32,36,68,70], the N aspect shows the lowest amount of SOC in our study. Sample plots representing the north aspect in our study had the lowest mean altitude (801.71 m) whereas other aspects, namely, NE, E, SE, S, SW, W, and NW had 1379.36 m, 1299.98 m, 1402.72 m, 1267.41 m, 1205.67 m, 1370.06 m, and 1385.65 m, respectively. A lower altitude, and thus a higher temperature, on the N aspect does not contribute more to SOC accumulation. A lower amount of SOC stocks in the N aspect is not due to the aspect itself but rather to the selection of sample plots (i.e., a sampling error). However, there was no significant difference in SOC stocks except for the N–E and N–NE aspects. Aspect does have an effect on SOC stocks as the temperature of the soil differs according to the aspect. But this condition applies well when the study area has a lower altitudinal range. In the areas with larger altitudinal variation, altitude can be a strong predictor compared to other variables, and is likely to cancel out the microclimatic effect due to the aspect [71].

Furthermore, our result shows a positive relationship between SOC and forest canopy cover. This result corroborates the findings reported by Gebeyehu et al. and Kara [24,52]. Canopy cover does not affect directly the change in the amount of SOC but influences the microclimate. The change in the microclimate of the soil habitat due to the alteration in canopy cover includes temperature, soil moisture, light, and wind speed [72]. These factors affect the activities of fauna and organisms in the soil [72], leading to variations in soil respiration intensity and the formation of SOC [73,74]. In fact, an increase in tree canopy cover helps reduce soil temperature [75–77] and slows down the rate of litter decomposition [78], resulting in more SOC retention.

The effect of topographical factors (altitude, slope, and aspect) on SOC is primarily observed due to the variation in climate. Therefore, the manipulation of the topographical variables is not easy under forest management activities. However, canopy cover management can be performed to increase SOC in forests.

### 4.2. SOC Accumulation of SOC under Different Forest Types under Group I and Group II

The amount of SOC increases along the altitudinal gradient [49–51]. This implies that forests at a higher altitude are likely to possess a higher amount of SOC stocks compared to forests at a lower altitude. Our study also shows similar findings. Moreover, the distribution of SOC in different forest types situated at various altitudinal gradients differed substantially in our study.

In Group I, our findings show that forest types located at higher altitudes have a higher amount of SOC stocks than forest types at lower altitudes. In particular, UMH and Q forests, located at higher altitudes in Nepal, have higher SOC concentrations compared to other major forest types at lower regions. Similar results (for Q forests) have also been reported by Seikh et al. [38]. The significant difference in the amount of SOC accumulation in the different forest types is possibly due to the cumulative effect of altitude, slope, aspect, canopy cover, and forest disturbance (e.g., forest harvesting), which ultimately influence temperature and microbial activities. The effect of altitude, slope, aspect (except for the N aspect), and canopy cover on SOC stocks found in this study is similar to that reported in previous studies [24,33,34,39,40,56–59]. Furthermore, forest harvesting affects the depletion of SOC stocks [79,80]. However, it depends on the accessibility to the forest which is difficult at higher altitudes due to the rugged terrain compared to lower regions. Forest disturbances by humans (tree cutting, bush cutting, litter collection, lopping, and cattle grazing) are lower at higher altitudes [40,77], which is likely to increase SOC in forests at higher altitudes.

In Group II, when considering all altitudinal ranges, the study result shows that mixed forests have the highest SOC stocks, followed by coniferous and broadleaved forests (Figure 7a). The result is similar to the findings reported by Devi [81]. Mixed forests are found in higher regions, i.e., starting from 657 m altitude (Table 1). The higher amount

of SOC stocks in mixed forests might be the result of the higher amount of SOC stocks in the broadleaved and coniferous forests lying at higher altitudes. In contrast to our study, Dulamsuren [82] reported the lowest amount of SOC stocks in mixed forests compared to other forests. The difference in altitudinal ranges between the two studies, i.e., 88–3993 m in our study and 1300–1500 m in Dulamsuren [82], could be the reason for the dissimilar result.

Moreover, our result demonstrates higher SOC stocks in coniferous forests than broadleaved forests. The finding is similar to the result reported by Vhiti et al. [83]. In our study, coniferous forests are found only at higher altitudes (i.e., altitude > 869 m), whereas broadleaved forests are found at lower altitudes up to 88 m in our study (Table 1). The variation in altitude difference—resulting in temperature difference—between coniferous and broadleaved forests could have influenced the average SOC stocks. We found a lower amount of SOC in the lower altitudinal region, which corroborates the finding reported by Devi [81]. A lower amount of SOC in broadleaved forests, particularly in lower regions, might be due to increased microbial activity at warmer temperatures [22], resulting in a higher rate of $CO_2$ release due to the rapid decomposition of soil organic matter.

On the other hand, the result shows that broadleaved forests have a higher SOC accumulation than coniferous and mixed forests when similar altitudinal regions are considered (Figure 7b), i.e., altitude > 657 m. Similar findings have been reported by various previous studies, e.g., [31,38,83,84]. The large canopy cover of broadleaved forests—compared to coniferous forests in our study (Table 1)—may be the reason for the former holding more SOC, as a larger tree canopy cover helps reduce soil temperature [75,76] and lowers the rate of decomposition of organic matter, leading to more SOC retention [23]. Furthermore, mixed forests are the result of disturbance [85,86], and they are likely to release a large amount of SOC into the atmosphere due to either heterotrophic respiration or in combination with fire [87–89]. This could be a possible reason for the lower amount of SOC in mixed forests than in broadleaved forests in the same region. Maintaining broadleaved forests at higher altitudes could support SOC retention, thus contributing to climate change mitigation, besides providing multiple benefits to people.

### 4.3. SOC Retention by Forests and its Implication in Climate Change Mitigation

Plants (above and below ground parts) are the main source of soil organic matter [90], of which 58% is assumed to be occupied by soil organic carbon [91]. Thus, forests play an important role in SOC retention. However, the amount of SOC depends on the characteristics of tree species, forest type, and the locality where they are present. Our result shows that altitude, aspect, slope, and canopy cover influence SOC accumulation in forests.

This study confirms that different forest types have different levels of SOC retention potential. Firstly, broadleaved forests have higher SOC retention than coniferous forests. Secondly, our study argues that forests at higher altitudes have a higher potential for SOC retention. Although temperature decreases with an increase in altitude, recent studies show that the rate of temperature increase in Nepal is higher in higher altitudinal regions [92,93], which might have implications for the storage of SOC in forests at higher altitudes.

### 5. Conclusions

SOC stocks in forests vary with altitude, aspect, slope, canopy cover, and forest type. This variation could be attributed to changes in the microclimate (soil temperature and moisture) of the area influenced by these locality factors and stand attributes. The significant increase in SOC amount with the increase in slope, altitude, and crown cover helps to understand the extent of SOC distribution in forests.

In general, forests at higher altitudes store more SOC than forests at lower regions. In particular, broadleaved forests at higher altitudes are the largest SOC reservoirs, compared to mixed and coniferous forests, provided that there is minimal human disturbance. As Nepal is facing a problem with the increasing rate of temperature in higher altitude regions [92], this can plausibly result in increased carbon emissions from forest soils in these regions. Broadleaved forests with a larger canopy cover in higher altitude regions have a

higher SOC retention potential, which is likely to contribute to mitigating the impact of climate change by sinking more carbon into the soil. Further research is needed to assess the mitigation potential of forests at higher altitudes in the context of a changing climate.

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**Data Availability Statement:** Data that support the findings of this study are available from the Forest Research and Training Centre (FRTC), Kathmandu, Nepal, but not publicly accessed due to the data sharing protocol of the FRTC. However, data can be obtained by following a formal process of written application with supporting documents.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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