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# Soil organic carbon fractions across soil depths vary among key tropical vegetation types

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**Abstract**
Analyzing the patterns of soil organic carbon (SOC) fractions is important for enhancing C sequestration and mitigating global warming. However, studies on SOC fractions and nutrient availabilities across multiple forest types within the same ecological zone (EZ) are limited. This study aimed to investigate how SOC fractions vary across tropical vegetation types and how soil nutrient availability mediates these effects. A total of 1224 soil samples were collected from two different depths: surface (0–15 cm) and sub-surface (15–30 cm), across six vegetation types; montane forest (MF), sub-montane forest (SMF), moist monsoon forest (MMF), open and sparse forest (OSF), grassland (GL) and forest plantation (FP) located in Knuckles Forest region (KFR), Sri Lanka. Total OC (TOC), microbial biomass C (MBC), $KMnO_4$ oxidizable C (LC), water soluble C (WSC), and soil nutrient availabilities (i.e., N, P, K, Ca, and Mg), soil pH, moisture content and electrical conductivity (EC) were quantified using standard chemical procedures. Results indicated that MF showed the highest SOC (4.52%), LC (0.071%), and WSC (0.047%) in the upper soil layer, while FP showed the lowest values (SOC 2.70%, LC 0.055%, WSC 0.014%). In contrast, MBC was highest in SMF and lowest in MF. The results revealed that vegetation types significantly and differently impact SOC fractions in both soil layers, depending on the characteristics of the vegetation types (i.e., cover and diversity), even within the same EZ. The estimated SOC values will be valuable for enhancing the SOC pool through the restoration of degraded soils, agroforestry, and plantations.

**Keywords** Carbon cycle · Climate change · Knuckles Forest Region · Soil carbon fractions · Soil carbon sequestration

## 1 Introduction

Studying SOC fractions and its' spatial distribution are prerequisites to build a soil C pool inventory, evaluating past losses or gains, and predicting the capacity for soil C sequestration [1, 2]. They are essential to understanding the C cycle with the potential of using this data to develop future land use policies [3].

Soil is recognized as a natural resource providing a sustainable flow of essential goods and services [4]. Research on soil C and its sequestration is prioritized within soil ecosystem services studies, alongside other key services such as water conservation and retention [5, 6]. Soil OC serves as a primary reservoir of C within the biosphere. Soil OC enhances soil fertility as it releases nutrients for plant growth, enhances soil structure, rehabilitates degraded soils, boosts biomass production and purifies both surface and groundwater [7].

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Soils within forest ecosystems are crucial to the global C cycle due to its' involvement across large areas on both regional and global levels, making it important to understand the spatial distribution of soil C storage in these ecosystems [8]. Diverse C pools that exist in the soil are generally referred to as soil CC fractions, with the two primary components being organic and inorganic C. The fertility, structure, and nutrient cycling of soil are significantly influenced by OC, which refers to C-containing substances deriving from living organisms or their decomposing remnants. This study assessed four distinct fractions of SOC to capture various components of the soil C continuum: TOC, microbial biomass C (MBC), labile C (LC), and water-soluble C (WSC). For instance, MBC represents a significant reservoir of SOC and plays a crucial role in the short-term stability and cycling of C within soil ecosystems, despite its relatively higher decomposition rates relative to other soil C fractions [9, 10]. Soil microorganisms may easily break down the fraction of organic C that is referred to as labile C [11]. Through increasing soil aggregation, microbial activity, and the stabilization of organic matter within the soil, it significantly contributes to soil C sequestration. Water-soluble C (WSC) is the portion of SOC that is readily soluble in water [12]. While water-soluble C accounts for a minor percentage of SOC, it plays a crucial role in soil C sequestration by fueling microbial activity, enhancing nutrient cycling, promoting soil aggregation, and helping to stabilize organic matter in soils [13, 14]. Soil C sequestration has become the simplest and the most effective way of depleting the concentration of greenhouse gases in the atmosphere and thereby slowing the pace of global warming [15, 16]. Forest ecosystems represent a significant reservoir of terrestrial C, spanning approximately 4.1 billion hectares worldwide [17]. Although forest soils are vital components of the global C cycle, less emphasis to estimating the capacity for sequestering substantial amounts of C in forest soils. Knowledge of soil C fractions supports insight into C sequestration in forest ecosystems by providing insights into C dynamics, identifying key C pools, monitoring management practices, forecasting sequestration potential, and informing climate change mitigation approaches. The ability to address soil C sequestration and its role in mitigating climate change is improved by incorporating knowledge of C fractions into research, monitoring, and management initiatives. [13, 14].

Nutrient cycling plays a vital role in forest conservation, particularly in tropical ecosystems where high rainfall can lead to nutrient leaching. In such environments, rapid nutrient uptake by plants helps to minimize these losses. However, nutrient availability in tropical forests can be affected by various factors such as soil pH, moisture content, organic matter, topographical variation, drainage properties, disturbance history, parent material, cation exchange capacity, litter decomposition rates, and extracellular phosphatase activity [18, 19]. In high-altitude tropical montane forests, the spatial distribution of nutrients in mineral soils may be further constrained by unfavorable chemical soil properties that limit root development [20].

The Knuckles Forest Region (KFR), a tropical forest ecosystem located in the mid-country of Sri Lanka with an approximate extent of 21,000 hectares, has been declared both as a National Man and Biosphere Reserve and a World Heritage Site, with its high ecological importance to the world [21]. The diverse climatic and landscape features of the Knuckles Forest have fostered a unique mix of ecosystems, supporting a rich and diverse array of fauna and flora. Many species found here are endemic or rare, with some being found exclusively in the Knuckles Region. These natural and human-influenced vegetation types in the KFR include montane forests, submontane forests, moist monsoon forests, open and sparse forests, forest plantations and grasslands. This study is also significant in that it responds to the limited research available on multiple forest types within a same ecological zone, thereby filling a vital gap in forestry research. Human activities, such as converting forests into agricultural land and urban areas, have significantly diminished the terrestrial carbon pool. This issue is particularly pronounced in tropical regions compared to other parts of the world. For instance, the Knuckles Forest Reserve has undergone significant shifts in land-use practices over time, transitioning from traditional subsistence agriculture and colonial plantation systems to contemporary conservation efforts. Historical practices such as cardamom cultivation within forested areas have contributed to ecological degradation, while current initiatives emphasize sustainable land management and biodiversity conservation under protected status. To date, few studies have examined the differences in carbon fractions between natural forests and human-influenced vegetation types, along with their distribution across the soil profile in tropical regions. This highlights the critical importance of monitoring, evaluating, and reporting on the soil health conditions of these vital tropical forest ecosystems.

The baseline information on C fractions in tropical forest soils is valuable for conservation and management purposes as they are the main indicators of soil fertility, as they release nutrients for plant growth, enhance soil structure, support biological and physical health, and act as a buffer against harmful substances. Although a substantial body of research exists on global-scale SOC modeling and mapping [22–24], there is comparatively limited work that explores the detailed dynamics of SOC and its influencing factors within tropical forest soils [17, 25, 26]. The study aims to quantify the SOC fractions in these different tropical vegetation types of this highly important forest ecosystem of KFR. We hypothesized that, within the same ecological zone, 1) the influence of vegetation types on soil C content would be more pronounced in the upper soil layer than in the deeper layer, and 2) these influences would be mediated by soil nutrient availability across the vegetation types. While SOC levels are significantly influenced by vegetation type, several other factors, including topography, climate, and soil characteristics, can also have a considerable impact on SOC stocks. SOC is critical for soil fertility, C sequestration, water regulation, soil structure, nutrient cycling, conservation of biodiversity, and ecosystem function. Climate risk reduction, conservation of the environment, and sustainable agriculture all depend on an understanding of the significance of SOC and managing soils to increase SOC levels. The findings of this study will be valuable for guiding future conservation and management efforts within the KFR, as well as supporting climate change mitigation programs in Sri Lanka. Additionally, the baseline data collected across various forest types will contribute essential information for addressing the current gaps in knowledge on below-ground carbon estimations in regional tropical forest ecosystems.

## 2 Materials and methods

### 2.1 Study area

The Knuckles Forest Region is situated in the Central Highlands of Sri Lanka. The terrain is extremely rugged with hills, rising up to a height of 1900 m. The gathering of spectacular peaks, over 35 rising above 900 m, is a unique feature in the Knuckles Forest range, found nowhere else on the island. The location of KFR at the boundary of the wet and dry zones (Intermediate Climatic Zone) has resulted in a mosaic climate in the area with a wide range of rainfall and temperature.

The average annual rainfall ranges from about 2540 mm on the eastern side to between 3810 and 5080 mm across the main Knuckles range [22]. The high elevation zones of the KFR are extremely wet across the entire year. Rainfall distribution is directly driven by the monsoonal rains in the south-west and the north-east, which causes climate variations inside the KFR because the zone is nearly perpendicular to the direction of the prevailing wind currents [23–25]. Conversely, the lower eastern slopes show significantly drier conditions, with mean annual rainfall below 2,000 mm, predominantly received during the northeast monsoon period (October–January) [24]. The area is also exposed to strong winds during monsoon periods [21].

Outside the Knuckles range, the mean annual temperature exceeds 26 °C, decreasing to roughly 21 °C at elevations above 915 m and reaching about 18.5 °C at the highest points [22]. Mountain peaks are frequently covered in mist or fog, although on the eastern slopes, the fog often disperse with daytime winds. Six major vegetation types including montane forests (MF), submontane forests (SMF), moist monsoon forests (MMF), open and sparse forests (OSF), grasslands (GL) and forest plantations (FP) were selected for the study. These types were chosen to represent contrasting vegetation conditions based on their differences in composition (e.g., plant species richness), function (e.g., litter cover), and structure (e.g., species cover). The establishment of pine (*Pinus caribea*) forest plantations was carried out on highly degraded landscape by the Forest Department of Sri Lanka bordering the KFR.

### 2.2 Soil sampling

Soil samples were collected covering selected vegetation types in the Knuckles Forest Region. A total of 204 main sampling sites were randomly selected considering the percentages of the vegetation cover of the particular forest type (i.e., a higher number of samples from a higher vegetation cover) and also depending on accessibility for the sites (Fig. 1). A total of 1224 individual samples were gathered and pooled to form 408 composite samples for depths of 0–15 and 15–30 cm. Number of sampling sites from each vegetation type; MF 18, SMF 48, MMF 58, OSF 30, GL 38, and FP 12. Samples were collected within different vegetation types, avoiding edges (roads, paths, other conditions), slopes, and valleys where possible.

### 2.3 Preparation of soil samples and analyses

Upon arrival at the laboratory, soil samples were processed for both wet and dry soil analyses. All visible organic matter, stones, and coarse roots were carefully removed to ensure sample consistency and accuracy in testing. Homogeneous soil samples were prepared after sieving the samples using a 2 mm mesh sieve. Field-fresh soil samples were used to analyze pH, electrical conductivity (EC), moisture content, available nitrogen (N), phosphorus (P) and microbial biomass C (MBC). The remaining soil samples were air dried, and ground to a fine powder of less than 0.15 mm and used for further

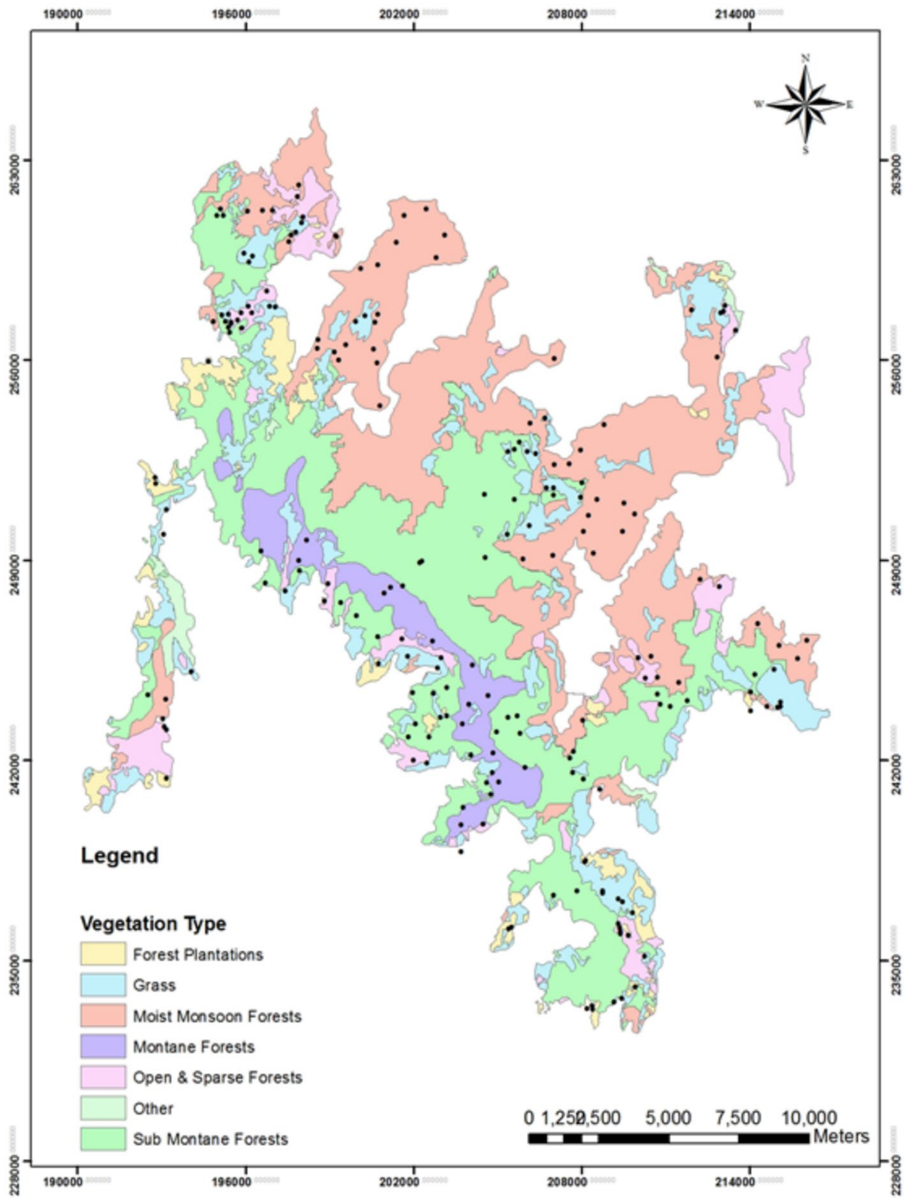


**Fig. 1** Soil sampling locations depicted on the vegetation map of Knuckles Forest Region (Coordinate System: SL Grid_99, Map Source: Forest Department, 2007)

analysis, such as SOC fractions as explained by [26] and available K, Ca and Mg. The moisture content of the soil samples was calculated using the following formula [31].

$$\text{Water Content}\ (\%) = (\text{W2} - \text{W3})/(\text{W3} - \text{W1}) \times 100$$

In this equation, W1 represents the weight of the empty container. W2 is the combined weight of the container and the wet soil sample after it has been weighed. After oven-drying the soil samples at 105 °C to a stable weight, W3 refers to the weight of the container plus the dry soil. The fresh soil samples were assessed for soil pH (using a 1:2.5 soil: water suspension method) and electrical conductivity (EC) (using a 1:5 soil: water suspension method) respectively using the multi-parameter analyzer [31]. Total organic carbon (TOC) was determined using acidified dichromate according to the modified Walkley's oxidation method [27]. A mixture of 1 g of ground soil, 10 ml of 5% potassium dichromate, 20 ml of $H_2SO_4$, and 50 ml of 0.4% $BaCl_2$ was prepared and left to stand overnight. The supernatant was then recorded at 600 nm using a UV-2450 Shimadzu spectrophotometer. Microbial biomass C was assessed using the Chloroform fumigation and extraction method [26]. A 5 g soil sample was extracted with 25 ml of 0.5 M $K_2SO_4$ solution. A separate subsample was fumigated with chloroform for 24 h before extraction. After digesting 4 ml of the samples with 1 ml of 0.0667 M potassium dichromate and 5 ml of concentrated $H_2SO_4$ at 150 °C for 30 min, both fumigated and unfumigated samples were titrated against 0.033 M acidified ferrous ammonium sulfate solution. Labile SOC was analyzed using the modified $KMnO_4$—oxidizable C method [28]. Five grams of soil were mixed with 2 ml of 0.2 M $KMnO_4$ and 20 ml of distilled water, and allowed to settle for 5–10 min. A 0.5 ml aliquot from the upper 1 cm of the suspension was diluted to 50 ml and measured at 550 nm using a UV-2450 Shimadzu spectrophotometer. WSC was estimated by the titration method using acidified ferrous ammonium sulphate [26]. 10 ml of distilled water was added to 1.5 g of soil, followed by shaking, centrifugation, and filtration. 4 ml of the filtrate were then mixed with 1 ml of 0.0667 M potassium dichromate and 5 ml of concentrated $H_2SO_4$, digested at 150 °C for 30 min, and subsequently titrated with 0.033 M acidified ferrous ammonium sulfate. Soil available N: $NO_3^-$ was determined by colorimetrically [29]. Absorbance taken at 410 nm wavelength using the UV spectrophotometer (UV-2450 Shimadzu). The Bicarbonate extractable $PO_4^{3-}$ was analyzed using the UV Spectrophotometer [30]. Available K, Mg and Ca in soil were estimated by the modified Morgan extraction method [31].

### 2.4 Statistical analyses

The effects of vegetation type, soil depth, and their interaction on SOC fractions were assessed using a two-way ANOVA with a general linear model (GLM). The interaction term was included to determine whether the effect of vegetation type on SOC fractions differed between soil depths. Post hoc analyses using Tukey's HSD test were conducted to examine pairwise differences among the combined levels of vegetation type and soil depth. Differences were considered significant at the 0.05 probability level.

## 3 Results

### 3.1 Soil pH, moisture and electrical conductivity

The soil pH varied from 4.49 to 5.93 indicating that soils are in the acidic range (Table 1). MMF soils showed a significantly high pH (5.93) compared to other vegetation types. The soil EC was significantly higher for the upper 0–15 cm soil layer in SMF (0.047 dS/m) and GL (0.019dS/m) for the layer below 15–30 cm soil layer.

GL-Grasslands, MF-Montane forests, MMF-Moist monsoon forests, SMF-Submontane forests, OSF-Open and sparse forests, FP-Forest plantations. Means with different letters indicate significant differences at $p < 0.05$.

**Table 1** Soil pH, electrical conductivity and moisture content in different vegetation types of the Knuckles Forest Region

| Vegetation type | Soil layer (cm) | pH range | Conductivity (dS/m) | Moisture content (%) |
|---|---|---|---|---|
| GL | 0–15 | $5.16^{cd}$ | $0.025^{ef}$ | $26.0^{de}$ |
| | 15–30 | $5.06^{cd}$ | $0.019^{f}$ | $25.4^{de}$ |
| MF | 0–15 | $4.88^{cd}$ | $0.038^{bc}$ | $42.2^{a}$ |
| | 15–30 | $4.67^{d}$ | $0.035^{cd}$ | $29.1^{bcd}$ |
| MMF | 0–15 | $5.93^{a}$ | $0.041^{b}$ | $22.8^{fg}$ |
| | 15–30 | $5.76^{ab}$ | $0.024^{ef}$ | $19.0^{h}$ |
| SMF | 0–15 | $5.31^{c}$ | $0.047^{a}$ | $32.7^{b}$ |
| | 15–30 | $5.21^{cd}$ | $0.037^{bc}$ | $28.3^{cd}$ |
| OSF | 0–15 | $5.31^{bcd}$ | $0.033^{cd}$ | $31.3^{bc}$ |
| | 15–30 | $5.15^{cd}$ | $0.027^{de}$ | $28.4^{bcd}$ |
| FP | 0–15 | $4.60^{cd}$ | $0.030^{cde}$ | $19.6^{efg}$ |
| | 15–30 | $4.48^{cd}$ | $0.022^{def}$ | $18.7^{gh}$ |

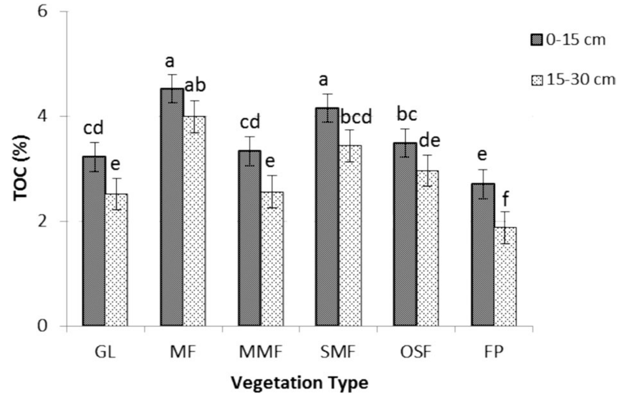


**Fig. 2** Total OC content in different vegetation types. Grasslands (GL), Montane Forests (MF), Moist Monsoon Forests (MMF), Sub-Montane Forests (SMF), Open and Sparse Forests (OSF), Forest Plantations (FP). Different letters indicate statistically significant pairwise differences among the interaction levels of vegetation type and soil depth ($p < 0.05$)

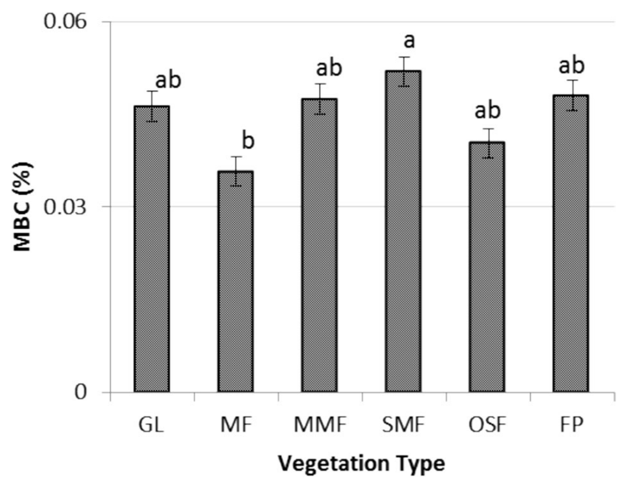


**Fig. 3** Microbial biomass C (MBC %) in the upper soil layer (0–15 cm) in different vegetation types of Knuckles Forest. Grasslands (GL), Montane forests (MF), Moist monsoon forests (MMF), Sub montane forests (SMF), Open and sparse forests (OSF), Forest plantations (FP). Different letters denote statistically significant differences among the vegetation types ($p < 0.05$)

### 3.2 Total organic carbon (TOC)

Total OC contents (also known as soil organic carbon, SOC content in this study) in different vegetation types at KFR varied between 2.70 to 4.52% in the 0–15 cm soil layer and 1.88 to 3.90% in the 15–30 cm layer (Fig. 2). The OC contents were in the decreasing order of MF > SMF > OSF > MMF > GL > FP in 15–30 cm soil depth. Both MF and SMF showed significantly higher SOC contents (4.52 and 4.17%, respectively) while FP showed the lowest SOC (1.88%) among the vegetation types. OSF showed relatively higher SOC content (3.53%) compared to MMF and GL.

### 3.3 Microbial biomass carbon (MBC)

Microbial activity decreases with soil depth due to the combined impacts of less organic matter intake, oxygen availability, temperature, nutrient availability, and pH gradients. Deeper soil depths allow microbial communities to survive and function, but at lower activity levels than in surface soils. Thus, only the top layer of soil was considered. The soil MBC ranged from 0.035 to 0.053% in the vegetation types studied. SMF soils showed the highest MBC (0.053%) followed by FP, MMF, GL and OSF (Fig. 3). MBC content of MF was significantly lower (0.035%) compared to SMF. MBC in MF soils exhibited a significant positive correlation with pH (Fig. 4).

### 3.4 $KMnO_4$–oxidizable carbon/labile C (LC)

The LC fraction in Knuckles Forest soils ranged from 0.055 to 0.071% among the different vegetation types with some significant changes at $p < 0.05$ (Fig. 5). The highest oxidizable C in the 0–15 cm soil layer was recorded in MF soils (0.071%), while the lowest was recorded in FP (0.062%). Both MF and SMF had significantly higher LC in both soil layers compared to the rest of the vegetation types. Also, LC decreased significantly from the upper to lower soil layers in all vegetation types.

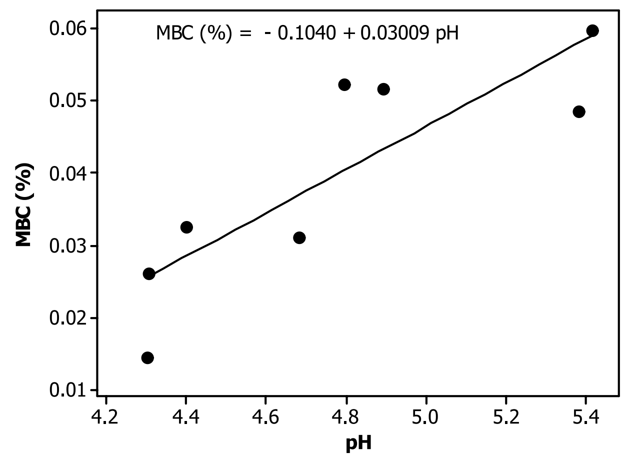


**Fig. 4** The correlation between MBC (%) and the pH in Montane Forest soils 0–15 cm soil layer and significance level; $p < 0.05$ ($R^2 = 72.5\%$)

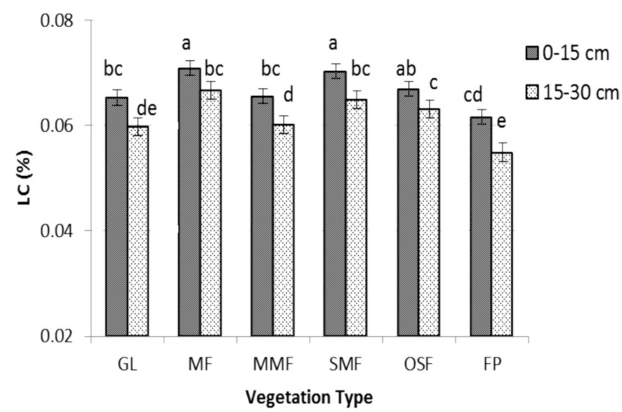


**Fig. 5** $KMnO_4$–oxidizable C (LC %) in different vegetation types. Grasslands (GL), Montane Forests (MF), Moist Monsoon Forests (MMF), Sub-Montane Forests (SMF), Open and Sparse Forests (OSF), Forest Plantations (FP). Different letters indicate statistically significant pairwise differences among the interaction levels of vegetation type and soil depth ($p < 0.05$)

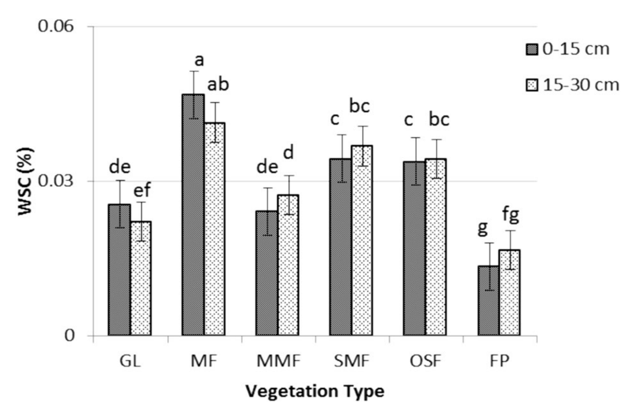


**Fig. 6** Water soluble C (WSC%) in different vegetation types. Grasslands (GL), Montane Forests (MF), Moist Monsoon Forests (MMF), Sub-Montane Forests (SMF), Open and Sparse Forests (OSF), Forest Plantations (FP). Different letters indicate statistically significant pairwise differences among the interaction levels of vegetation type and soil depth ($p < 0.05$)

## 3.5 Water soluble carbon (WSC)

The WSC significantly varied from 0.014 to 0.047% among the different vegetation types (at $p < 0.05$) (Fig. 6). Both soil layers at MF showed significantly higher WSC contents (0.047 and 0.042%, respectively) compared to all other vegetation types. Consistent with all other parameters, FP showed the lowest WSC.

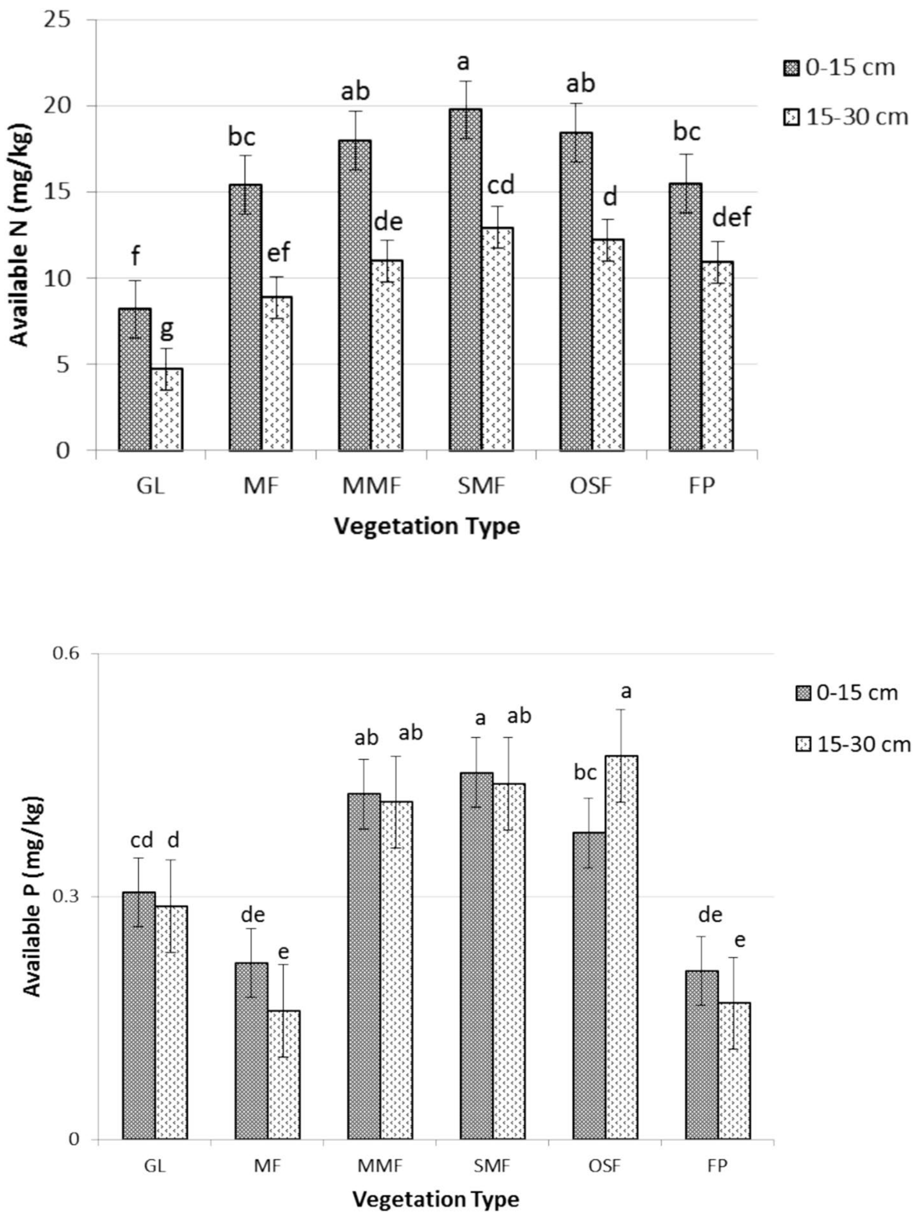


**Fig. 7** Available soil N and P in different vegetation types of the Knuckles Forest Region. **a** Available N, (**b**) Available P (mg/kg). Grasslands (GL), Montane Forests (MF), Moist Monsoon Forests (MMF), Sub-Montane Forests (SMF), Open and Sparse Forests (OSF), Forest Plantations (FP). Different letters indicate statistically significant pairwise differences among the interaction levels of vegetation type and soil depth ($p < 0.05$)

### 3.6 Available nitrogen and phosphorus

Available N and P in KFR soils ranged between 8.18 to 19.76 mg/kg and 0.21 to 0.45 mg/kg, respectively between the different vegetation types in the 0–15 cm soil layer (Fig. 7a and b). Compared to other vegetation types, the availability of N and P was notably higher in SMF (21.23 and 0.49 mg/kg) and OSF (22.08 and 0.47 mg/kg) soils. In contrast, MF soils exhibited notably deficient P availability relative to the other vegetation types in the KFR. A significant positive correlation was detected between N availability and TOC content (Fig. 8); however, no such relationship was evident for P availability.

### 3.7 Available K, Ca and Mg

Soil K availability of Knuckles Forest Region ranged from 260 to 3225 mg/kg (Fi9. 4a). The highest K availability was indicated in MF (3225 mg/kg) followed by FP (2656 mg/kg) soils within top 15 cm layer. The Ca availability in soil varied from 175.0 to 1004.0 mg/kg (Fig. 9b). The SMF soil in the Ca availability was high (1004.0 mg/kg) followed by MF soils (896.0 mg/

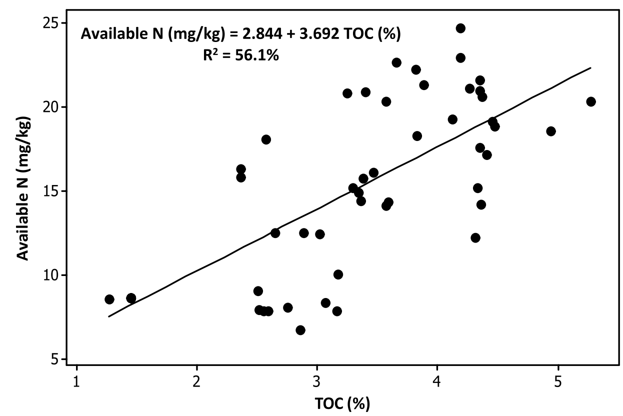


**Fig. 8** Relationship between available N (mg/kg) and TOC (%) within 0–15 cm soils of Knuckles Forest Region

kg). Availability of soil Mg in different vegetation types of Knuckles Forest Region ranged from 54.48 to 339.70 mg/kg (Fig. 9c). The highest Mg availability was observed in SMF (339.70 mg/kg) followed by GL (244.92 mg/kg) and MF (241.07 mg/kg) soils. Among these nutrients, only Ca availability showed a significant positive correlation with water-soluble carbon (WSC) (Fig. 10), while K and Mg availability did not exhibit significant correlations with WSC (Table 2).

## 4 Discussion

This study explored the impact of different vegetation types on SOC fractions across soil depths, as well as the role of soil nutrient availability in mediating these SOC fractions. The study initially hypothesized that the impact of vegetation types on soil carbon content would be more pronounced in the upper (0–15 cm) soil layer compared to the deeper soil layer. However, the findings suggest that the various types of vegetation exert a pronounced impact on SOC fractions, not only in the upper soil layer, as hypothesized, but also in the deeper soil layer. These changes may be due to the differing climate, nutrient content, soil properties, and landscape conditions that influence the vegetation types even within the same ecological zone.

The content of the SOC was significantly higher in both MF and SMF soils indicating a high level of organic matter in forest soils [32]. This was also evidenced by [33], who reported the highest total C content in natural forests (8.2 kg $m^{-2}$) in the Knuckles Forest region. This might be caused by the wetter climatic conditions that resulted in a luxurious growth of all kinds of vegetation types and a rich biodiversity in these natural forests, particularly due to their location in the south-western slopes (600–1300 m asl) of the Knuckles Mountain range. Additionally, the low decomposition rate of organic matter due to relatively low temperatures at high altitudes (above 600 m) has led to an increase in SOC levels in forest soils. This is also evidenced by [34], who reported that SOC content declined with rising average annual temperatures, with temperature sensitivity values strongly and positively correlated with SOC turnover rates.

Soil OC serves as the primary energy source for soil microorganisms [35]. SMF has reported the highest MBC content in its soils among the vegetation types might be due to the elevated SOC content that facilitated the higher microbial growth in SMF soils. [36] also emphasized that soils rich in OC contain a large population of microorganisms due to the supply of sufficient energy, thus increasing the soil MBC. However, MF, which showed the highest total SOC content, indicated the lowest MBC among the study sites. This might be due to the unsatisfactory growth of microbes at the relatively low soil pH (4.88) and the low temperature existing with the high altitudes (> 1300 m asl), resulting in a lower MBC content in MF soils. The significant positive relationship observed with MBC content and pH levels of MF also emphasized that low temperatures were not favorable for optimum growth of microbes, as shown by [36].

Forest plantation (FP) showed the lowest SOC content across all the vegetation types studied. This was also compatible with the findings of [34], as they reported the lowest in tea plantations 4 kg $m^{-2}$ in the Knuckles Forest. This may be due to reduced forest cover and lower plant diversity in FP compared to other vegetation types, as previous studies have confirmed that the abundance and diversity of plant species can influence the soil organic matter content and nutrients [37]. The natural/anthropogenic disturbances (i.e., wind, fire, drought, diseases, forest clearing) can alter soil moisture, temperature patterns, and forest species succession, thereby affecting both the amount and composition of biomass that returns to the soil [38], affecting the SOC contents of soils. Changes in canopy cover induced by such disturbances

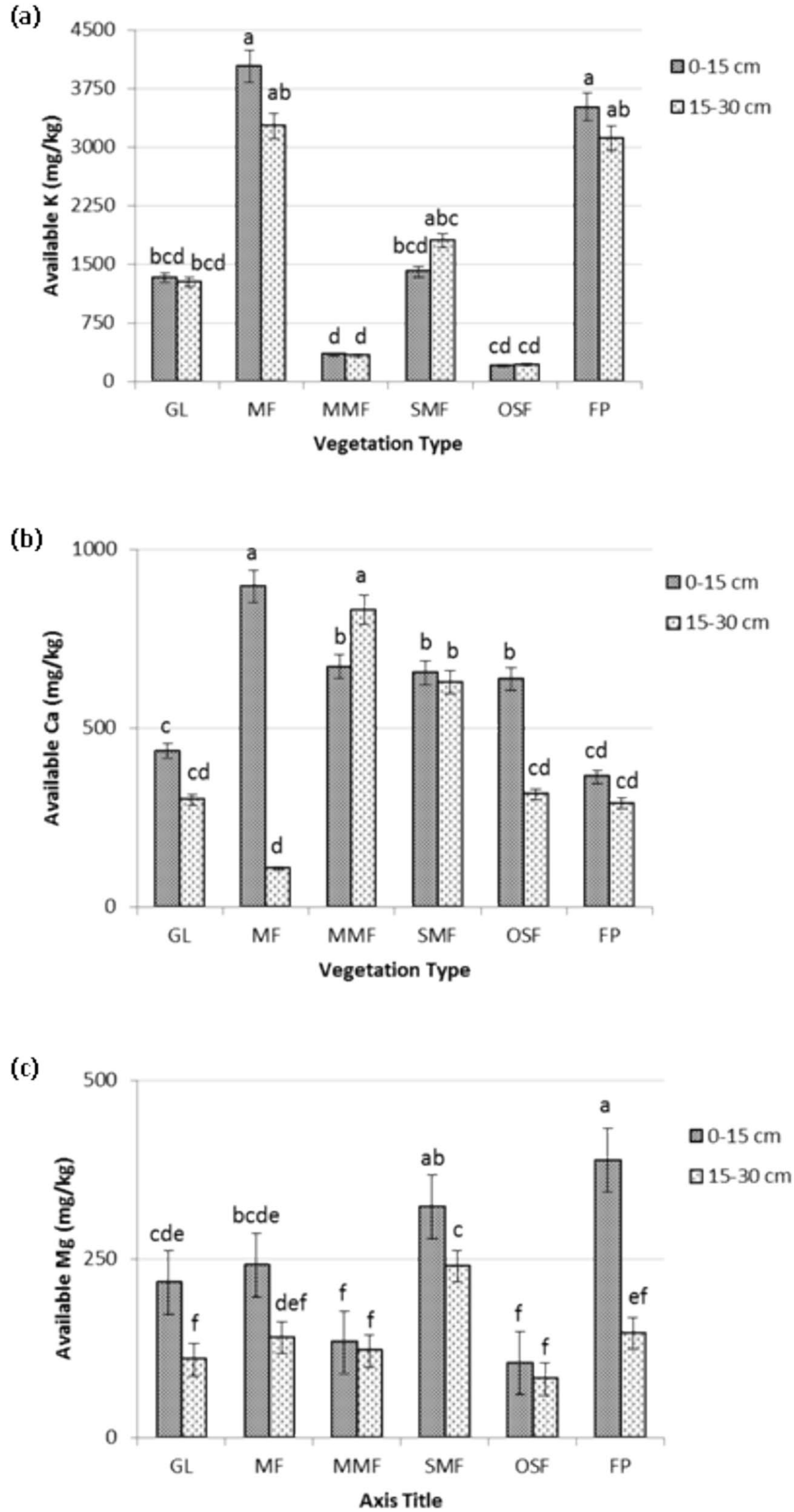


**Fig. 9** Available soil nutrients in different vegetation types of the Knuckles Forest. **a** Available K (**b**) Available Ca (**c**) Available Mg (mg/kg). Grasslands (GL), Montane Forests (MF), Moist Monsoon Forests (MMF), Sub Montane Forests (SMF), Open and Sparse Forests (OSF), Forest Plantations (FP). Means with different letters indicate significant pairwise differences among the combined vegetation type and soil depth levels ($p < 0.05$)

can impact soil erosion [39], thereby modifying SOC levels in the surface layer of FP soils. In contrast, MF contains a dense forest cover, which leads to a less soil erosion and a higher accumulation of SOC in the forest soil.

Grasslands (GL) at KFR showed a significantly lower SOC content in comparison to the natural forests, including MF and SMF. However, the SOC levels in GL were higher compared to FP. These man-made grasslands in the KFR have resulted

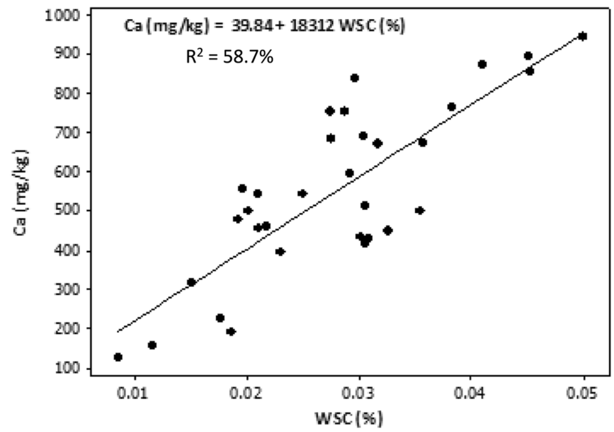


**Fig. 10** Relationship between available Ca and WSC of Knuckles Forest Region within 0–15 cm soil layer

**Table 2** Correlation between C fractions and soil available nutrients of Knuckles Forest Region within 0–15 cm soil depth

| Correlation | Model (linear) | $R^2$ (%) |
|---|---|---|
| TOC vs. N | N = 2.844 + 3.692 TOC | 56.1 |
| TOC vs. P | P = 0.201 + 0.053 TOC | 5.3 |
| TOC vs. K | K = 1107 + 23.4 TOC | 0.0 |
| TOC vs. Ca | Ca = 421.7 + 53.8 TOC | 2.8 |
| TOC vs. Mg | Mg = 49.93 + 42.9 TOC | 11.9 |
| LC vs. N | N = − 19.31 + 500.5 LC | 23.3 |
| LC vs. P | P = − 0.059 + 6.83 LC | 4.6 |
| LC vs. K | K = 514 + 11914 LC | 0.1 |
| LC vs. Ca | Ca = − 39.5 + 10065 LC | 4.1 |
| LC vs. Mg | Mg = − 66.23 + 3691 LC | 4.2 |
| WSC vs. N | N = 11.77 + 50.18 WSC | 0.8 |
| WSC vs. P | P = 0.324 + 0.47 WSC | 0.1 |
| WSC vs. K | K = 1775–32113 WSC | 2.7 |
| WSC vs. Ca | Ca = 39.84 + 18312 WSC | 65.5 |
| WSC vs. Mg | Mg = 160.5 + 292 WSC | 0.1 |

from the abandonment of tea plantations established during the colonial period. During the colonial period, large expanses of natural forest were cleared to establish plantations, including tea and coffee. However, the tea plantations have been abandoned for more than 30 years due to low productivity, and since then they have slowly converted into grasslands dominated by *Cymbopogon nardus*, resulting in a lower SOC content compared to other vegetation types. Compared to GL, OSF also contained similar levels of SOC without any significant difference. This might also be due to anthropogenic influences, such as slash-and-burn agriculture, which may have contributed to the formation of OSF and reduced vegetation cover, leading to lower accumulation of plant residues.

Moist Monsoon Forests (MMF), which are located in areas below 700 m, reported a considerable decrease in SOC in comparison to MF and SMF. Soil OC levels in MMF were relatively similar to both OSF and GL soils. The low rainfall from north-east monsoons and potential land cover changes may have contributed to these changes, particularly for lower SOC levels. In consistent with the second hypothesis, soil available N and Ca were found to mediate the impacts of vegetation types on SOC fractions. For instance, soil N availability is strongly influenced by OC dynamics, as organic matter serves as a key source of nutrients and energy for microbial activity. In this study soil available N showed a significant and positive correlation with total OC and $KMnO_4$—oxidizable carbon because, they mostly consume OC as their energy source [35, 36]. The highest N availability in SMF soils could be related to higher SOC in SMF soils. The N dynamics in mineral soils is known to correlate positively with TOC. Higher N availability in SMF soils could relate to elevated MBC levels. However, MF soils, where the highest SOC content was recorded, indicated a comparatively lower N availability due to the acidic pH levels, low temperature and resulting low MBC content. Similarly, soil organic matter is also a key factor in controlling soil P availability, hence showing a positive correlation with the OC contents in SMF.

While this study focused on the chemical properties of soils, including SOC fractions and nutrient availability, we acknowledge that physical properties such as soil texture and bulk density also influence SOC dynamics. Future research could benefit from incorporating these physical parameters to provide a more integrated understanding of SOC storage mechanisms across different vegetation types.

## 5 Conclusions

The Knuckles Forest Region (KFR), a tropical forest ecosystem in the South Asian region, plays a crucial role in sequestering atmospheric CO2 in its forest soils. The climatic conditions, slope aspects, water regimes, and other factors that distinguish the vegetation types in the KFR have led to significant differences in SOC stocks. The findings suggest that highly dense forests from wetter parts of the KFR, such as montane (MF) (4.52%) contain higher SOC contents, indicating the effect of vegetation type in determining the soil C contents in both the upper and deeper soil layers, while forest plantations (FP) (2.70%) contain the lowest SOC content, highlighting the effect of vegetation characteristics (e.g., cover and diversity), on soil carbon C variations within the same ecological zone. Furthermore, the carbon fraction results for LC and WSC (0.071% and 0.047%, respectively) showed the highest concentrations in MF soils, while FP (0.055% and 0.014%, respectively) exhibited the lowest values. Additionally, MF showed the lowest microbial biomass C content at high elevations (> 1300 m asl), which may be due to unfavorable environmental conditions (i.e., temperature, humidity, and pH) that inhibit optimal microbial growth. The findings also suggest that the impacts of vegetation types on SOC fractions are mediated by soil available N and Ca. This baseline information on soil C fractions under different vegetation types will address the dearth of detailed information on SOC fractions and the potential of C sequestration in soils under different land use types in the tropical forest ecosystems. These findings will be useful for future conservation and management purposes of the forests considering their highly valuable ecosystem services provided on a global scale. Additionally, they can support future green projects, $CO_2$ reduction initiatives, and contribute to carbon trading efforts in the future.

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**Data availability** The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

## Declarations

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

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