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Research Article

Examining the Fluctuation of Soil Organic Carbon Levels: An Analysis of the Shuklaphanta National Park in Nepal

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Soil organic carbon (SOC) is a crucial carbon reservoir that needs to be monitored for deforestation and forest degradation. The top one-meter layer of soil contains around 1500–1600 Pg of carbon. Assessing the SOC pool is essential for understanding the soil system's carbon sequestration potential (CSP) as a mitigation strategy and determining whether it acts as a source or sink for atmospheric CO_2, depending on the level of saturation. However, there are limited studies on SOC in Nepal's forests. This research aims to assess SOC variation in the Shuklaphanta National Park in Nepal. It focuses on determining SOC according to depth and analyzing the variation of SOC among the core area of the national park, grasslands, and buffer zone community forests (CFs) and identifying the factors that contribute to the variation in soil carbon across different land uses. The study was conducted using a systematic sampling method with a sampling intensity of 6.59% on 180 soil samples taken from permanent plots set up by the Forest Resource Assessment (FRA) Nepal. The analysis was based on SOC estimated up to the depth of 0–10, 11–20, and 21–30 cm using a modified Walkley–Black wet oxidation method. The study also analyzed contributing factors affecting soil carbon such as vegetation, forest fire, rate of forest resource use, and different soil properties like pH and bulk density. The study found that the mean SOC% up to the depths of 0–10 cm, 11–20 cm, and 21–30 cm was 2.08, 0.98, and 0.68, respectively, in forest areas. Mean SOC % in grasslands was found to be 1.7, 1.68, and 1.87 in 0–10, 11–20, and 21–30 cm, respectively, and in community forests, it was found to be 1.3, 0.98, and 0.58 in 0–10, 11–20, and 21–30 cm, respectively. Similarly, the vertical mean SOC in $tC \cdot ha^{-1}$ (0–30 cm) was found to be 41.75 $tC \cdot ha^{-1}$ in the core area of the national park, 46.64 $tC \cdot ha^{-1}$ in grassland, and 37.50 $tC \cdot ha^{-1}$ in CFs. The study also found that there was variation in SOC with depth and that most of the SOC was concentrated in the topsoil in the core area of the national park and buffer zone community forests. Deep layers of SOC were found in grasslands, core area of the national park, and CF in decreasing order. The study implies that the national park has enormous potential to recapture atmospheric CO_2 into the soil. Participating in the sustainable management of the national park can enhance the soil quality and help meet strategies to mitigate climate change. Factors such as vegetation cover, fire, bulk density, and vegetation type were found to be promising for SOC concentration.

1. Introduction

Soil is a food store for vegetation, from which vegetation receives nutrients from the soil in a cyclic process [1]. Forest ecosystems store more than 1 trillion tones of C, which is twice the amount of free C in atmosphere [2]. Globally, carbon in terrestrial ecosystem is 2477 billion tons, where soil and vegetation account for approximately 81% and 19%, respectively [3]. Changes in this pool influence the C concentration of the atmosphere [4]. Worldwide, vegetation and soil taxonomic units indicate that the soil stores ~1500–1600 Pg of C in the first meter [5]. Forest area covers more than 80% of all terrestrial aboveground C and more than 70% of soil organic carbon (SOC) [6]. This amount of C directly affects the soil carbon through the C cycle. The deep and shallow root systems in the soil determine the depth of C sink into the soil. SOC is controlled by the balance of C inputs form plants production and the output through decomposition [7]. Monitoring of soil C is necessary for deforestation and forest degradation by the Intergovernmental Panel on Climate Change (IPCC) forest C inventory. The vertical distribution of C in forest soil is shallower than shrubland or grassland, which makes the carbon stock of forest soil more vulnerable to environmental factors like climate [8]. Soil C surveys usually consider a fixed soil depth, typically one meter [9]. Forest area change is the most important factor for the uncertainty of soil carbon sink [10]. Deforestation releases large amount of sequestered carbon that in turn negatively impact SOC in the upper layer of soil [11, 12]. Carbon sequestration in the terrestrial ecosystem especially into soil is important in the case of developing countries like Nepal where land use change and agricultural area extension are more frequent [13]. The total emission of greenhouse gases (GHGs) from Nepal is estimated at 39256 Gg (0.025%) and per capita emission is 1977 kg [14]. The soil carbon content in forest and shrubland of Nepal is 432 million metric tons in 1990, 350 million metric tons in 2000, and 326 million metric tons in 2005 [15] up to the depth of 100 cm. Forest structure in the Terai is being dominated by low-quality trees [16]. The carbon sequestration potential of different forest types under different management regimes needs to be explored [17]. Despite the largest carbon pool soil C, only a few projects are working straightforward on soil C management. The reason could be crediting C sequestration in soils usually faces bigger challenge than other forest component as aboveground biomass (AGB). Another specific reason is the complex response of soil C stocks to reforestation, deforestation, and afforestation activities. Monitoring the slight variation in small C changes compared to the large C pool is a time-consuming task due to the substantial local variability in soil C content and the expensive nature of soil C measurement procedures [18]. A research by Henry et al. [18] quantified the total soil C among two forest type and grassland. However, there are very limited literature studies on the soil carbon sequestration potential of the protected area of Nepal. Therefore, this research was intended to assess the variation of SOC in the Shuklaphanta National Park (SNP) by determining SOC according to depth, studying variation of SOC among core forest area, grassland, and buffer zone community forest and analyzing the factor contributing to the soil carbon change.

2. Materials and Methods

SNP lies in southwestern part of Far-Western Nepal extended from the flood plain of Terai to the Churia range (Figure 1). Its area is 305 km^2 and is used for swamp deer (*Rucervus duvaucelii*) conservation with the buffer zone (BZ) of 243.5 km^2. Latitude and longitude are 28 49–28.57 N and 80 07–08.15 *E*, respectively, at an altitude of 174–1386 m above the sea level.

The study area has tropical monsoon climate with four different seasons, namely, winter, spring, summer, and monsoon with a hot temperature range of 5°C–46°C. The maximum of 639.17 mm precipitation was recorded in August and the minimum of 3.98 mm was recorded in November. The monsoon typically begins from July and continues until late September to early October. Soil of sal (*Shorea robusta*) dominant forest varies from loam to sandy with slight acidic nature, and the grassland at riverside soil is clayey loam with alkaline nature. The common soil types found in the park are sandy loam, silty loam, and clayey loam [19].

2.1. Methods of Data Collection

2.1.1. Sampling Design. The study was carried out in FRA-field inventory plot number as prepared [20] in the Shuklaphanta National Park (area = 305 km^2) and its BZ (area = 243.5 km^2) (Figure 1). For this study, a sampling method called systematic sampling was used with a sampling rate of 6.59%. GPS points of the soil sample were located with Garmin Etrex *10*. The radius of each circular plot was 20 m. Thus, the area of each circular plot would be 1.26 km^2 (if the area of each circular plot = 3.1416 ∗ 400 m^2 = 1256.64 m^2 ∗ 16). There were altogether 16 circular plots in four clusters. Altogether, four permanent plots with their 16 subplots were used for soil sampling. As per the ANSAB [21] protocol, a 0.56-meter radius circle was created within each subplot to collect soil samples for the soil survey. All of the permanent plots inside the Shuklaphanta National Park (SNP) were used for sampling. The percentage (%) OC, SOC (t ha^{-1}), and bulk density of soil were determined from the forest of SNP. Soil to a depth of only 30 cm was extracted due to inaccessibility at some places, inconvenience, and financial limitation.

Soil samples were taken from different horizon as suggested by the authors in [22] up to the depth of 30 cm. Soil samples were collected from depths of 0–10, 11–20, 21–30, and 0–30 cm for carbon content analysis [23, 24]. SOC was estimated by the modified Walkley–Black titration [25] method as used by FRTC. Altogether, 180 soil samples were taken for the test. The composite of each (10 cm) horizontal layer of three soil samples taken from every plot was made. A metal core was used for the collection of soil samples in the center of each main subplot up to the depth of 30 cm. Sampling intensity was 6.59% of the whole. Finally, all the equipment was calibrated, and the freshly extracted soil samples were placed into plastic bags, which were tightly sealed with rubber and labeled appropriately. The samples were then transported to the laboratory of the Forest Research and Training Center (FRTC) for analysis of soil carbon.

2.1.2. Soil Organic Carbon Determination. Soil samples were obtained from depths of 0–10 cm, 11–20 cm, and 21–30 cm, with one composite sample taken from each sampling plot. The bagged samples were then placed into preweighed sampling bags and dried at room temperature before being ground into small particles and sieved through a 0.2 mm·mesh. The titrimetric method described by Walkley and Black [26] was used to determine the percentage of soil organic carbon (SOC), with the formula

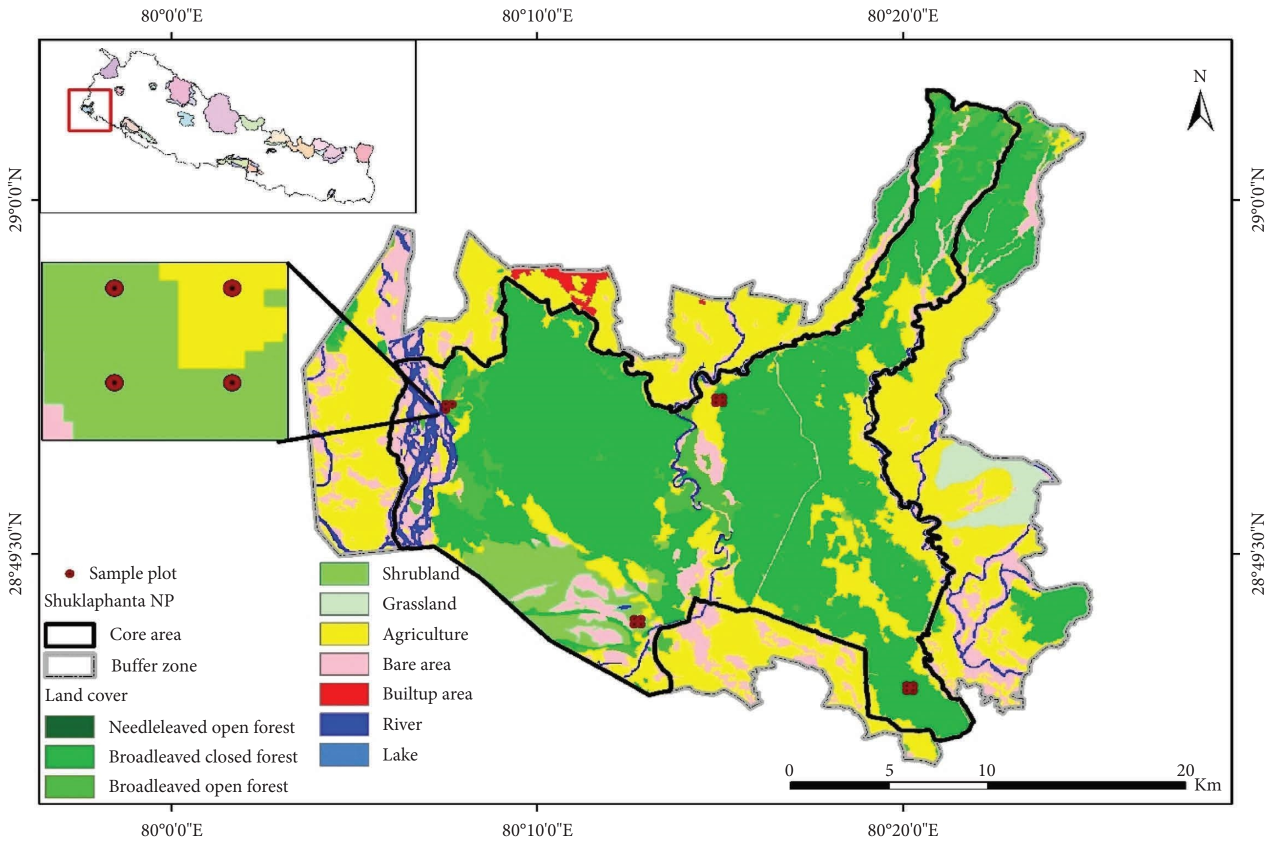

Figure 1: Map showing location of the study area.

Carbon (%) = 3.951/g [1 − T/S], where g represents the weight of the sample in grams, T is the total volume of ferrous solution consumed during the sample titration (in ml), and S represents the total volume of ferrous solution consumed during the blank titration (in ml).

The stock density of soil organic carbon was calculated as follows: soil organic carbon (SOC) = §*x d x* % C, where SOC represents the soil organic carbon stock per unit area in t/ha-1, § denotes the soil bulk density in gm·cm^{-3}, d represents the total depth from which the sample was taken (in cm), and % C is the carbon concentration (in %). This was then expressed in tons per hectare as per the method described by Joshi et al. [27].

2.1.3. Bulk Density. Soil bulk density was determined by using the core sampling method of known volume without disturbing the natural structure. Soil sampler of the length 10 cm and of diameter 5.5 cm (r = 2.75) was used for the soil sample collection. The soil samples were subjected to ovendrying at 105°C until a constant weight was achieved, according to Joshi et al. [27]. Once dried, the soil was passed through a 2 mm sieve to separate stones, which facilitated moisture correction. The total weight of coarse fragments was then estimated for each soil sample obtained from various sampling sites and subtracted from the soil weight to obtain an accurate soil weight. Soil bulk density was calculated by using the following relationship [28]:

$$\text{bulk density (gm/cc)} = \frac{\text{oven dry weight of soil (gm)}}{\text{volume of the soil (cc)}}, \tag{1}$$

where volume of the soil = volume of core − volume of the stone.

2.1.4. Statistical Analysis. Variation in soil carbon was analyzed by comparing data among the core area forest land, grassland, and buffer zone community forest of the SNP. Primary field data were used for comparison. Key-informant interview was also conducted for the identification of the contributing factor affecting soil carbon change. All these statistical analyses were done using MS Excel, SPSS, and R software. A GIS-based map was prepared for mapping the area and used to locate the point, while the vegetation type was identified from the satellite image provided from FRA Nepal, and the software used was Erdas Imagine 9.3 (Figure 1).

3. Results and Discussion

SOC variation was observed among the different forest types (core area forest land, buffer zone community forest, and grassland). The protected area is mainly dominated by sal forest (*Shorea robusta*), grassland of *Imperata cylindrica*, and community forest of *Magnolia pterocarpan*. It is surrounded by 243.5 km^2 of the buffer zone area. SOC was determined from the upper 30 cm layer. According to FAO [15], the data status of carbon in below ground biomass was 126 million metric ton (mmt) in the year 2005, 135 mmt in 2000, and 97 mmt in 1990 in Nepal. Soil carbon to the depth of 100 cm was 432 mmt in 1990, 350 mmt in 2000, and 326 mmt in the year 2005 [15].

3.1. Soil Carbon

3.1.1. Determination of Soil Organic Carbon (%) with Depth. Throughout the study period, we observed that the concentration of SOC was higher in the upper layer or A horizon and decreased with increasing depth, which is consistent with the findings of several other studies [27, 29]. This higher SOC content in the upper layer is primarily due to the presence of high levels of soil organic matter. In addition, our study's results coincide with those of Khanal et al. [17]. Soil organic carbon is a crucial component of forest soils and ecosystems [30], and it is a soil quality indicator that correlates with climate and land cover types such as forest, shrubland, and grassland [31, 32]. On the other hand, there is a general consensus that forest degradation is linked to a decrease in soil properties such as lower SOC and increased bulk density due to compaction [33]. Additionally, Morisada et al. [34] suggested that soil compaction resulting from weight or disturbance, consolidation, soil aggregates, and soil fauna has an impact on soil bulk density, but it is inversely proportional to the SOC content in natural forests.

The SOC disturbance is difficult to quantify than tree biomass as the soil process is slow, complex, and laborious to measure [35]. Root biomass only contributes 8% of the total biomass in tropical wet forest; thus, soil C inputs due to forest remnant root biomass decomposition after conversion could be negligible [36]. Different tests and analysis of data from the forest across the national park show that organic carbon concentrates on the upper 0–10 cm layer and then decreased gradually (Figure 2). The SOC carbon in the first 10 cm was found to be highest in all the vegetation type of the national park. Mean SOC (%) upto 0–10 cm, 11–20 cm, and 21–30 cm was found to be 2.08, 0.98, and 0.68, respectively, in the core forest area of the national park.

Deepest SOC horizon was observed in grassland. The mean value of organic carbon in the grassland up to the 0–10 cm layer was 1.74, which was slightly lower than the forest area. Although the concentration is lower than the forest in the 0–10 cm layer, it exceeded with the depth. SOC percentage was found to be 1.68 and 1.87 in the 11–20 cm and 21–30 cm layers, respectively. Similarly, SOC remained almost constant, that is, 14.59 tC ha^{-1} in the upper 20 cm and increases in 21–30 cm to 17.46 tC ha^{-1}. The result showed similar pattern with the previous study by Jobaggy and Jackson [5], in which it was suggested that the woody AGB input and relatively low decomposability in forest increase SOC storage in the surface soil compared to grassland. In the forest, organic material is higher in the top horizon than in the grassland, but it decreases down the profile. In the grassland, it remains relatively constant [37].

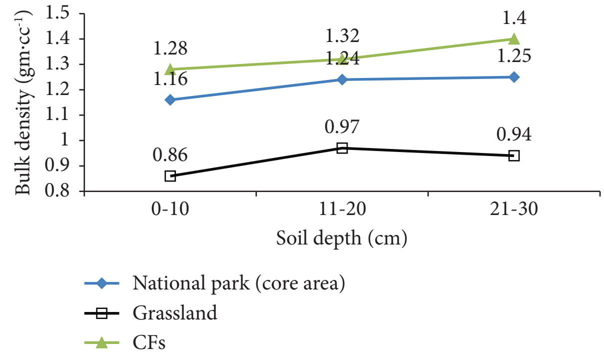

Figure 2: Bulk density (BD) in different vegetation types along the depth.

This phenomenon is brought about by the manner in which the organic matter enters the soil; in forest, due to litterfall, and in grassland, due to both litterfall and root decay and depth. The obtained data show variation of SOC along with the depth mainly. The study on SOC frequently concentrated on the upper 30 cm of soil, in which the organic material is concentrated and where processes of C mineralization and immobilization are more active [38], and then it goes on decreasing with depth. A similar pattern was also observed in this study where SOC in tC ha^{-1} was found to be 22.65, 11.80, and 7.30 at the intervals of 0–10, 11–20, and 21–30 cm from the surface layer, respectively (Table 1). Lowest % OC was observed in the buffer zone community forest area located in FRA plot id 8–72–3, 8–72–1, and 8–72–6. Mean % OC in the upper 0–10 cm layer was found to be 1.48 and almost similar to the lower layer in the core forest area of the national park. It was found to be 0.94 and 0.58 in 11–20 cm and 21–30 cm, respectively. Similarly, the vertical mean SOC in tC·ha^{-1} (0–30 cm) was found as 41.75 tC ha^{-1} in the core forest area, 46.64·tC ha^{-1} in grassland, and 37.50 tC ha^{-1} in community-managed forest. A similar outcome was observed by Khanal et al. [17] in Jarneldhara and Lipindevi. The study conducted by Khanal et al. [17] found SOC 52.3 ± 3.0 and 31.6 ± 2.0 t·ha^{-1} upto 0–20 cm soil depth. Similarly, the study conducted in Hariyali CF of Kanachanpur district found lower SOC than in Jarneldhara and higher than in Lipindevi CF.

3.1.2. Variation in SOC within Vegetation Types. The findings of this study showed variation of SOC along the depth mainly in the national park (core area). It is more constant in grassland up to the depth of 30 cm that store large amount of carbon. SOC was found highest in the grassland. The similar study by Jobaggy and Jackson [5] reported that in temperate grassland, 59% of the SOC is located below 20 cm depth due to shift in species composition that has a deep root system. The first 20 cm of the soil was found to contain 50% in the forest, with grassland in between 42%, of the SOC relative to the layer of 0–100 cm. A similar pattern was observed here though the research was limited up to the 30 cm, and SOC was found the highest below 20 cm (Figure 3).

Table 1: Soil C in different layers of soil.

Vegetation type	Parameters								
	% OC			SOC (tC ha^{-1})			Bulk density (BD)		
	0–10	11–20	21–30	0–10	11–20	21–30	0–10	11–20	21–30
Forest (core area)	2.08	0.982	0.62	22.65	11.8	7.3	1.16	1.24	1.25
Grassland	1.74	1.68	1.87	14.59	14.59	17.46	0.86	0.97	0.94
CFs	1.37	0.936	0.58	17.8	11.88	7.81	1.3	1.32	1.41

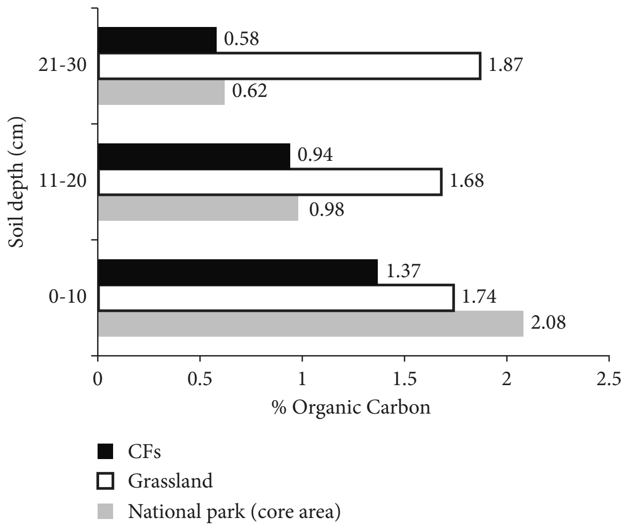

Figure 3: OC percentage (%) in CFs, national park (core area), and grasslands.

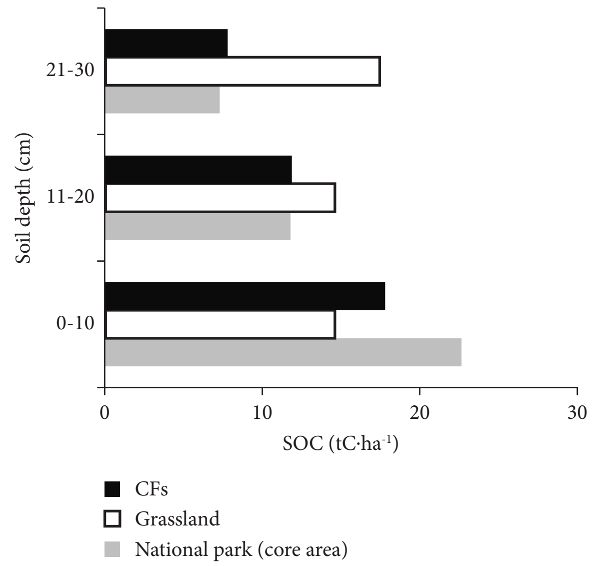

Figure 4: SOC vs. soil depth for CF, national park (core area), and grassland.

Grasslands have great potential to sequester C as studied by in 45 grassland sites. He found that the degradation of grassland leads to losses of 3–5% in the temperate and tropical regions, while improvement could increase SOC sequestration by 14–17% in the temperature and tropical regions (Figure 4).

Variation in SOC differs with depth and vegetation type both. This implies that land use change from protected area to CF negatively affected the carbon concentration in soil. The core area of the national park is less disturbed by human as anthropogenic activities are strictly prohibited inside the national park. On the other hand, CF is frequently intervened by human activities, and thus releases soil C easily into the atmosphere.

(1) Soil pH. Soil pH determines the acidic, neutral, or basic nature of soil. Decomposition of organic matter is processed by the microorganisms. These organisms are more or less balanced by the soil pH that in turn determines the ecophysiology of the plant. The soil was slightly acidic without crossing the threshold of mean pH 6.76 (0–10 cm) in the first 10 cm top soil. While increasing the depth, it is nearly neutral in average (neutral at some sites also). It ranges between 6.84 in 11–20 cm and 6.88 in 21–30 cm depth. pH was calculated from composite data only.

(2) Bulk Density of Soil. Bulk density is one of the main factors affecting SOC. In relation to soil depth, SOC is inversely proportional while BD is directly proportional to it. Bulk density was observed lower at the upper layer and increased as the depth increases. The mean bulk density of the soil at 0–30 cm soil depths was measured. Bulk density was found the highest with 1.40 gm·cc^{-1} in CFs and the lowest with 0.94 gm·cc^{-1} in grassland (Figure 2).

The mean bulk density ranges between 1.16 and 1.25 gm·cc^{-1} in the forest area. It was slightly lower comparing to others in grassland, that is, ranging from 0.86 to 0.97 gm·cc^{-1}. It was 1.29–1.41 gm·cc^{-1} in community-managed forest. SOC and bulk density are inversely proportional to each other [39]. SOC goes on decreasing with depth while bulk density goes on increasing. SOC and bulk density in the first 10 cm of the reserved forest (22.65 tC ha^{-1}), Figure 5 is comparable with the study done by Shrestha [40] in the Ghodaghodi lake area, Kailali, where mean SOC was found to be 21.28 tC ha^{-1}. The mean bulk density was found to be 1.21 gm·cc^{-1} and 1.16 gm·cc^{-1} in SNP. SOC in grassland adjacent to lake was found to be 14.72 tC ha^{-1} in the surface layer with the mean bulk density of 0.92 gm·cc^{-1}. Similar result was also found in the grassland of the SNP where bulk density was found to be 0.86 and SOC 14.59 (Figure 5).

A difference of 0.06 in bulk density and 0.13 in SOC was observed in this study compared to that of Shrestha [40]. From Figure 6, it was clear that the soil bulk density of the CF has increases from 1.2 gm·cc^{-1} to 1.4 gm·cc^{-1} with the depth and SOC decreases from 17.80 to 7.8 tC ha^{-1}. Since most of

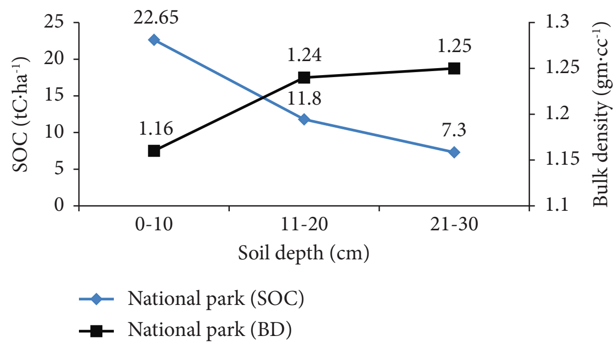

Figure 5: Bulk density (BD) and mean SOC in the national park.

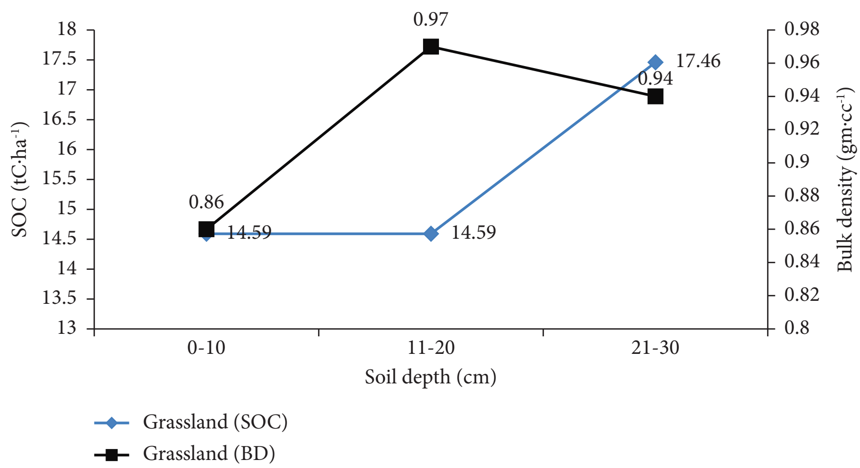

Figure 6: Bulk density (BD) and mean SOC in grassland.

the organic carbon is concentrated on top soil, bulk density is lowered.

(3) Fire and Deforestation. Fire was prominent all over the forest except the moist dense mixed forest in the southwestern part of the national park. The surface fire was rampant especially over the CFs. Only trees were present in the name of vegetation while understory vegetation were burnt and grass was almost wiped out by fire. Such fire was dominant on the southern part of national park (6–73 and 8–72) where the vegetation is dominated by sal (*Shorea robusta*). Loss of vegetation may be one of the reasons that affected the low SOC of the CFs. It may promote C loss from the forest. Dominancy of sal forest promotes fire while fire was not observed in the dense mixed forest in the southwestern part of the national park [19].

(4) Biomass. Out of the total four sites, three sites were mostly dominated by sal (*Shorea robusta*) forest and one with mixed moist and dense forest. The SOC is controlled by the balance of carbon inputs form plants production and the output through decomposition [41], deep and shallow root system in the soil. The direct contribution of organic matter on the upper soil increases the SOC on the top layer. The highest concentration of SOC on the surface layer of the reserved forest indicates the input of high organic matter from vegetation (Figure 7).

The good vegetation status of the forest helps to store SOC within it without any immediate loss to atmosphere. Major tree species in the national park are *Shorea robusta*, *Trachycarpus takil*, *Terminalia arjuna, Syzygium aromaticum*, *Lagerstroemia parviflora*, *Hovenia acerba*, *Lagerstroemia indica*, and *Magnolia pterocarpa*. Grassland was covered with dense 5–8 feet grass such as *Imperata cylindrica*, *Heteropogon contortus*, and *Phragmites karka*. Soil was humus rich up to the depth of 30 cm. Root biomass was proportionate with SOC. The major part of the area is covered by sal forest; thus, it must be a major contributor of carbon to the soil. The total stems volume of the sal (*Shorea robusta*) in Far-Western Province is 21775 (000 m^3), that is, 30% of the total stem volume. In the study by Jobbagy and Jackson [5], SOC with the depth in the profile was found to be strongly related to the vegetation type. The variations are attributed to the vertical distribution of the root and to a lesser degree to climate and the clay content. The decrease in depth is most pronounced under shrubs, followed by grassland and least prominent under forest [38]. According to Hiederer [38], the major condition influencing SOC independent of climate are land use/land cover, SOC content, soil depth, and clay content.

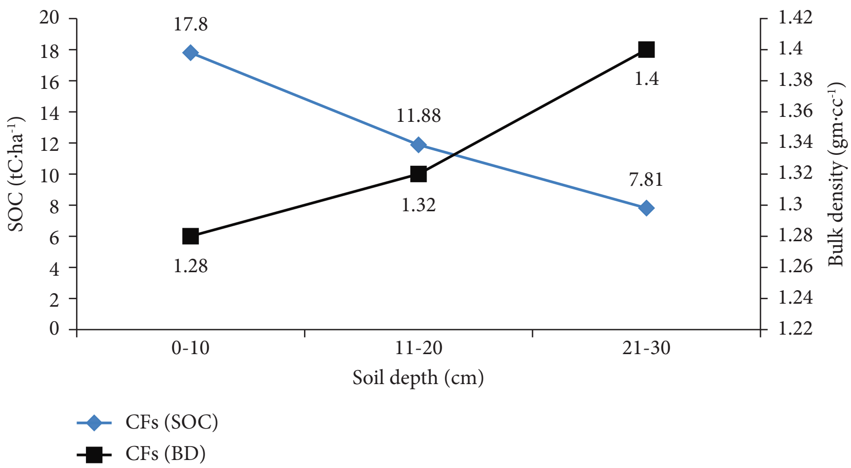

Figure 7: Bulk density (BD) and mean SOC in CFs.

4. Conclusion

Upon analysis of the soil samples, it was found that the amount of soil organic carbon (SOC) varies considerably with depth. The concentration of SOC was observed to be higher in the uppermost layer (0–10 cm) of the soil and gradually decreased with increasing depth. The depth of SOC was greater in grassland compared to community forests (CFs), and the former was found to store more carbon even beyond a depth of 30 cm. This suggests that the conversion of protected forests to CFs has a negative impact on soil carbon concentration, as CFs are more frequently disturbed by human activities than dense forests. As a result, even slight changes in land use in forest areas can lead to the loss of SOC into the atmosphere. Factors such as fire, vegetation type, dominant species, and soil properties were found to contribute to changes in SOC levels in the study area. Overall, the results indicate that the national park has stored a significant amount of carbon, making it an important asset in mitigating climate change.

Improved management of the national park can encompass a range of measures that promote increased soil carbon sequestration. One approach could be to promote the protection and restoration of forests within the park. This could involve measures such as limiting deforestation and forest degradation, as well as reforestation efforts in areas that have previously been deforested. Increasing vegetation cover and promoting the growth of trees and other plants can help to increase carbon sequestration in the soil. In addition to promoting forest conservation and restoration, other management strategies could also be implemented to enhance soil carbon sequestration. For example, reducing the use of heavy machinery and promoting sustainable land management practices can help to maintain soil structure and increase the organic matter content, which can enhance carbon sequestration. Incorporating cover crops and other soil-improving practices can also increase the amount of carbon stored in the soil. To ensure that the management strategies implemented are effective, monitoring and reporting on changes in soil carbon levels is also critical. Regular soil sampling and analysis can help to track changes in soil carbon sequestration over time and inform future management decisions.

Overall, improved management of the national park for increased soil carbon sequestration requires a multifaceted approach that incorporates forest conservation and restoration, sustainable land management practices, and regular monitoring and reporting. By implementing these measures, the national park can play a critical role in mitigating climate change by capturing atmospheric carbon in the soil [17].

Data Availability

The data used to support the findings of this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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