Bangladesh J. Bot. **53**(3): 567-576, 2024 (September) DOI: https://doi.org/10.3329/bjb.v53i3.76274

TREE CARBON STOCK AND SEASONAL INFLUENCE ON SOIL PROPERTIES IN SHIVPURI-NAGARJUN NATIONAL PARK, NEPAL

TIL MAYA DHAKAL[1], LAL BAHADUR THAPA, RAM KAILASH PRASAD YADAV AND CHANDRA PRASAD POKHREL*

Central Department of Botany, Institute of Science and Technology, Tribhuvan University, Kirtipur, Kathmandu, Nepal

Keywords: National Park, seasonal effect, soil depth, soil nutrients, carbon stock

Abstract

The carbon stock stored within the biomass of tree species is vital in the forest ecosystem as it contributes significantly to the carbon balance. In addition, the physicochemical properties of soil play a critical role in influencing overall ecosystem health. In the present study the carbon stock and influence of seasonal change on soil physicochemical properties along soil depths in the Shivpuri Nagarjun National Park (SNNP), Nepal were analyzed. The above-ground biomass carbon stock was found to be 227.09 t/ha and below-ground stock was 45.42 t/ha. Tree species *Castanopsis tribuloides* exhibited the highest values of above and below-ground tree carbon stock. The soil of the study site was sandy loam and slightly acidic. High temperature and moisture in the monsoon season were followed by an increased bulk density during the pre-monsoon with deeper soil layers. The sand, silt, and clay contents did not differ significantly across the seasons and depths. The key soil nutrients, like carbon, total nitrogen, phosphorus, and potassium were high during the monsoon season at the topsoil layer, which gradually declined with increasing depth in all seasons. The study highlights that the total tree carbon stock in the study site is 272.51 t/ha, with significant seasonal and depth-related variations in soil attributes. The monsoon season, characterized by maximum soil moisture and higher concentrations of essential soil components, is crucial in influencing soil physicochemical properties and offers important insights for forest conservation and management.

Introduction

Forests are crucial in global carbon circulation and climate regulation as essential elements of terrestrial ecosystems (Brockerhoff *et al.* 2017). The above-ground biomass of tree species comprises a significant portion of the overall carbon stock within forest ecosystems, serving as a crucial reservoir for mitigating climate change (Propa *et al.* 2021, Kumar *et. al*. 2024). As significant carbon sinks, forests sequester atmospheric carbon dioxide through the uptake and storage of carbon within vegetation and soils (Ahmed *et al.* 2021, Whitehead 2011). Further, the carbon stock significantly contributes to the organic matter and then influences the soil's physicochemical characteristics (Alam *et al.* 2024, Freschet *et al*. 2013).

Soil type and components in a particular area play a significant role in determining the vegetation, influencing composition, cover, rate of growth, and vigor (Sigdel *et al.* 2015). Physicochemical characteristics of soils differ spatially and temporally due to various factors such as temperature, moisture, topography, vegetation cover, and microbial activities (Gautam and Mandal 2013). Such factors fluctuate in the soil with seasonal change which has great significance for the functioning and health of forest ecosystems. Therefore, regular monitoring of soil physicochemical parameters is critical for vegetation and soil management (Ataullah *et al*. 2017; Sinore *et al.* 2022).

The protected areas such as national parks are designated to preserve biodiversity and natural ecosystems where above-ground elements like wildlife and plant species are prioritized but the

*Author for correspondence: <chandra.pokhrel@cdb.tu.edu.np>. [1]Department of Botany, Siddhanath Science Campus, Tribhuvan University, Mahendranagar, Kanchanpur, Nepal.

soil is often overlooked. The neglect of soil research in protected areas may lead to issues such as soil degradation, habitat loss, and impaired ecosystem resilience. Recognizing the importance and regular assessments of soil attributes in such areas is essential for effectively conserving biodiversity and long-term sustainability (Rodrigues *et al.* 2018). Therefore, assessments on carbon dynamics with the characterization of soil based on seasonal changes and soil depth have great significance in making informed decisions about land use, effective forest conservation, and ecosystem services. Moreover, such studies are crucial for soil restoration and provide critical insights into the complex relationship between soil and ecosystems (Adhikari and Hartemink 2016). The present study was carried out in the Shivpuri-Nagarjun National Park (SNNP) with the major aim of estimating tree carbon stock with seasonal influences on soil physicochemical properties across soil depths.

Materials and Methods

The present study was carried out in Panimuhan site within Shivpuri Nagarjun National Park (SNNP) located in Kathmandu, Bagmati Province, Nepal (27°47'N to 85°22'E, 1731 to 1869 m asl) (Fig. 1). The elevation of SNPP ranges from 960 to 2732 m asl. as the transition between subtropical and temperate zones. The temperature of the SNPP ranges from 2-17°C during the winter season and 19-30^{o}C during the summer, with a mean annual rainfall of 1400 mm (SNNP 2017). The Pani Muhan site of SNPP is characterized by *Schima wallichii, Alnus nepalensis*, *Pinus roxburghii*, *Castanopsis* spp., *Quercus* spp. and *Rhododendron* spp. as the major tree species.

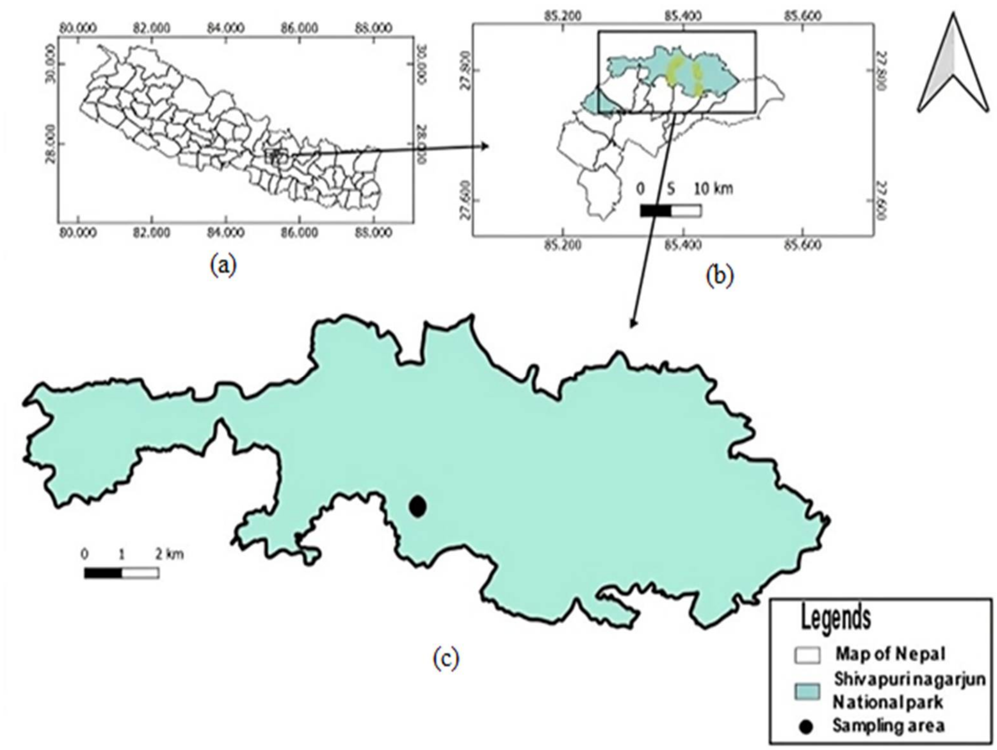

Fig. 1. Map of the study site showing Kathmandu district (a), Sivapuri-Nagarjun National Park (SNNP) (b), and Pani Muhan site in SNPP (c).

Three horizontal transects were established at a minimum distance of 500 m from each other at the study site. Along each transect, three quadrats of size 10 ×10 m were sampled keeping a minimum distance of 100 m between the two quadrats. Individuals of tree species in each plot were counted. The height and diameter at breast height (DBH) of trees were measured. Plant species were identified following Malla *et al.* (1986). Above- and below-ground tree biomass (AGTB and BGB) were calculated using the non-destructive allometric equation following Chave *et al.* (2005) for moist climates.

Above-ground tree biomass (AGTB) (kg/m^2) = $0.0509 \times \rho D^2 H$

Where, ρ = specific gravity of wood, D = diameter at breast height (DBH) in cm, H = height of tree in m. Below ground (root) biomass (BGB) (kg/m^2) was calculated by a root-to-shoot ratio value of (1:5) or 20% of AGTB (MacDicken 1997). AGTB was converted to kg ha^{-1}, and carbon stock above-ground and below-ground tree biomass carbon (AGTBCs) was calculated by multiplying biomass kg ha^{-1} by the carbon fraction factor 0.47.

Soil samples were collected during three seasons *viz.*, pre-monsoon (April-May), monsoon (July-August), and post-monsoon (November-December) from three depths (0-10, 10-20, and 20-30 cm) from the surface in the year 2022. Soil samples were cored from four corners and the center of each quadrat which were sampled for carbon estimation. The soils were then mixed to form a composite sample for each quadrat. A total of 81 composite soil samples (3 transects × 3 quadrats × 3 depth × 3 seasons) were collected in zipper bags and transported to the laboratory. The samples were air-dried under the shade and sieved through a 2 mm sieve before laboratory analyses.

The temperature of the soil was measured onsite. Moisture content, bulk density (BD), pH, and texture including other parameters were measured in the laboratory. Soil organic carbon (SOC) was estimated following Walkley and Black (1934) and soil organic matter (SOM) was calculated by multiplying the soil organic carbon content by 1.724. Soil organic carbon stock was determined by multiplying SOC by soil depth and bulk density. Total nitrogen (TN) was determined following the Kjeldhal method (Jackson 1967). Available phosphorus (AP) and available potassium (AK) were estimated following Bremer and Mulvaney (1982) and Olsen and Somers (1982), respectively.

The data sets were checked for normality before executing the statistical tests. The effects of sampling season, soil depths, and their interaction on soil physicochemical properties were assessed using Two-way analysis of variance (Two-way ANOVA) with post-hoc for multiple comparisons. Results were considered statistically significant at $p \leq 0.05$. All the analyses were performed using the Statistical Package for Social Science (SPSS Version 25)

Results and Discussion

Twenty-two tree species were found in the study site (Table 1). Among them, *Castanopsis* spp., *Quercus* spp., *Rhododendron arboretum, Saurauia nepaulensis, Schima wallichii, Alnus nepalensis, Pinus roxburghii, Lyonia ovalifolia* were the common tree species. A previous study in the Panimuhan site of SNPP identified a *Schima-Pinus-Alnus* plant community dominated by trees *Schima wallichii, Alnus nepalensis,* and *Pinus roxburghii* (Dhakal *et al.* 2024).

Both above- and below-ground tree biomass exhibited variations across these species in the study site. The AGTB ranged from 0.06to 151.28 t/ha, with a mean value of 21.96 ± 8.53 t/ha, while BGB ranged from 0.05 to 30.26 t/ha with a mean value of 4.39 ± 1.70 t/ha. Similarly, AGTBC ranged from 0.03 to 71.10 t/ha with a mean value of 10.32 ± 4.01 t/ha and BGBCs from 0.01 to 14.22 t/ha with a mean value of 2.06 ± 0.80 t/ha. The total AGTBC was found to be 227.09 t/ha, and BGBC contributed 45.42 t/ha (Table 1).

Table 1. Above and below-ground tree biomass and carbon stock of different tree species in the study site. BGB = below ground biomass; BGBC = below ground biomass carbon; AGTB = above-ground tree biomass; AGTBC = above-ground tree biomass carbon.

SN	Species	AGTB (t/ha)	BGB (t/ha)	Total biomass (t/ha)	AGTBCs (t/ha)	BGBCs (t/ha)	Total carbon stock (t/ha)
1	*Albizia julibrissin* Durazz.	1.17	0.23	1.40	0.55	0.11	0.66
2	*Alnus nepalensis* D. Don	64.90	12.98	77.88	30.5	6.10	36.6
3	*Betula alnoides* Buch.-Ham. Ex D.Don	0.53	0.11	0.64	0.25	0.05	0.30
4	*Castanopsis indica* (Roxb. ex Lindl.) A.DC.	0.51	0.10	0.61	0.24	0.05	0.29
5	*Castanopsis tribuloides* (Sm.) A.DC.	151.28	30.26	181.54	71.10	14.22	85.32
6	*Eriobotrya dubia* (Lindl.) Decne.	3.58	0.72	4.30	1.68	0.34	2.02
7	*Eurya acuminata* DC.	1.80	0.36	2.16	0.85	0.17	1.02
8	*Eurya japonica* Thunb.	0.31	0.06	0.37	0.14	0.03	0.17
9	*Fraxinus floribunda* C.K.Schneid.	16.78	3.36	20.14	7.89	1.58	9.47
10	*Lyonia ovalifolia* C.H.Curtis	0.06	0.01	0.07	0.03	0.01	0.04
11	*Lindera nacusua* (D.Don) Merr.	3.84	0.77	4.61	1.80	0.36	2.16
12	*Myrica esculenta* Buch.-Ham. ex D.Don	1.72	0.34	2.06	0.81	0.16	0.97
13	*Myrsine capitellata* Wall.	14.91	2.98	17.89	7.01	1.40	8.41
14	*Myrsine semiserrata* Wall.	0.25	0.05	0.30	0.12	0.02	0.14
15	*Pinus roxburghii* Sarg.	4.27	0.85	5.12	2.00	0.40	2.40
16	*Prunus cerasoides* Buch.-Ham. ex D.Don	55.47	11.09	66.56	26.07	5.21	31.28
17	*Prunus nepalensis* Jacques & Hérincq	1.47	0.29	1.76	0.69	0.14	0.83
18	*Pyrus pashia* Buch.-Ham. ex D.Don	50.02	10.00	60.02	23.51	4.70	28.21
10	*Quercus lamellose* Sm.	3.39	0.68	4.07	1.60	0.32	1.92
20	*Rhododendron arboretum* Sm.	0.72	0.14	0.86	0.34	0.07	0.41
21	*Saurauia napaulensis* DC.	1.31	0.26	1.57	0.62	0.12	0.74
22	*Schima wallichii* (DC.) Korth.	104.88	20.98	125.86	49.29	9.86	59.15
	Total	483.18	96.64	579.79	227.09	45.42	272.51
	Mean value with ± SE	21.96 ± 8.53	4.39 ± 1.70	23.68 ± 6.34	10.32 ± 4.01	2.06 ± 0.80	11.66 ± 3.81

Individually, *Castanopsis tribuloides* displayed the highest AGTB and BGB with the high value of carbon stock, followed by *S. wallichi* and *A. nepalensis* (Table 1). It could be due to the larger-sized tree species which consequently have higher biomass and carbon. Conversely, *Lyonia ovalifolia* was reported to have the least AGTB and BGB with the least carbon stock. The DBH showed a positive correlation with biomass and carbon stock (Salunkhe *et al.* 2018). Larger-sized trees, such as *C. tribuloides*, tend to store more carbon due to their greater biomass which underscores the importance of considering species-specific characteristics and biomass dynamics when evaluating carbon stocks in forest ecosystems. Hence, such trees contribute to increasing overall biomass and carbon sequestration capacity. The trees with lower AGTB and BGB, along with their reduced carbon stock highlight the significant impact of tree size on carbon storage capabilities. Besides carbon storage, both the larger and smaller-sized trees deposit organic carbon into the soil through leaf litter and root turnover, thus affecting soil carbon dynamics and soil physicochemical parameters.

The physical properties of the soil in different seasons and depths are summarized in Table 2. Results of two-way ANOVA indicated significant effects of season and depth on soil temperature and soil moisture (Table 2). The interactive effect of season and soil depth was also significant on soil temperature ($p < 0.001$), and soil moisture ($p < 0.01$). However, their interaction effect ($p > 0.05$) was not significant (Table 2). The soil temperature was the highest (24.22 ± 1.30) in the surface layer (0-10 cm) during the pre-monsoon season and the lowest (11.61 ± 1.00) in the same layer during the post-monsoon season. Overall soil temperature was in order: pre-monsoon > monsoon > post-monsoon. Regarding the effect of soil depth, the temperature was found to decrease with soil depths during both pre-monsoon and monsoon seasons but a reverse trend was found in the post-monsoon (Table 2). This suggests that the soil moisture and thermal conductivity variations during different seasons influence soil temperature profile.

There was high moisture content during the monsoon season at the depth of 10-20 cm (46.31 ± 0.78%) and the moisture was low (14.22 ± 0.58%) during the pre-monsoon season at the surface layer (0-10 cm). High BD was recorded in the 20-30 cm layer (1.57 ± 0.42 g/cm^3) during the pre-monsoon season, while it was 0.92 ± 0.06 g/cm^3 in the upper layer during post-monsoon (Table 2). An increasing trend of BD and moisture was found with soil depth. This result likely indicates compaction and enhanced water retention capacity at lower depths, which may be due to the accumulation of finer soil particles. Also, the weather of Nepal remains warm to hot during pre-monsoon and monsoon seasons while the post-monsoon season is relatively cool and dry. This difference in temperature along soil depth can be attributed to the elevated air temperatures during these seasons, which led to the warming of the upper soil layer (Bajracharya *et al.* 2023). A decrease in air temperature in the post-monsoon season may also result in a cooling effect on the surface soil layer.

Similarly, the occurrence of maximum rainfall during the monsoon season is responsible for higher soil moisture content in the soil. The higher moisture content in the lower depth could be attributed to the infiltration process of rainwater and litter and canopy cover of the forest. A high BD value in 20-30 cm depth might be due to various factors including less SOM and high soil compaction. Baumert *et al.* (2018) reported that the deeper layers of the soil have more compaction, less SOM, and less aggregation. Gautam and Chettri (2020) reported an increased bulk density in deeper soil layers. Tanveera *et al.* (2016) highlighted that higher SOM enhances the soil structure, porosity, and water-holding capacity, making the soil more fertile and less compact. Similarly, Boyle *et al.* (1989) reported that various chemical exudates from roots and microbes (for example: glomalin, polysaccharides, organic acids, etc.) present in SOM enhance soil aggregation. The current study also reported high SOM on the upper soil layer (Table 3) indicating the influence of SOM on BD and other soil parameters.

Overall soil texture of the study site was found sandy loam. Sandy loam soil texture is common in forest ecosystems along tropical to subtropical regions of Central Nepal (Khadaka *et al.* 2018). This study reported a high percentage of sand (65.77 ± 1.90%) and silt (26.63 ± 2.60%) in the 20-30 cm depth during the pre-monsoon, while the highest clay particle (14.83 ± 0.65%) was measured in the 0-10 cm during the post-monsoon. Similarly, the lowest percentage of sand (62.46 ± 2.43) was found during the pre-monsoon at 0-10 cm depth. Sand and silt decreased with soil depth, while clay particles increased with soil depth. Season and depth had no significant effect on sand particles ($p > 0.05$) but silt and clay particles varied significantly with depth ($p < 0.001$) (Table 2). The percentages of sand and silt were increased and the percentage of clay decreased with soil depth. This suggests that the finer soil fractions accumulate deeper in the soil

Table 2. Soil physical properties of different seasons and depths and two-way ANOVA statistics. The mean values are ± SD.

Season	Depth (cm)	Temperature (°C)	Moisture (%)	BD (g/cm3)	Sand (%)	Silt (%)	Clay (%)
Pre-monsoon	0-10	24.22 ± 1.30^{Aa}	14.22 ± 0.58^{Cc}	0.93 ± 0.07^{Ab}	62.46 ± 2.43^{Aa}	25.21 ± 2.80^{Ab}	12.31 ± 0.69^{Aa}
	10-20	21.94 ± 0.82^{Ab}	16.79 ± 1.20^{Cb}	1.20 ± 0.13^{Ab}	64.70 ± 1.70^{Aa}	26.16 ± 2.90^{Aa}	9.13 ± 1.80^{Ab}
	20-30	21.00 ± 0.75^{Ab}	18.17 ± 0.92^{Ca}	1.57 ± 0.42^{Aa}	65.77 ± 1.90^{Aa}	26.79 ± 2.80^{Aa}	7.54 ± 1.90^{Ab}
Monsoon	0-10	22.61 ± 1.10^{Ba}	46.31 ± 0.78^{Ab}	0.95 ± 0.07^{Ab}	62.90 ± 2.00^{Aa}	23.66 ± 2.60^{Aa}	13.42 ± 0.86^{Aa}
	10-20	21.11 ± 0.74^{Ab}	47.04 ± 0.99^{Aab}	1.00 ± 0.07^{Ab}	63.63 ± 2.00^{Aa}	25.20 ± 2.50^{Aa}	11.05 ± 1.30^{Aa}
	20-30	18.83 ± 0.66^{Bc}	47.78 ± 1.40^{Aa}	1.30 ± 0.22^{Aa}	64.72 ± 1.90^{Aa}	26.63 ± 2.60^{Aa}	8.74 ± 1.50^{Ab}
Post-monsoon	0-10	11.61 ± 1.00^{Cc}	25.12 ± 1.10^{Bb}	0.92 ± 0.06^{Ac}	63.19 ± 0.75^{Aa}	21.97 ± 0.06^{Aa}	14.83 ± 0.65^{Aa}
	10-20	14.16 ± 0.90^{Bb}	26.59 ± 0.73^{Ba}	1.11 ± 0.14^{Ab}	64.00 ± 0.71^{Aa}	22.62 ± 1.50^{Ab}	13.37 ± 1.20^{Aa}
	20-30	16.50 ± 0.66^{Ca}	27.46 ± 0.81^{Ba}	1.39 ± 0.04^{Aa}	65.10 ± 0.70^{Aa}	23.30 ± 1.80^{Aa}	11.59 ± 1.80^{Ab}
Two way ANOVA	Season	$F = 612.72$	$F = 6649.14$	$F = 4.75$	$F = 0.467$	$F = 1.39$	$F = 0.71$
		$p < 0.001$	$p < 0.001$	$p = 0.012$	$p = 0. 629$	$p = 0.255$	$p = 4.91$
	Depth	$F = 3.92$	$F = 46.41$	$F = 50.82$	$F = 2.97$	$F = 10.02$	$F = 16.92$
		$p = 0.024$	$p < 0.001$	$p < 0.001$	$p = 0.057$	$p < 0.001$	$p < 0.001$
	Season × depth	$F = 62.74$	$F = 3.88$	$F = 1.68$	$F = 1.08$	$F = 0.30$	$F = 0.64$
		$p < 0.001$	$p = 0.007$	$p = 0.391$	$p = 0.369$	$p = 0.875$	$p = 0.632$

Different uppercase letters along the columns indicate significant differences across seasons of the same depth, and lowercase letters indicate significant differences across depths of the same season. Values are means ± SD (n = 9). BD: bulk density.

Table 3. Soil chemical properties of different seasons and depths and two-way ANOVA statistics. The mean values are ± SD.

Season	Depth (cm)	pH	SOC (%)	SOM (%)	SOCs (t/ha)	TN (%)	AP (kg/h)	AK (kg/h)
Pre-monsoon	0-10	5.61 ± 0.20^{Ba}	4.05 ± 0.17^{Ba}	6.97 ± 0.29^{Ba}	37.80 ± 03.84^{Ba}	0.20 ± 0.03^{Ba}	36.12 ± 04.53^{Aa}	140.32 ± 06.10^{Ba}
	10-20	5.77 ± 0.30^{Aa}	3.32 ± 0.23^{Bb}	5.71 ± 0.39^{Bb}	40.11 ± 05.69^{Ba}	0.12 ± 0.01^{Bb}	20.29 ± 03.55^{Ab}	111.49 ± 23.78^{Bb}
	20-30	5.64 ± 0.23^{Aa}	2.34 ± 0.09^{Bc}	4.03 ± 0.16^{Bc}	36.67 ± 08.88^{ABa}	0.10 ± 0.00^{Ab}	09.48 ± 02.19^{Bc}	57.69 ± 10.98^{Ac}
Monsoon	0-10	5.01 ± 0.26^{Ca}	4.39 ± 0.19^{Aa}	7.55 ± 0.33^{Aa}	41.80 ± 03.50^{Aa}	0.31 ± 0.09^{Aa}	38.37 ± 12.64^{Aa}	194.81 ± 16.60^{Aa}
	10-20	5.26 ± 0.20^{Ba}	4.14 ± 0.11^{Aa}	7.13 ± 0.20^{Aa}	41.81 ± 03.34^{Aa}	0.25 ± 0.07^{Aa}	31.93 ± 08.72^{Aab}	116.08 ± 12.09^{Ab}
	20-30	5.21 ± 0.30^{Ba}	3.370 ± 0.32^{Ab}	5.80 ± 0.55^{Ab}	44.17 ± 11.05^{Aa}	0.15 ± 0.06^{Ab}	25.04 ± 05.46^{Ab}	61.58 ± 09.45^{Ac}
Post-monsoon	0-10	6.14 ± 0.40^{Aa}	3.88 ± 0.14^{Ba}	6.68 ± 0.25^{Ba}	35.81 ± 02.36^{Bab}	0.11 ± 0.01^{Ca}	29.42 ± 06.01^{Aa}	138.46 ± 23.50^{Ba}
	10-20	5.21 ± 0.31^{Cb}	3.68 ± 0.55^{Ba}	6.34 ± 0.95^{Ba}	41.02 ± 07.57^{Ba}	0.11 ± 0.01^{Ca}	23.28 ± 04.62^{Aa}	108.53 ± 18.37^{Bb}
	20-30	5.36 ± 0.26^{ABb}	2.21 ± 0.45^{Bb}	3.80 ± 0.78^{Bb}	30.68 ± 05.80^{Bb}	0.11 ± 0.04^{Aa}	13.79 ± 04.99^{Bb}	52.77 ± 08.62^{Ac}
Two-way ANOVA	Season	$F = 27.42$	$F = 53.13$	$F = 53.24$	$F = 7.75$	$F = 41.73$	$F = 19.82$	$F = 19.12$
		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Depth	$F = 3.50$	$F = 178.3$	$F = 178.6$	$F = 2.46$	$F = 17.66$	$F = 54.03$	$F = 279.7$
		$p = 0.035$	$p < 0.001$	$p < 0.001$	$p = 0.009$	$p < 0.001$	$p < 0.001$	$p < 0.001$
	Season × depth	$F = 12.37$	$F = 6.33$	$F = 6.33$	$F = 2.25$	$F = 5.87$	$F = 2.96$	$F = 9.93$
		$p < 0.001$	$p < 0.001$	$p < 0.001$	$p = 0.072$	$p < 0.001$	$p = 0.025$	$p < 0.001$

Different uppercase letters along the columns indicate significant differences across seasons of the same depth, and lowercase letters indicate significant differences across depths of the same season. Values are means ± SD (n = 9). SOC: soil organic carbon, SOM: soil organic matter, SOCs: soil organic carbon stock, TN: total nitrogen, AP: available phosphorus, AK: available potassium.

profile, potentially due to differential erosion or deposition process. These results align with those of Gautam and Mandal (2013) who also reported similar patterns.

The SOC, SOM, TN and AK were significantly influenced by seasons, soil depths, and their interactions ($p < 0.001$) (Table 3). The contents of soil nutrients were high in the upper layer (0-10 cm) during monsoon, but the values decreased with increasing depth (10-30 cm). Moreover, the season appeared as the factor significantly affecting SOC ($p < 0.001$). However, soil depth and the interaction between depth and season did not show a significant effect on soil chemical properties ($p > 0.05$) (Table 3). It shows seasonal nutrient mobilization and surface accumulation, suggesting the influence of seasonal factors.

The highest mean value of SOC (44.17 ± 11.05 t/ha) was found in the layer of 20-30 cm during the monsoon and the lowest value was recorded in the post-monsoon (30.68 ± 05.80 t/ha) at a similar depth (Table 3). Likewise, soil depth showed a strong influence on available phosphorus ($p < 0.001$), and the interaction effect of soil depth and season was also found to be significant ($p < 0.05$) indicating that variation of AP is influenced by both soil depth and season (Table 3). The AP exhibited its peak value (38.37 ± 12.64 kg/h) during the monsoon season at 0-10 cm depth. Conversely, the lowest value (09.48 ± 02.19 kg/h) was found during the pre-monsoon season at a depth of 20-30 cm; these values declined with increasing depth (Table 3). This results highlights how phosphorus availability is affected by both the soil profile and seasonal changes.

The surface layer (topsoil) tends to accumulate more organic matter due to the decomposition of plant residues (Hoffland *et al.* 2020). This accumulation enriches the surface soil with organic carbon, nitrogen, and other nutrients. Hoffland *et al.* (2020) also reported that the surface layer of the soil receives more SOM inputs from plant litter. The moisture is positively correlated with SOC, SOM, TN and AP (Lei *et al.* 2019). Organic matter in the soil acts as a sponge, improving soil structure by creating aggregates and increasing pore spaces. These pores can hold water, enhancing the soil's water-holding capacity (Parajuli and Duffy 2013), and moisture content also enhances soil microbial activity and organic matter decomposition, which increase the concentration of nitrogen, and phosphorus in the soil (Curtin *et al.* 2012).

The soil nutrients in the current study showed their decreased concentration with increasing soil depth. SOM was found to be decreased in deeper soil layers which reflects reduced microbial activities in deeper regions (Table 3). These results are in support of the findings of many previous studies by Gautam and Mandal (2013) and Gautam and Chettri (2020) who highlighted the depth-wise decrease of soil nutrients. In addition, the SOM, SOC and TN are positively correlated with each other and with SOC stock (Sigdel *et al.* 2015).

In the present study, the surface layer (0-10 cm) was found to be more responsive to seasonal variation. This could be attributed to its direct exposure to environmental factors such as temperature, precipitation, and other climatic variables. Babur and Dindaroglu (2020) also described that the surface layer of the soil is more influenced by seasonal changes in temperature and moisture because it is more exposed to change in the atmospheric conditions, such as solar radiation, air temperature, precipitation, and wind. Previous studies by Lepcha and Devi (2020) also found high values of soil physicochemical parameters in different ecosystems during the monsoon season. This suggests that both the seasonal variations and different soil depths under investigation had significant effects on the measured soil attributes.

In conclusion, *Castanopsis tribuloides* exhibited the highest values of above and below-ground tree carbon stock, while *Lyonia ovalifolia* showed the lowest. The total tree carbon stock of the study area was 272.51 t/ha. Similarly, seasonal variations and soil depths had significant effects on measured soil attributes. The pre-monsoon season exhibited the highest temperatures, which generally decreased with soil depth. Monsoon season showed maximum soil moisture, while bulk density peaked during the pre-monsoon period and increased with depth. The soil texture was found to be sandy loam. The pH levels indicated the slightly acidic soil which changed with season and depths. Furthermore, key soil components such as soil organic carbon, soil organic matter, soil carbon stock, total nitrogen, available phosphorus, and available potassium reached their highest concentrations during the monsoon season at the topsoil layer, gradually declining with depth. The present research emphasizes the significance of the monsoon season and upper soil layers in influencing soil physicochemical properties, providing valuable insights into forest soil ecology leading to forest conservation and management.

Acknowledgments

University Grants Commission, Nepal is acknowledged for providing research fellowship to the first author. Department of National Parks and Wildlife Conservation, Nepal provided research permissions. Special thanks go to Mr. Nabin Lamichhane for his invaluable assistance in both field and laboratory work.

References

Adhikari K and Hartemink AE 2016. Linking soils to ecosystem services - A global review. Geoderma **262**, 101-111.Ahmed A, Ahmed T and Ataullah M 2021. Carbon stock of different parts of major plant species of three ecological zones of Bangladesh sundarbans. Bangladesh J. Bot. **50**(2): 373-385.

Alam MA, Yeasin M and Ahmed A 2024. Carbon pool and respiration of rhizosphere soils of different mangrove plant species in bangladesh sundarbans. Bangladesh J. Bot. **53**(1): 131-140.

Ataullah M, Chowdhury MMR, Hoque S and Ahmed A 2017. Physico-chemical properties of soils and ecological zonations of soil habitats of Sundarbans of Bangladesh. Int. J. Pure Appl. Res. **1**(1): 80-93.

Babur E and Dindaroglu T 2020. Seasonal changes of soil organic carbon and microbial biomass carbon in different forest ecosystems. In: Uher I editors. Environmental Factors Affecting Human Health; Crotia: IntechOpen. pp. 231-258.

Bajracharya SR, Pradhananga S, Shrestha AB and Thapa R 2023. Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, J. Hydrol. Reg. Stud. **45**(1): 101316.

Baumert VL, Vasilyeva NA, Vladimirov AA, Meier IC, Kogel-Knabner I and Mueller CW 2018. Root exudates induce soil macro aggregation facilitated by fungi in the subsoil. Front. Environ. Sci. **6**(11): 1-17.

Boyle M, Frankenberger WT and Stolzy LH 1989. The influence of organic matter on soil aggregation and water infiltration. J. Prod. Agric. **2**(4):290-299.

Bremner JM and Mulvaney CS 1982. Nitrogen-total. In: Methods of soil analysis, Page AL (Eds). pp. 595-624. Amer. Soc. Agronom., USA.

Brockerhoff EG, Barbaro L, Castagneyrol B, Forrester DI, Gardiner B, González-Olabarria JR, Lyver POB, Meurisse N, Oxbrough A, Taki H and Thompson ID 2017. Forest biodiversity, ecosystem functioning, and the provision of ecosystem services. Biodivers. and Conserv. **26:** 3005-3035.

Chave J, Andalo C, Brown S, Cairns MA, Chambers JQ, Eamus D, Folster H, Fromard F, Higuchi N, Kira T, Lescure JP, Nelson BW, Ogawa H, Puig H, Riéra B and Yamakura T 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia **145**: 87–99

Curtin D, Beare MH and Hernandez-Ramirez G 2012. Temperature and moisture effects on microbial biomass and soil organic matter mineralization. Soil Sci. Soc. Am. J. **76**(4): 55-67.

Dhakal TM, Thapa LB, Yadav RKP and Pokhrel CP 2024. Plant communities in Shivapuri-Nagarjun National Park, Central Nepal. Banko Janakari **33**(2): 11–23

Freschet GT, Cornwell WK, Wardle DA, Elumeeva TG, Liu W, Jackson BG, Vadimir GO, Nadejda A, Soudzilovskaia JT and Johannes HC 2013. Linking litter decomposition of above-and below-ground organs to plant–soil feedbacks worldwide. J. Ecol. **101**(4): 943-952. 10.1111/1365-2745.12092

Gautam B and Chettri MK 2020. Physicochemical properties of tropical forest topsoil in relation to depth in Western, Nepal. Banko Jankari **30**(1): 39-68.

Gautam T and Mandal TN 2013. Soil characteristics in the moist tropical forest of Sunsari, District, Nepal. Nepal J. Sci. Tech. **14**(1): 35-40.

Hoffland E, Kuyper TW, Comans RNJ and Creamer RE 2020. Eco-functionality of organic matter in soils. Plant Soil. **455**(1): 1-6.

Jackson ML 1967. Soil chemical analysis. Prentice Hall of India Pvt. Ltd., New Delhi. pp. 498.

Khadka D, Lamichhane S, Timilsina AP, Baral BR, Sah K, Joshi BD, Joshi S and Adhikari P 2018. Soil physicochemical characterization in the different soil layers of National Maize Research Program, Rampur, Chitwan, Nepal. J. Maize Res. Dev. **3**(1): 28-44.

Kumar P, Kumar A, Patil M, Hussain S and Singh AN 2024. Factors influencing tree biomass and carbon stock in the Western Himalayas, India. Front. for. glob. Change. **6**: 1328694.

Lei Z, Yu D, Zhou F, Zhang Y, Yu D, Zhou Y and Han Y 2019. Changes in soil organic carbon and its influencing factors in the growth of *Pinus sylvestris* var. *mongolica* plantation in Horqin Sandy Land, Northeast China. Sci. Rep. **9**(1):1-12.

Lepcha NT and Devi NB 2020. Effect of land use, season, and soil depth on soil microbial biomass carbon of Eastern Himalayas. Ecol. Process. **9**(1): 54-58.

MacDicken K 1997. A Guide to Monitoring carbon Storage in Forestry and Agroforestry Projects. Winrock Int. Instit. Agricult. Develop.

Malla SB, Rajbhandary SB, Shrestha, TB, Adhikari PM and Adhikari SR 1986. *Flora of Kathmandu Valley*. Ministry of Forests and Soil Conservation, Depart. Medicin. Plants, Kathmandu, Nepal.

Olsen SR and Sommers LE 1982. Phosphorus. In: Methods of Soil Analysis Part 2, Page AL (Eds) pp. 159-165. Amer. Soc. Agronom., USA.

Parajuli PB and Duffy S 2013. Evaluation of soil organic carbon and soil moisture content from agricultural fields in Mississippi. Open J. Soil Sci. **3**(2): 81-90.

Propa MJ, Hossain MI and Ahmed A 2021. Carbon stock and respiration of rhizosphere soils of Sal (*Shorea Robusta* Roxb. Ex. Gaertn. F.) in relation to some environmental variables of different Sal forest stands of Bangladesh. Bangladesh J. Bot. **50**(3): 685-693.

Rodrigues PMS, Schaefer CEGR, de Oliveira Silva J, Ferreira Júnior WG, dos Santos RM and Neri AV 2018. The influence of soil on vegetation structure and plant diversity in different tropical savannic and forest habitats. J. Plant Ecol. **11**(2): 226-236.

Salunkhe O, Khare PK, Kumari R and Khan ML 2018. A systematic review on the aboveground biomass and carbon stocks of Indian forest ecosystems. Ecol. Process. **7**: 1-12.

Sigdel RS, Dipesh R, Upendra B, Lekhendra T, Ranjan A and Dahal S 2015. Physicochemical characteristics of soil along an altitudinal gradient at the southern aspect of Shivapuri Nagarjun National Park, Central Nepal. Int. Res. J. Earth Sci. **3**(2): 1- 6.

Sinore T, Chernet M, Detamo K and Yohannes M 2022. Effect of soil management practices on soil physico-chemical properties: A case of Wera Sub-Watershed, Southern Ethiopia. Appl. Environ. Soil Sci. **2022**: 5370477

SNNP 2017. Shivpuri Nagarun National Park and Buffer Zone Management Plan Fiscal year 2074/075-079-080 (2017/018-2021-022). Available in https://dnpwc.gov.np/media/publication/Management_Plan_2075_Shivapuri.pdf

Tanveera A, Kanth TA, Tali PA and Naikoo M 2016. Relation of soil bulk density with texture, total organic matter content, and porosity in the soils of Kandi area of Kashmir valley, India. Int. Res. J. Earth Sci. **4**(1): 1-6.

Walkley A and Black LA 1934. An Examination of the determining method for determining organic soil matter and proposed modification of the chromic acid titration method. Soil Sci. **37**: 29-38.

Whitehead D 2011. Forests as carbon sinks—benefits and consequences. Tree Physiol. **31**(9): 893-902.

(Manuscript received on 25 May, 2024; revised on 18 September, 2024)