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Soil physicochemical properties and microbial biomass in agriculture and abandoned lands of Shivapuri-Nagarjun National Park, Kathmandu, Nepal

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ABSTRACT

Evaluating soil physicochemical and biological properties helps us to understand ecosystem functions and nutrient dynamics. This study assessed the physicochemical and microbial properties of soil in agricultural and abandoned lands within Shivpuri-Nagarjun National Park, Nepal. Soil samples were collected from both agricultural and abandoned lands at soil depths of 0-10, 10-20, and 20-30 cm during the pre-monsoon, monsoon, and post-monsoon seasons. The physicochemical parameters of the soil were analyzed using standard protocols. The chloroform fumigation extraction method was used for determining microbial biomass carbon and nitrogen. Soil temperature decreased with increasing depth during both the pre-monsoon and monsoon seasons but increased with depth during the post-monsoon season. Agricultural land exhibited higher proportions of silt and clay, whereas abandoned land was characterized by a higher sand content. In agricultural soils, soil organic carbon was 2.63%, total nitrogen and available phosphorus were 0.21% and 72.16 kg ha^{-1}, respectively, while available potassium was 636.55 kg ha^{-1}. These nutrient levels peaked during the monsoon season and declined with increasing soil depth. Similarly, microbial biomass carbon (465.82 µg g^{-1}) and nitrogen (48.58 µg g^{-1}) were also higher in agricultural land, showing a decreasing trend with depth. The microbial biomass carbon-to-nitrogen ratio ranged from 9.61 to 19.41. The first (PC1) and second (PC2) components of Principal Component Analysis (PCA) accounted for 35.5% and 12.4% of the total variance, respectively. Overall, agricultural land, upper soil layers, and the monsoon season were identified as the most influential factors contributing to improved soil characteristics.

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1. INTRODUCTION

The pedosphere is the most active and vital layer of the Earth's surface (Herreño et al., 2023). Soil is an important natural resource, which provides numerous ecosystem services, supports plant growth and development, retains water, and nutrient cycling (Anikwe & Ife, 2023). The physicochemical properties of soil determine soil quality and provide information about the capacity of soil to supply mineral nutrients (Amgain et al., 2020; Nepal & Mandal, 2018). Similarly, soil microorganisms play a crucial role in maintaining soil biochemical properties and ecosystem functions (Dobrovol'skaya et al., 2015), soil organic matter processes (Nguyen-Sy et al., 2022) and formation of soil structure (Chandra et al., 2016). Soil microbial biomass, hence, is a dynamic labile pool of plant-available nutrients (Yokoyama et al., 2017). However, changes in practices on land use and management can affect soil physicochemical or biological properties (Abera & Belachew, 2011; Novara et al., 2017). Therefore, the results of soil mapping illustrate the distribution of soil fertility, which can help maintain soil fertility and improve land management (Suntoro et al., 2024).

Abandonment of agricultural lands is a significant phenomenon of land-use change with profound ecological and environmental consequences. It was estimated that the global area of farmland abandonment accounts for around 8-

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10% of the world's total cultivated area (Campbell et al., 2008). Urbanization and industrialization have created a significant gap in income between the agricultural and non-agricultural sectors, leading to widespread abandonment of farmlands (Zhou et al., 2019). Agricultural activities in rural areas have declined significantly due to the outmigration of people to urban areas for employment, better education, and other amenities. Several studies have indicated that, on average, 37% of arable land in Nepal is abandoned (Dahal et al., 2020; Ojha et al., 2017).

Agricultural land abandonment is particularly pronounced in the buffer zones surrounding national parks, largely due to human–wildlife conflicts and restrictive park policies that limit resource use and traditional land management practices (Silwal et al., 2022). Soil infertility and degradation of soil quality may also contribute to land abandonment within park premises. Shivapuri-Nagarjun National Park (SNNP), situated near the capital city, Kathmandu, is a forested area, which comprises the majority of land cover (74.45%), followed by shrubland (20.45%), abandoned land (3.22%), and agricultural land (1.8%) (SNNP, 2017). This indicates that a significant area of land within the park has been abandoned, which was previously cultivated. However, studies regarding the causes and consequences of abandonment remain limited.

Previous studies in the national park have focused on vegetation (Dhakal et al., 2023), insects (Budhathoki et al., 2021), birds and wild mammals (Poudyal et al., 2023), and soil organic carbon (Shapkota & Kafle, 2021). These studies provide critical insights into vegetation, biodiversity, and ecosystem functioning, which could be helpful for sustainable forest management practices. In addition, analyzing the soil characteristics of abandoned and agricultural land is important for soil fertility assessment, understanding soil degradation processes, land restoration planning, and environmental impact assessment (Paudel et al., 2014). This study aims to assess the physicochemical properties and microbial biomass in the soils of agricultural and abandoned lands within the SNNP, taking into account seasonal variations and soil depth gradients.

2. MATERIALS AND METHODS

2.1. Study site

This study was carried out in Shivapuri-Nagarjun National Park (SNNP). The National Park is located in the mid-hill region towards the northern side of the Kathmandu Valley, Nepal (Fig. 1). There are two villages, where the study was confined within the National Park (i) Okhreni (27°79'53''N, 85°42'14''E; elevation 1950 m) and (ii) Chilauni (27°79'36''N, 85°42'18''E; elevation 1976 m). The area experiences a subtropical monsoon climate, with temperature range of 2°C to 17°C during the winter season and 19°C to 30°C during the summer, and the mean annual rainfall is 2,727 mm (SNNP, 2017).

The villages contain abundant agricultural lands, including both actively farmed areas and abandoned traces of past cultivation. Common crops like maize, wheat, millet, mustard, beans, etc. were grown in the agricultural fields. Seasonal vegetables are also grown alongside these staple crops. In contrast, the abandoned lands lack significant vegetation and are primarily used for grazing and forage collection.

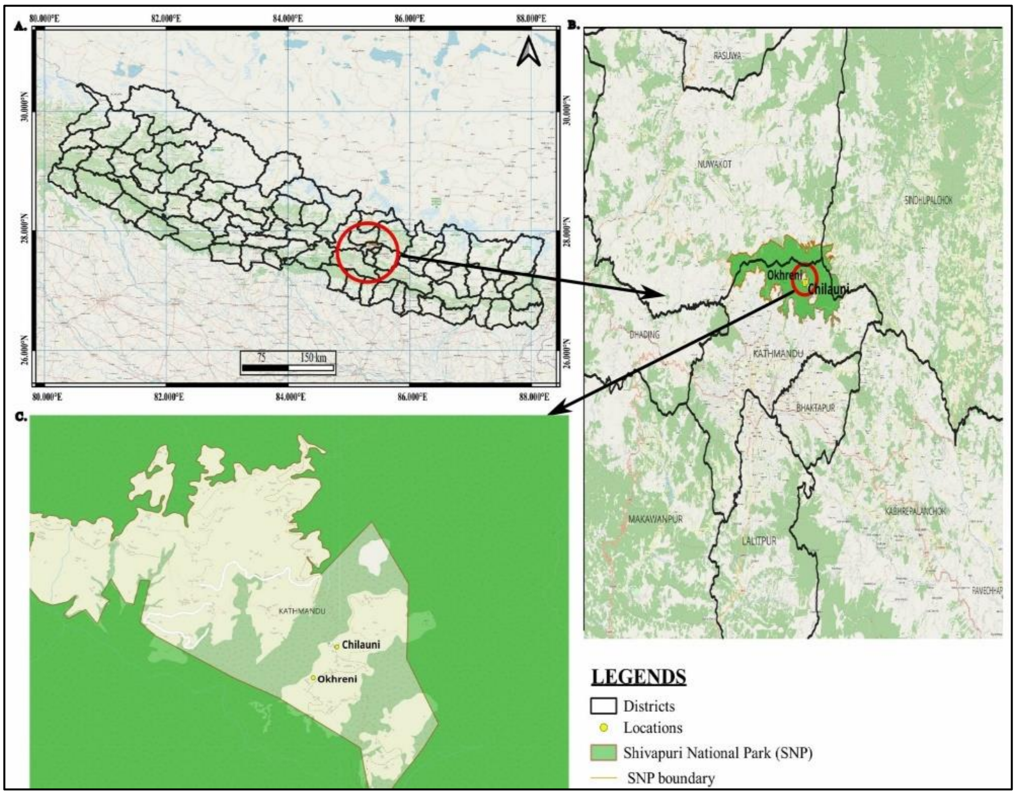

Figure 1. Map of the study site (a) Nepal showing Kathmandu district, (b) Kathmandu district showing SNNP, and (c) SNNP showing the study site.

Table 1. Soil physical properties in different land use types across seasons and soil depths.

Land use type	Seasons	Depths (cm)	Temperature (°C)	Moisture (%)	BD (gcm^{-3})	Sand (%)	Silt (%)	Clay (%)
Agricultural land	Pre-monsoon	0-10	28.81± 0.89αaA	14.18±4.64αbC	1.23±0.18βaA	63.32±0.76βaA	22.88±1.05αaB	13.78±0.89αaA
		10-20	27.07±0.82αbA	17.14±4.36αaC	1.23±0.17βaA	62.89±0.82βaA	23.68±2.00αaA	13.63±1.12αaA
		20-30	22.77±1.39αcA	18.71±3.25αaB	1.36±0.08αaA	62.42±1.23αaA	24.08±1.90αaA	13.71±1.14αaA
	Monsoon	0-10	27.61 ±0.99αaB	40.13±5.16αaA	0.95±0.77αbB	63.09±0.66βaA	24.90±0.79αaA	12.22±0.93αcB
		10-20	23.14±0.50αbB	41.15±6.16αaA	1.07±0.18αabA	63.57±0.49βaA	22.09±1.25αbA	14.55±1.07αbA
		20-30	22.03±1.21αbA	40.68±8.17αaA	1.16±0.18βaB	63.02±1.01αaA	20.83±.128αcB	15.85±0.94αaB
	Post-monsoon	0-10	13.77±0.97αbC	22.99±12.49αbA	1.03±0.08αbB	63.60±0.80βaA	25.66±0.85αaA	10.73±0.73βbC
		10-20	16.77±0.66αaC	23.93±6.31αabB	1.12±0.15bA	63.01±0.66αaA	23.42±1.46αbA	13.33±1.29αaA
		20-30	17.66±1.00βaB	24.64±11.14αaB	1.32±0.12αaAB	62.90±0.69αaA	23.16±1.58αbA	14.04±1.50αaA
Abandoned land	Pre-monsoon	0-10	29.77±0.14αaA	12.29±2.19αbC	1.50±0.15αcA	66.01±1.24αaA	21.37±1.13βaA	12.05±0.93αbA
		10-20	26.50±0.86αaA	13.55±7.96αaB	1.57±0.12αbA	64.66±1.0αbA	21.74±1.38βaB	13.59±0.86αaA
		20-30	23.11±1.16αbA	16.23±4.28αaB	1.68±0.08βaA	63.69±0.88βbA	22.50±1.59αaAB	13.69±1.19αaA
	Monsoon	0-10	27.77±1.39αaB	32.44±6.21βaA	0.99±0.06αcB	66.10±0.84αaA	22.11±0.62βaA	11.87±0.62αbA
		10-20	22.17±1.39αbB	37.34±6.20αaA	1.19±0.12αbB	64.56±0.84αbA	22.09±0.80αaB	13.44±1.31αaA
		20-30	19.22±0.83βcB	38.95±12.96αaA	1.44±0.19αaB	64.10±1.19αbA	21.69±1.28αaB	13.87±0.87βaA
	Post-monsoon	0-10	10.33±1.22βcC	18.66±5.59αaB	1.02±0.14αcB	65.18±0.68αaA	22.48±1.60βcA	12.77±0.73αbA
		10-20	16.36±2.60αbC	18.80±7.67αaB	1.25±0.12αbB	62.31±1.12αbB	24.11±1.19aA	13.57±0.98αabA
		20-30	19.38±0.88αaB	18.11±4.93αaB	1.34±0.23αaB	61.90±1.24αbB	23.63±1.77αbA	14.46±1.21αaA

Three-way ANOVA	Temperature F value	Temperature *p* value	Moisture F value	Moisture *p* value	BD F value	BD *p* value	Sand F value	Sand *p* value	Silt F value	Silt *p* value	Clay F value	Clay *p* value
Land use (LU)	8.57	0.004	2.19	0.141	62.78	0.001	66.07	0.001	21.64	0.001	3.01	0.085
Season (S)	1119.6	0.001	106.58	0.001	65.62	0.001	14.02	0.001	16.24	0.001	2.93	0.056
Depth (D)	49.415	0.001	12.23	0.001	51.05	0.001	38.79	0.001	2.54	0.082	54.82	0.001
LU×S	4.947	0.008	3.27	0.041	10.64	0.001	17.89	0.001	2.51	0.085	14.05	0.001
LU×D	0.671	0.513	2.79	0. 064	2.90	0.058	18.24	0.001	12.34	0.001	0.84	0.434
S×D	186.04	0.001	4.96	0.001	2.55	0.042	2.45	0.048	7.11	0.001	5.09	0.001
LU×S×D	14.33	0.001	1.98	0.100	0.82	0.509	0.68	0.602	3.95	0.004	5.04	0.001

Remarks: Values are mean ± SE. Different alphabets 'a, b, c' represent the significant differences across depths within the season; 'A, B, C' represent the significant differences across seasons within the same depth (One-way ANOVA); and 'α, β' represent significant differences between land use types within the same season and depth (independent sample t-test); BD: Bulk density, LU: Land use, S: Seasons, D: depth.

Table 2. Chemical properties of soil among land use types across seasons and soil depths.

Land use type	Seasons	Depths (cm)	pH	SOC %	TN %	AP (kg ha^{-1})	AK (kg ha^{-1})
Agricultural land	Pre-monsoon	0-10	4.97±0.33βaB	2.59±0.32αaA	0.20±0.16αaA	57.41±22.09αaA	491.20±40.74αaB
		10-20	5.13±0.32αaC	2.40±0.36αaA	0.19±0.04αaA	42.86±21.41αbB	404.97±47.15αabB
		20-30	5.13±0.25αaB	1.83±0.64αbA	0.18±0.07αaA	46.76±25.31αbAB	321.33±15.38αbAB
	Monsoon	0-10	6.21±0.19βaA	2.63±0.23αaA	0.21±0.05αaA	72.16±15.91αaA	636.55±44.25αaA
		10-20	6.22±0.08βaA	2.26±0.43αabA	0.16±0.05αabB	64.08±9.85αabA	473.42±51.67αabA
		20-30	6.17±0.17βaA	1.88±0.41αbA	0.15±0.05bαAB	56.44±8.06αbA	435.28±43.68αbA
	Post-monsoon	0-10	5.83±0.46αaA	2.26±0.37αaA	0.14±0.04αaA	36.69±4.31βaB	260.03±29.36αaC
		10-20	5.84±0.37αaB	1.91±0.48αbA	0.13±0.05αaC	33.13±9.85αaB	237.54±25.05αbC
		20-30	5.97±0.45αaA	1.88±0.75αbA	0.10±0.03αbB	34.40±5.67αaB	222.92±19.01αbB
Abandoned land	Pre-monsoon	0-10	5.08±0.15αbC	1.56±0.28βaA	0.12±0.06βaB	51.09±11.53βaA	388.06±67.37βaA
		10-20	5.21±0.15αaC	1.37±0.19βabA	0.08±0.05βbB	34.22±3.82αbA	287.55±40.46βbA
		20-30	5.34±0.20αaC	1.28±0.03βbA	0.08±0.07βbA	31.13±11.39αbA	287.44±34.92βbA
	Monsoon	0-10	6.43±0.07αaA	1.57±0.40βaA	0.15±0.05βaA	53.84±6.37αaA	402.45±25.34βaA
		10-20	6.43±0.05αaA	1.39±0.14βabA	0.12±.06αabA	32.79±3.65βbA	320.23±38.00βbA
		20-30	6.48±0.03αaA	1.11±0.12βbAB	0.09±0.03βbA	31.12±3.23βbA	253.88±33.37βcA
	Post-monsoon	0-10	5.62±0.26αbB	1.50±0.39βaA	0.11±0.02αaB	46.23±11.76αaA	258.31±35.62αaB
		10-20	5.87±0.20αabB	1.24±0.35βabA	0.12 ±0.04αaA	35.45±8.56αbA	216.09±36.12αabB
		20-30	5.95±0.20αaB	0.92±0.51βaB	0.10±0.04αaA	29.29±5.67αbA	186.13±49.81αbB

Three- way ANOVA		pH F value	pH *p* value	SOC % F value	SOC % *p* value	TN % F value	TN % *p* value	AP F value	AP *p* value	AK F value	AK *p* value
	Land Use (LU)	6.74	0.010	184.65	0.001	3.59	0.001	22.37	0.001	328.70	0.001
	Season (S)	294.37	0.001	4.69	0.011	3.59	0.03	22.37	0.001	328.70	0.001
	Depth (D)	4.88	0.009	24.09	0.001	5.56	0.005	22.31	0.001	133.20	0.001
	LU×S	5.44	0.005	0.27	0.764	5.63	0.004	16.50	0.001	63.17	0.001
	LU×D	0.83	0.439	0.78	0.461	0.04	0.958	2.52	0.083	1.81	0.167
	S×D	1.09	0.365	0.29	0.883	0.66	0.615	1.01	0.404	11.71	0.001
	LU×S× D	0.39	0.814	1.31	0.269	0.26	0.901	0.50	0.734	4.83	0.001

Remarks: Values are mean ± SE. Different alphabets 'a, b, c' represent the significant differences across depths within the season; 'A, B, C' represent the significant differences across seasons within the same depth (One-way ANOVA); and 'α, β' represent significant differences between land use types within the same season and depth (independent sample t-test). SOC: Soil Organic Carbon, TN: Total Nitrogen, AP: Available Phosphorous, AK: Available Potassium, LU: Land use, S: Seasons, D: depth.

2.2. Soil sampling and soil analyses

Soil samples were collected from both agricultural and abandoned land sites during 2020 and 2021. Three transects were established in each land-use type. In each transect, three square plots of 10 × 10 m² were established for soil sampling, with approximately 100 m spacing between plots. From each plot, soil cores were extracted from three different depths: (i) 0-10 cm, (ii) 10-20 cm, and (iv) 20-30 cm. The collected samples were thoroughly mixed from each plot to create a composite sample of approximately 1 kg. Soil samples were collected during pre-monsoon, monsoon, and post-monsoon seasons. Altogether 162 composite samples (2 land-use types × 3 transects × 3 plots × 3 depths × 3 seasons) were collected. The samples were dried, gently crushed, and sieved using a mesh with a pore size of ≤ 2 mm. Soil samples were transported in iceboxes and stored in the refrigerator (<4°C) until use.

A soil thermometer was used to measure the temperature on-site. The dry weight method was used for moisture content (MC), following Piper (2019). Bulk density (BD) was measured using the core method (Blake & Hartge, 1986) and soil texture was estimated by using the Bouyoucos hydrometer (Bouyoucos, 1962). Soil and water ratio (1:2.5) was prepared, and soil pH was measured using a digital pH meter (Jackson, 1969). Soil organic carbon (SOC) was estimated by the Walkley-Black method followed by Gelman et al. (2012). Total Nitrogen (TN), available phosphorus, and potassium were estimated following the Kjeldahl method (Jackson, 1969), Olsen's sodium bicarbonate extraction method (Olsen et al., 1954), and the ammonium acetate extraction method (Jackson, 1969), respectively. Soil microbial biomass carbon and nitrogen were determined by using the chloroform fumigation extraction method (Brookes et al., 1985). After determining microbial biomass carbon and nitrogen in the soil, the microbial C: N ratio was calculated

2.3. Statistical analysis

The effects of land-use types, seasons, soil depths and their interactions on soil physicochemical and microbial parameters were analyzed using Three-way analysis of variance (ANOVA). The differences in the soil parameters among each land use type, seasons, and depth were compared using One-way ANOVA. An independent sample t-test was used for the comparison of the parameters between agriculture and abandoned lands. The software Statistical Package for the Social Sciences (SPSS, version 25) was used for the analyses (IBM Corp., 2017). Principal Component Analysis (PCA) was performed to visualize the overall impact of seasons and land use type on soil parameters along the soil depth gradient. This analysis was carried out using the software R (R Core Team, 2023).

3 RESULTS

3.1. Physical properties of soil

Soil temperature varied with land-use type (p = 0.004), seasons (p = 0.001), and depths (p = 0.001) (Table 1). Temperature was recorded as high during the pre-monsoon season (29.77 ± 0.14°C) in the abandoned land. Soil temperature decreased with increasing soil depth from pre-monsoon to monsoon seasons. However, it increased with increasing depth in the post-monsoon season. The interaction of land-use type, seasons, and depths showed a significant effect, but the interaction between land-use type and depths was not significant (Table 1).

Average soil moisture (SM) ranged from 12.29% to 41.15%, and the bulk density (BD) ranged from 0.95 g cm^{-3} to 1.68 g cm^{-3}. Agricultural land showed the highest SM, while the abandoned land exhibited the highest bulk density (BD) during the monsoon season (Table 1). The SM and BD increased with depth in all seasons and land types. The SM varies with season and soil depth (p = 0.001). In contrast, BD varied with land use, season, and depth (p = 0.001); however, the interaction of land-use type and depth, as well as the effects of land use types, seasons, and depths, did not show significant effects (p > 0.05) (Table 1).

Soil of the agricultural land showed the highest silt (25.66±0.85%) and clay content (15.85±0.94%), while the abandoned land had a higher sand content (66.10±0.84%) (Table 1). Generally, the sand and silt contents decreased, while the clay content increased with increasing soil depth. Sand content varied with the season and soil depth (p = 0.001), except for the interaction of these factors. The silt content varied according to land use and season (p = 0.001), but not with depth. Similarly, clay content also differed with depth (p = 0.001), but not between agricultural and abandoned lands, or among seasons (Table 1).

3.2. Chemical properties of soil

The mean soil pH ranged from 4.97±0.33 to 6.48±0.03. A high value of pH was found in the abandoned land at 20-30 cm in the monsoon, while the value was low in the agricultural land at 0-10 cm in the pre-monsoon (Table 2). Soil pH was high in the deeper soil layer across the seasons in both agriculture and abandoned lands. Variation in soil pH was found between types of land-use (p = 0.01), among the seasons (p = 0.001), and across the depths (p = 0.009). Interaction between land-use type and seasons was also found to be significant (p = 0.005) (Table 2). The soil was slightly acidic in both land use types.

Amount of SOC varied from 0.92 ± 0.51 to 2.63 ± 0.23 %. Agricultural land contained a higher concentration of SOC than abandoned land, particularly during the monsoon, compared to the pre- and post-monsoon periods (Table 2). The carbon content decreased in the deeper soil layer. Overall, carbon concentration was significantly higher in agricultural land compared to the abandoned land across all seasons and depths (p < 0.005). Land use, season, and depths showed significant effects on SOC (p = 0.001) (Table 2). The content of total nitrogen (TN) ranged from 0.08 ± 0.07 to 0.21 ± 0.05 %, available phosphorus (AP) from 29.29 ± 5.67 to 72.16 ± 15.91 kg ha^{-1}, and available potassium (AK) ranged from 186.13 ± 49.81 to 636.55 ± 44.25 kg ha^{-1}. These nutrients were high in the upper layer of soil (0-10 cm) during the monsoon season in agricultural land, while concentrations decreased at 20-30 cm during the post-monsoon season in abandoned land, except for TN during the pre-monsoon season. Nutrient values followed the order monsoon > pre-monsoon > post-monsoon (Table 2).

Table 3. Microbial biomass carbon (BMC) and microbial biomass nitrogen (MBN) among land use types across the seasons and depths.

Land use type	Seasons	Depths (cm)	MBC (µg g⁻¹ soil)		MBN (µg g⁻¹ soil)		MBC: MBN	
Agricultural land	Pre-monsoon	0-10	317.64±49.35αaB		26.03±2.49αaB		12.23±1.87βaB	
		10-20	220.43±57.60αbB		15.69±4.29αbA		14.71±4.41αaA	
		20-30	146.50±26.06αcB		11.02±2.11αcB		13.69±3.07αaB	
	Monsoon	0-10	465.82±43.10αaA		48.58±4.59αaA		9.61±0.62αbC	
		10-20	308.61±91.88αbA		20.05±3.99αbA		15.28±3.17αaA	
		20-30	219.02±29.92αcA		18.93±3.25αcA		11.66±1.07βbB	
	Post-monsoon	0-10	287.73±14.38αaB		17.73±1.77αaC		16.35±1.59αaA	
		10-20	155.60±13.88βbB		9.47±1.99βbB		17.03±3.57βaA	
		20-30	82.26±8.56αcC		4.51±0.32βcC		18.30±2.28αaA	
Abandoned land	Pre-monsoon	0-10	288.04±7.83βaB		18.94±0.88βaB		16.28±0.66αbA	
		10-20	248.01±9.39αbA		16.66±2.37αbA		17.07±2.46αaA	
		20-30	160.13±68.16αcA		10.23±5.20αcA		16.11±2.09αbB	
	Monsoon	0-10	310.49±9.42βaA		24.22±1.19βaA		14.00±0.70βbB	
		10-20	241.85±7.64βbA		17.64±3.05αbA		16.82±2.44βaA	
		20-30	96.68±8.34βcB		9.35±2.24βcA		15.40±2.97αabB	
	Post-monsoon	0-10	235.94±6.06βaC		15.81±1.08βaC		17.37±1.25αbA	
		10-20	170.06±10.75αbB		11.86±1.84αbB		18.17±1.43αabA	
		20-30	80.08±6.68αcB		7.47±2.45αcA		19. 41±1.57ααA	
	Three-way ANOVA		F value	*p* value	F value	*p* value	F value	*p* value
		Land Use (LU)	53.52	0.001	99.168	0.001	44.51	0.001
		Season (S)	116.32	0.001	243.64	0.001	41.71	0.001
		Depth (D)	363.83	0.001	391.94	0.001	12.59	0.001
		LU×S	42.917	0.001	79.794	0.001	3.415	0.036
		LU×D	13.166	0.001	60.027	0.001	1.365	0.259
		S×D	6.04	0.001	31.264	0.001	4.157	0.003
		LU×S×D	0.506	0.731	12.265	0.001	0.615	0.653

Remarks: Values are mean ± SE. Different alphabets 'a, b, c' represent the significant differences across depths within the season; 'A, B, C' represent the significant differences across seasons within the same depth (One-way ANOVA); and 'α, β' represent significant differences between land use types within the same season and depth (independent sample t-test).

Influence of land-use type (p = 0.001), season (p = 0.03), and soil depth (p = 0.005) on TN was found to be significant. Similar results were found in case of AP and AK (p = 0.001). However, the interaction effect of these factors did not have a significant influence on soil parameters as they did when considered individually (Table 2).

3.3. Microbial biomass carbon and nitrogen

Range of microbial biomass carbon (MBC) was 80.08 ± 6.68 to 465.82 ± 43.10 µg g^{-1}, and microbial biomass nitrogen (MBN) varied from 4.51 ± 0.32 to 48.58 ± 4.59 µg g^{-1} of soil (Table 3). Land use type, season, and depths altered the MBC and MBN significantly (p = 0.001). Both parameters were high during the monsoon, followed by pre- and post-monsoon seasons. In comparison to the abandoned land, higher concentrations of MBC and MBN were observed in agricultural land, while they were decreased in deeper layer soils in both land-use types across the seasons (Table 3). The ratio of MBC: MBN ratio ranged from 9.61 ± 0.62 to 19.41 ± 1.57 µg g^{-1} (Table 3). Each of the factors influenced the ratio but interaction of them did not result in significant alteration in the ratio (Table 3). Agriculture soil exhibited lower MBC: MBN ratio during the monsoon than the abandoned land, while it was higher during post-monsoon season. Overall, the agricultural land, monsoon season, and surface-layer soil enhanced microbial biomass.

3.4. Principal component analysis (PCA)

The PCA revealed overall influence of the explanatory variables on the soil physicochemical and microbial properties. Figure 2A shows the percentage of variance explained. PC1 and PC2 axes explained 35.5% and 12.4% of the total variations. Agricultural and abandoned lands were distinctly separated owing to the higher concentrations of SOC, AP, AK, TN, EC, and soil temperature in the agricultural land against soil pH, BD, and MBC: MBN ratios associated with the abandoned land (Fig. 2B). Soil properties like clay percentage, MBC, MBN, AP, AK, and temperature were associated with the monsoon season which distinguished it from the pre-and post-monsoon seasons, which were characterized by higher contents of SOC, EC, and silt (Fig. 2C). Likewise, soil characteristics including SOC, MBN, AP, and TN in the topsoil (0-10 cm) differentiated it from the soil sublayers (Fig. 2D).

4. DISCUSSION

Current results displayed that the soil temperature varied across land-use types, seasons, and soil depths. The highest mean temperature occurred in abandoned land during the pre-monsoon season, and it decreased with depth in both the pre-monsoon and monsoon seasons, but increased in the post-monsoon season. Soil temperature variations reflect the complex relationship between land use, seasonal changes, and soil depth. During the pre-monsoon season, abandoned lands, being less vegetated and more exposed, absorb and retain heat more efficiently, resulting in higher temperatures (Pokharel & Hallett, 2015). As the season transitions into the monsoon and post-monsoon periods, soil moisture levels increase, affecting temperature. Temperature decreases with depth in the pre- and monsoon seasons, which may be due to the direct sunlight and warmer air temperatures at the surface. Increased soil moisture after the monsoon season can enhance thermal conductivity in deeper layers, resulting in rising temperatures with depth (Roxy et al., 2010). Vegetation cover also acts as a thermal insulator, significantly affecting soil temperature (Onwuka, 2018).

The maximum soil moisture content (MC) was observed in agricultural land during the monsoon season, while the minimum was found in the pre-monsoon season. High soil moisture may be linked to low hydraulic conductivity (Rendana et al., 2021). MC also shows an increasing trend of increment with soil depth. Potential factors affecting the MC are precipitation during monsoon, SOM, soil texture, and BD, which directly affect the water-retention capacity of soil (Feifel et al., 2024). Additionally, the pre-monsoon season is characterized by lower soil moisture, which contributes to increased BD, consistent with findings by Enkova and UrÍK (2012) that soil moisture reduces BD. As water moves downward due to gravity and there is less evaporation from deeper soil layers, the MC increases with depth (Gautam & Mandal, 2013).

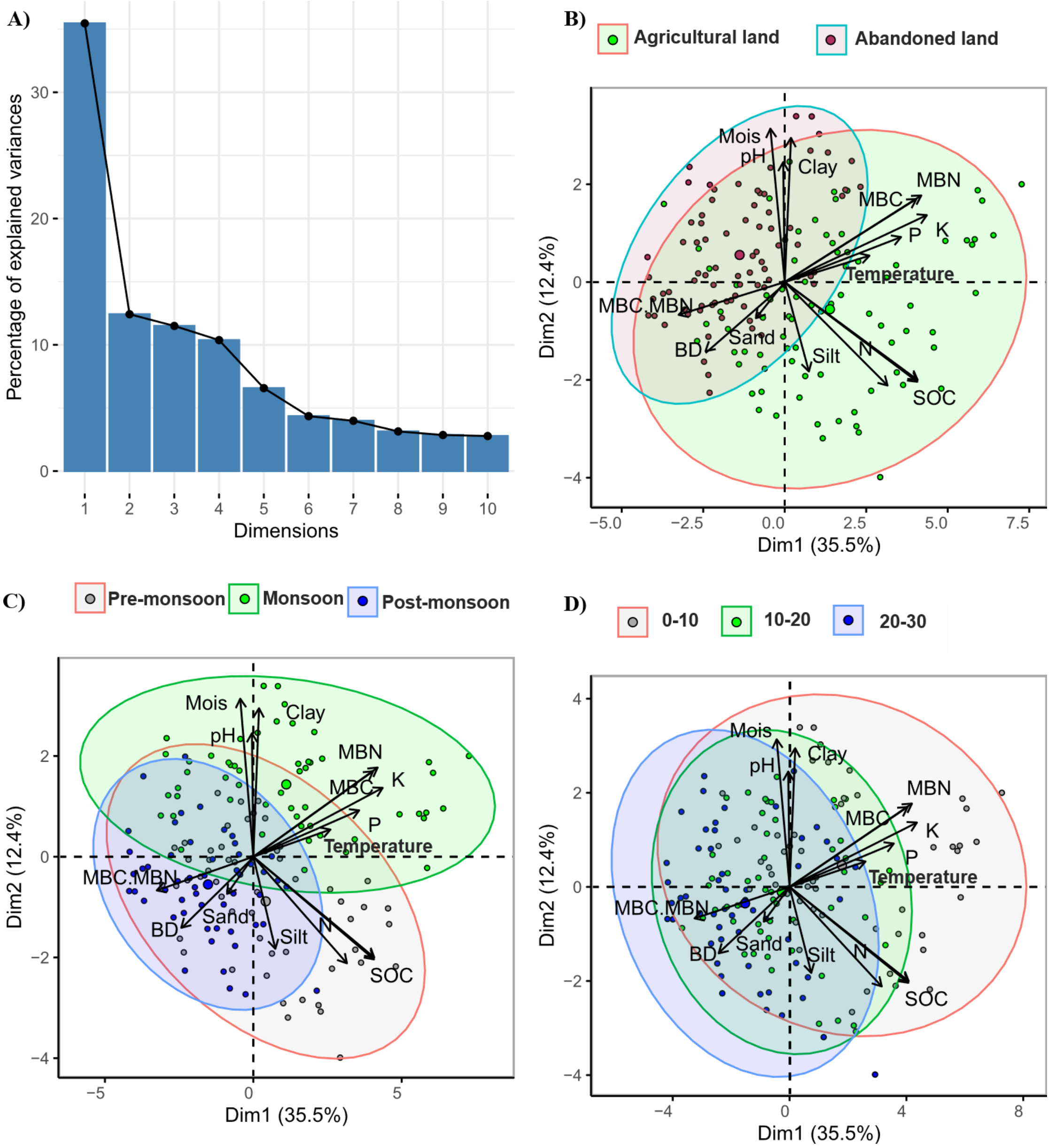

Figure 2. PCA biplot shows effects of seasons, depths, and land-use types on soil physicochemical and microbial properties. Figure 2A explains the percentage of variations, 2B explains the impact of land use, 2C explains the impact of seasons, and 2D describes the effect of soil depths. Mois: soil moisture, BD: bulk density, SOC: soil organic carbon, N: total nitrogen, P: available phosphorous, K: available potassium, MBC: microbial biomass carbon, MBN: microbial biomass nitrogen.

High BD was found in abandoned land at greater depths during the pre-monsoon season. This finding aligns with earlier findings (Lei et al., 2019; Rodríguez-León et al., 2021). These studies reported higher BD in abandoned land than in agricultural land. The higher BD in abandoned land may be due to lower SOM content and grazing activities. The negative correlation between bulk density and SOM, as observed by Athira et al. (2019), indicates that BD decreases as SOM increases. Higher BD in deeper soil layers is also attributed to the reduced SOM, which compacts the soil below (Bangroo et al., 2017; Gautam & Chettri, 2020; Kafle, 2019). Regarding soil texture, the percentage of sand and silt decreased with increasing soil depth. This process causes clay to accumulate in deeper soil horizons, while larger particles like sand and silt remain in the upper layers due to their size and weight (Gautam & Mandal, 2013; Zhang et al., 2014).

The soil was found to be slightly acidic across land use types, seasons, and depths. Our results showed an increase in pH with increasing soil depth. Typically, lower pH values are observed in topsoil due to higher SOM and the decomposition process, which produces organic acids and thus lowers the pH (Zhou et al., 2019). Assefa et al. (2020) also found acidic soils at the surface. The dilution effect has been seen in the soil as the pH tends to decrease during the rainy season (Acharya & Shrestha, 2015).

Higher concentrations of NPK during the monsoon season are attributed to enhanced microbial activity and decomposition (Agbeshie et al., 2020; Lepcha & Devi, 2020). Similarly, Sharma and Kafle (2020), Magar et al. (2020), and Zhang et al. (2021) also reported high values of SOC, AP, and AK in the surface layer, with declines at greater depths. Tree litter fall, which decomposes on the surface, contributes significantly to the increment of SOC and other nutrients (Amgain et al., 2020; Ganai et al., 2018). High concentrations of MBC and MBN were found in agricultural land during the monsoon and are low in abandoned land during the post-monsoon. Both MBC and MBN decreased with increasing soil depth across both land use types. These results align with Agbeshie et al. (2020) and Liu et al. (2020), who found low concentrations in abandoned land. High MBC and MBN in agricultural land are likely due to the accumulation of organic manure and carbon present in the soil, which tends to lead to a higher MB.

Seasonal variations in MBC and MBN were observed, with peak values during the rainy season and their low contents during the post-monsoon (Table 3). Elevated temperature during the monsoon season accelerates litter decomposition and microbial activity, leading to increased nutrient immobilization by microbes (Lepcha & Devi, 2020; Tripathi & Singh, 2013). Reduction in MBC and MBN in deeper soils might be due to the corresponding decline in organic matter (Limbu et al., 2020; Padalia et al., 2018). In agricultural land, the lower MBC: MBN ratio during the monsoon suggests a relative decrease in carbon due to increased nitrogen availability from organic matter decomposition, whereas in the post-monsoon, the higher MBC: MBN ratio may be due to the reduced nutrient leaching (Manral et al., 2023). Ratio of microbial C: N is an important indicator of the organization and composition of the microbial community, which reflects the dynamics of organic matter decomposition in soil (Tao et al., 2020). A low MBC: NBN ratio suggests a higher bacterial population, while a high ratio indicates fungal dominance (Campbell et al., 1991; Ravindran & Yang, 2015). Our findings indicate that the microbial population is dominated by fungi.

The concentration of both SMBC and SMBN in both land types decreased with increasing depth. The increasing SMBC:SMBN ratio, as shown by this study with respect to soil depth, indicates slow decomposition of organic matter. Li et al. (2013) also reported a significant increase in the SMBC to SMBN ratio with increasing depth in the soil layer. Higher MBN and MBC contents in the surface layers of agricultural lands indicate that the surface soil has higher microbial activity, indicative of good soil quality.

PCA showed relationships among soil parameters and various land use types. It proved to be an effective method for examining how the changes in land use affect specific soil characteristics (Biro et al., 2013). PCA revealed the influence of the explanatory variable (land-use, seasons, and depths) on soil physicochemical and microbial characters (Fig. 2). Soil silt content and higher values of MBC, MBN, AP, AK, SOC, and temperature were positively correlated with agricultural land. The pre-monsoon season was characterized by association with SOC values, whereas the parameters MBC, MBN, K, and Clay percentage were found to increase during the monsoon. This pattern of temporal variations in soil parameters further illustrated a distinct effect of depth through PCA.

CONCLUSION

The study revealed that the soil's physicochemical and microbial characteristics varied with land-use types, seasons, and soil depths. During the pre-monsoon season, mean soil temperatures were higher across land use types. The temperature decreased with increasing depth during both the pre- and monsoon seasons. However, during the post-monsoon period, the temperature increased with increasing depth. During the monsoon, higher soil moisture was recorded in agricultural land, increasing with depth. Bulk density in abandoned land increases in the pre-monsoon season but decreases in the post-monsoon season. Agricultural land exhibited the highest silt and clay content, whereas abandoned land had a higher proportion of sand. Similarly, pH, SOC, TN, available phosphorus, and available potassium were increased in soil during the monsoon season in agricultural land. The role of soil physiochemical properties and microbial biomass carbon and nitrogen is crucial for soil nutrient dynamics, thereby affecting plant and crop productivity. Therefore, the results can inform sustainable soil management practices in agricultural and abandoned lands.

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Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

References

Abera, Y., & Belachew, T. (2011). Effects of landuse on soil organic carbon and nitrogen in soils of Bale, Southeastern Ethiopia. *Tropical and subtropical agroecosystems*, *14*(1), 229-235. https://www.revista.ccba.uady.mx/ojs/index.php/TSA/article/view/538/519.

Acharya, R., & Shrestha, B. B. (2015). Physiochemical Characteristics of Soil of a Mixed Shorea Robusta Forest in Rupandehi District, Nepal. *Journal of Natural History Museum*, *26*(0), 155-162. https://doi.org/10.3126/jnhm.v26i0.14139.

Agbeshie, A. A., Abugre, S., Adjei, R., Atta-Darkwa, T., & Anokye, J. (2020). Impact of Land Use Types and Seasonal Variations on Soil Physico-chemical Properties and Microbial Biomass Dynamics in a Tropical Climate, Ghana. *Advances in Research*, *21*(1), 34–49. https://doi.org/10.9734/air/2020/v21i130180.

Amgain, R., Khadka, D., Joshi, S., & Malla, R. (2020). Depth-wise variations of soil physicochemical properties in the apple growing area of Mustang district, Nepal. *Journal of Agriculture and Natural Resources*, *3*(2), 92-103. https://doi.org/10.3126/janr.v3i2.32486.

Anikwe, M. A. N., & Ife, K. (2023). The role of soil ecosystem services in the circular bioeconomy [Review]. *Frontiers in Soil Science*, *Volume 3 - 2023*. https://doi.org/10.3389/fsoil.2023.1209100.

Assefa, F., Elias, E., Soromessa, T., & Ayele, G. T. (2020). Effect of Changes in Land-Use Management Practices on Soil Physicochemical Properties in Kabe Watershed, Ethiopia. *Air, Soil and Water Research*, *13*, 1178622120939587. https://doi.org/10.1177/1178622120939587.

Athira, M., Jagadeeswaran, R., & Kumaraperumal, R. (2019). Influence of soil organic matter on bulk density in Coimbatore soils. *International Journal of Chemical Studies*, *7*(3), 3520-3523. http://www.chemijournal.com/archives/2019/vol7issue3/PartBF/7-3-360-895.pdf.

Bangroo, S. A., Najar, G. R., & Rasool, A. (2017). Effect of altitude and aspect on soil organic carbon and nitrogen stocks in the Himalayan Mawer Forest Range. *CATENA*, *158*, 63-68. https://doi.org/10.1016/j.catena.2017.06.017.

Biro, K., Pradhan, B., Buchroithner, M., & Makeschin, F. (2013). Land use/land cover change analysis and its impact on soil properties in the northern part of Gadarif region, Sudan. *Land Degradation & Development*, *24*(1), 90-102. https://doi.org/10.1002/ldr.1116.

Blake, G. R., & Hartge, K. H. (1986). Bulk density. In A. Klute (Ed.), *Methods of soil analysis. Part 1. Physical and mineralogical methods* (2nd ed.). Madison, USA: American Society of Agronomy.

Bouyoucos, G. J. (1962). Hydrometer Method Improved for Making Particle Size Analyses of Soils. *Agronomy Journal*, *54*(5), 464-465. https://doi.org/10.2134/agronj1962.00021962005400050028x.

Brookes, P. C., Landman, A., Pruden, G., & Jenkinson, D. S. (1985). Chloroform fumigation and the release of soil nitrogen: A rapid direct extraction method to measure microbial biomass nitrogen in soil. *Soil Biology and Biochemistry*, *17*(6), 837-842. https://doi.org/10.1016/0038-0717(85)90144-0.

Budhathoki, N., Dhakal, S., & Dyola, U. (2021). Diversity of hoverflies (Diptera: Syrphidae) in Nagarjun, Shivapuri Nagarjun National Park, Nepal. *Biodiversitas Journal of Biological Diversity*, *22*(12). https://doi.org/10.13057/biodiv/d221220.

Campbell, C. A., Biederbeck, V. O., Zentner, R. P., & Lafond, G. P. (1991). Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem. *Canadian Journal of Soil Science*, *71*(3), 363-376. https://doi.org/10.4141/cjss91-035.

Campbell, J. E., Lobell, D. B., Genova, R. C., & Field, C. B. (2008). The Global Potential of Bioenergy on Abandoned Agriculture Lands. *Environmental Science & Technology*, *42*(15), 5791-5794. https://doi.org/10.1021/es800052w.

Chandra, L. R., Gupta, S., Pande, V., & Singh, N. (2016). Impact of forest vegetation on soil characteristics: a correlation between soil biological and physico-chemical properties. *3 Biotech*, *6*(2), 188. https://doi.org/10.1007/s13205-016-0510-y.

Dahal, G. R., Pandit, B. H., & Shah, R. (2020). Abandoned agricultural land and its reutilisation by adoption of agroforestry: a case study from Kaski and Parbat Districts of Nepal. *Journal of Forest and Livelihood*, *19*(1), 1-16. https://www.forestaction.org/app/webroot/vendor/tinymce/editor/plugins/filemanager/files/JFL%2019%20(1)/1%20Dahal%20et%20al.pdf.

Dhakal, T., Thapa, L. B., Pokhrel, C. P., & Yadav, R. K. P. (2023). Plant communities in Shivapuri Nagarjun National Park, Central Nepal. *Banko Janakari*, *33*(2), 11-23. https://doi.org/10.3126/banko.v33i2.55086.

Dobrovol'skaya, T. G., Zvyagintsev, D. G., Chernov, I. Y., Golovchenko, A. V., Zenova, G. M., Lysak, L. V., . . . Umarov, M. M. (2015). The role of microorganisms in the ecological functions of soils. *Eurasian Soil Science*, *48*(9), 959-967. https://doi.org/10.1134/S1064229315090033.

Enkova, L. K., & UrÍK, M. (2012). Soil moisture and its effect on bulk density and porosity of intact aggregates of three Mollic soils. *The Indian Journal of Agricultural Sciences*, *82*(2), 172–176. https://doi.org/10.56093/ijas.v82i2.15297.

Feifel, M., Durner, W., Hohenbrink, T. L., & Peters, A. (2024). Effects of improved water retention by increased soil organic matter on the water balance of arable soils: A numerical analysis. *Vadose Zone Journal*, *23*(1), e20302. https://doi.org/10.1002/vzj2.20302.

Ganai, A., Dar, M., Chesti, M., Bhat, Z., Khanday, M., & Dar, N. (2018). Macronutrients status of apple (cv. red delicious) orchard soils of Jammu and Kashmir India. *International Journal of Chemical Studies*, *6*(2), 3314-3319. https://www.chemijournal.com/archives/?year=2018&vol=6&issue=2&ArticleId=2358&si=.

Gautam, B., & Chettri, M. K. (2020). Physicochemical properties of tropical forest top soil in relation to depth in western Nepal. *Banko Janakari*, *30*(1), 39-48. https://doi.org/10.3126/banko.v30i1.29181.

Gautam, T. P., & Mandal, T. N. (2013). Soil Characteristics in Moist Tropical Forest of Sunsari District, Nepal. *Nepal Journal of Science and Technology*, *14*(1), 35-40. https://doi.org/10.3126/njst.v14i1.8876.

Gelman, F., Binstock, R., & Halicz, L. (2012). Application of the Walkley–Black titration for the organic carbon quantification in organic rich sedimentary rocks. *Fuel*, *96*, 608-610. https://doi.org/10.1016/j.fuel.2011.12.053.

Herreño, B., De la Colina, F., & Delgado-Iniesta, M. J. (2023). Edaphosphere: A Perspective of Soil Inside the Biosphere. *Earth*, *4*(3), 691-697. https://doi.org/10.3390/earth4030036.

IBM Corp. (2017). *IBM SPSS Statistics for Windows, Version 25.0*. In Armonk, New York: IBM Corp.

Jackson, M. L. (1969). *Soil Chemical Analysis: Advanced Course : a Manual of Methods Useful for Instruction and Research in Soil Chemistry, Physical Chemistry of Soils, Soil Fertility, and Soil Genesis* (2nd ed.). UW-Madison Libraries Parallel Press.

Kafle, G. (2019). Vertical Distribution of Soil Organic Carbon and Nitrogen in a Tropical Community Forest of Nepal. *International Journal of Forestry Research*, *2019*(1), 3087570. https://doi.org/10.1155/2019/3087570.

Lei, Z., Yu, D., Zhou, F., Zhang, Y., Yu, D., Zhou, Y., & 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. *Scientific Reports*, *9*(1), 16453. https://doi.org/10.1038/s41598-019-52945-5.

Lepcha, N. T., & Devi, N. B. (2020). Effect of land use, season, and soil depth on soil microbial biomass carbon of Eastern Himalayas. *Ecological Processes*, *9*(1), 65. https://doi.org/10.1186/s13717-020-00269-y.

Li, W., Yang, G., Chen, H., Tian, J., Zhang, Y., Zhu, Q. a., . . . Yang, J. a. (2013). Soil available nitrogen, dissolved organic carbon and microbial biomass content along altitudinal gradient of the eastern slope of Gongga Mountain. *Acta Ecologica Sinica*, *33*(5), 266-271. https://doi.org/10.1016/j.chnaes.2013.07.006.

Limbu, D. K., Koirala, M., & Shang, Z. (2020). Soil Microbial Biomass Carbon and Nitrogen in Himalayan Rangeland of Eastern Nepal: A Comparison between Grazed and Non-grazed Rangelands. *Journal of Rangeland Science*, *10*(2), 217-227. https://journals.iau.ir/article_670805.html.

Liu, D., Wang, B., Bhople, P., Davlatbekov, F., & Yu, F. (2020). Land rehabilitation improves edaphic conditions and increases soil microbial biomass and abundance. *Soil Ecology Letters*, *2*(2), 145-156. https://doi.org/10.1007/s42832-020-0030-x.

Magar, L. K., Kafle, G., & Aryal, P. (2020). Assessment of Soil Organic Carbon in Tropical Agroforests in the Churiya Range of Makawanpur, Nepal. *International Journal of Forestry Research*, *2020*(1), 8816433. https://doi.org/10.1155/2020/8816433.

Manral, V., Bargali, K., Bargali, S. S., Karki, H., & Chaturvedi, R. K. (2023). Seasonal Dynamics of Soil Microbial Biomass C, N and P along an Altitudinal Gradient in Central Himalaya, India. *Sustainability*, *15*(2), 1651. https://doi.org/10.3390/su15021651.

Nepal, S., & Mandal, R. A. (2018). Soil quality index and nutrient in Badekhola and Brindaban catchments, Nepal. *MOJ Ecology & Environmental Sciences*, *3*(1), 54-57. http://medcraveonline.com/MOJES/MOJES-03-00066.pdf.

Nguyen-Sy, T., Do, V. T. T., & Duy, D. P. (2022). Soil carbon mineralization affected by hot water and ultrasound pretreatment. *Sains Tanah Journal of Soil Science and Agroclimatology*, *19*(1), 7. https://doi.org/10.20961/stjssa.v19i1.57554.

Novara, A., Gristina, L., Sala, G., Galati, A., Crescimanno, M., Cerdà, A., . . . La Mantia, T. (2017). Agricultural land abandonment in Mediterranean environment provides ecosystem services via soil carbon sequestration. *Science of The Total Environment*, *576*, 420-429. https://doi.org/10.1016/j.scitotenv.2016.10.123.

Ojha, H. R., Shrestha, K. K., Subedi, Y. R., Shah, R., Nuberg, I., Heyojoo, B., . . . McManus, P. (2017). Agricultural land underutilisation in the hills of Nepal: Investigating socio-environmental pathways of change. *Journal of Rural Studies*, *53*, 156-172. https://doi.org/10.1016/j.jrurstud.2017.05.012.

Olsen, S. R., Cole, C. V., Watanabe, F. S., & Dean, L. A. (1954). *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*. US Department of Agriculture: Washington, DC, USA, Circular no. 939.

Onwuka, B. (2018). Effects of soil temperature on some soil properties and plant growth [Review]. *Advances in Plants & Agriculture Research*, *8*(1), 34-37. https://medcraveonline.com/APAR/APAR-08-00288.pdf.

Padalia, K., Bargali, S., Bargali, K., & Khulbe, K. (2018). Microbial biomass carbon and nitrogen in relation to cropping systems in Central Himalaya, India. *Current Science*, *115*(9), 1741-1750. https://www.currentscience.ac.in/Volumes/115/09/1741.pdf.

Paudel, K. P., Tamang, S., & Shrestha, K. K. (2014). Transforming land and livelihood: Analysis of agricultural land abandonment in the Mid Hills of Nepal. *Journal of Forest and Livelihood*, *12*(1), 9-9. https://nepjol.info/index.php/JFL/article/view/65677/49813.

Piper, C. S. (2019). *Soil and plant analysis* (Vol. 368). Scientific Publishers. https://www.scientificpubonline.com/bookdetail/soil-plant-analysis/9788172336202/0

Pokharel, A. K., & Hallett, J. (2015). Distribution of rainfall intensity during the summer monsoon season over Kathmandu, Nepal. *Weather*, *70*(9), 257-261. https://doi.org/10.1002/wea.2544.

Poudyal, L. P., Koju, N. P., Bista, M., Thapa, S., Dahal, D. R., Khadka, S., & Pandey, B. P. (2023). Checklist of wild mammals of Shivapuri Nagarjun National Park, Nepal. *Nepalese Journal of Zoology*, *7*(1), 48-59. https://doi.org/10.3126/njz.v7i1.56310.

R Core Team. (2023). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. https://cran.r-project.org/doc/manuals/r-release/fullrefman.pdf

Ravindran, A., & Yang, S.-S. (2015). Effects of vegetation type on microbial biomass carbon and nitrogen in subalpine mountain forest soils. *Journal of Microbiology, Immunology and Infection*, *48*(4), 362-369. https://doi.org/10.1016/j.jmii.2014.02.003.

Rendana, M., Idris, W. M. R., Abdul Rahim, S., Ali Rahman, Z., & Lihan, T. (2021). Characterization of physical, chemical and microstructure properties in the soft clay soil of the paddy field area. *Sains Tanah Journal of Soil Science and Agroclimatology*, *18*(1), 8. https://doi.org/10.20961/stjssa.v18i1.50489.

Rodríguez-León, C. H., Peña-Venegas, C. P., Sterling, A., Castro, D., Mahecha-Virguez, L. K., Virguez-Díaz, Y. R., & Silva-Olaya, A. M. (2021). Soil Quality Restoration during the Natural Succession of Abandoned Cattle Pastures in Deforested Landscapes in the Colombian Amazon. *Agronomy*, *11*(12), 2484. https://doi.org/10.3390/agronomy11122484.

Roxy, M. S., Sumithranand, V. B., & Renuka, G. (2010). Variability of soil moisture and its relationship with surface albedo and soil thermal diffusivity at Astronomical Observatory, Thiruvananthapuram, south Kerala. *Journal of Earth System Science*, *119*(4), 507-517. https://doi.org/10.1007/s12040-010-0038-1.

Shapkota, J., & Kafle, G. (2021). Variation in Soil Organic Carbon under Different Forest Types in Shivapuri Nagarjun National Park, Nepal. *Scientifica*, *2021*(1), 1382687. https://doi.org/10.1155/2021/1382687.

Sharma, M., & Kafle, G. (2020). Comparative assessment of profile storage of soil organic carbon and total nitrogen in forest and grassland in Jajarkot, Nepal. *Journal of Agriculture and Natural Resources*, *3*(2), 184-192. https://doi.org/10.3126/janr.v3i2.32505.

Silwal, T., Devkota, B. P., Poudel, P., & Morgan, M. (2022). Do Buffer Zone Programs Improve Local Livelihoods and Support Biodiversity Conservation? The Case of Sagarmatha National Park, Nepal. *Tropical Conservation Science*, *15*, 19400829221106670. https://doi.org/10.1177/19400829221106670.

SNNP. (2017). *Shivapuri Nagarjun National Park (SNNP) and Buffer Zone Management Plan Fiscal Year 2074/75-087/079 (2017/018-2021/022)*. Shivapuri Nagarjun National Park Office, Panimuhan, Budhanilkantha, Kathmandu, Nepal. https://dnpwc.gov.np/media/publication/Management_Plan_2075_Shivapuri.pdf

Suntoro, S., Herdiansyah, G., & Mujiyo, M. (2024). Nutrient status and soil fertility index as a basis for sustainable rice field management in Madiun Regency, Indonesia. *Sains Tanah Journal of Soil Science and Agroclimatology*, *21*(1), 10. https://doi.org/10.20961/stjssa.v21i1.73845.

Tao, Y., Zhou, X.-B., Zhang, S.-H., Lu, H.-Y., & Shao, H. (2020). Soil nutrient stoichiometry on linear sand dunes from a temperate desert in Central Asia. *CATENA*, *195*, 104847. https://doi.org/10.1016/j.catena.2020.104847.

Tripathi, N., & Singh, R. S. (2013). Cultivation impacts soil microbial dynamics in dry tropical forest ecosystem in India. *Acta Ecologica Sinica*, *33*(6), 344-353. https://doi.org/10.1016/j.chnaes.2013.09.009.

Yokoyama, D., Imai, N., & Kitayama, K. (2017). Effects of nitrogen and phosphorus fertilization on the activities of four different classes of fine-root and soil phosphatases in Bornean tropical rain forests. *Plant and Soil*, *416*(1), 463-476. https://doi.org/10.1007/s11104-017-3225-x.

Zhang, J., Li, H., Zhang, H., Zhang, H., & Tang, Z. (2021). Responses of Litter Decomposition and Nutrient Dynamics to Nitrogen Addition in Temperate Shrublands of North China. *Frontiers in Plant Science*, *Volume 11 - 2020*. https://doi.org/10.3389/fpls.2020.618675.

Zhang, L., Zhao, R., & Xie, Z. (2014). Response of soil properties and C dynamics to land-use change in the west of Loess Plateau. *Soil Science and Plant Nutrition*, *60*(4), 586-597. https://doi.org/10.1080/00380768.2014.922407.

Zhou, W., Han, G., Liu, M., & Li, X. (2019). Effects of soil pH and texture on soil carbon and nitrogen in soil profiles under different land uses in Mun River Basin, Northeast Thailand. *PeerJ*, *7*, e7880. https://doi.org/10.7717/peerj.7880.