

DYNAMICS OF SOIL MICROBIAL BIOMASS CARBON AND TOTAL NITROGEN UNDER DIFFERENT LAND USE IN INDO-MYANMAR HOTSPOT REGION, NAGALAND

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ABSTRACT

Soil microbial biomass and nitrogen, a vital nutrient pool for ecosystem nutrient cycling is affected by several factors including climate, edaphic, and land-use change. Focusing on Phek, India which lies within the Indo-Myanmar Biodiversity Hotspot, this study investigates how land use system (forest, permanent agriculture, horticulture, and jhum cultivation) season and soil depth influence soil microbial biomass carbon (MBC) and total nitrogen (TN). Soil samples were collected from three depths up to 30 cm across four seasons. Soil physical and chemical properties varied significantly with season, land-use and soil depth ($p < 0.001$), with forest soils maintaining the highest water holding capacity and lowest bulk density. In contrast, agricultural soils exhibited significant compaction ($BD\ 1.0\text{--}1.5\text{ g cm}^{-3}$). Forest soils recorded highest MBC ($\sim 520\ \mu\text{g g}^{-1}$) in the topsoil (0–10 cm), whereas agricultural soils reached a minimum of $40\text{--}50\ \mu\text{g g}^{-1}$ at depth (20–30 cm). TN stocks were highest in surface Jhum soils during winter ($\sim 310\text{ Mg ha}^{-1}$) but declined drastically with depth. Statistical analysis revealed that SOC, TN, and MBC are strongly positively correlated, while BD and soil temperature negatively affect microbial pools. The findings highlight that forest-to-agriculture conversion significantly degrades microbial-driven nutrient cycling, emphasizing the need for sustainable fallow management and reduced disturbance to preserve soil health in this ecologically sensitive landscape.

Keywords: land use, microbial biomass carbon, soil depth, seasonal dynamics, total nitrogen

INTRODUCTION

The soil microbial biomass acts as a crucial role in regulating carbon and nitrogen dynamics, which serves as a primary metric for evaluating soil health, microbial functionality, and nutrient availability. Characterized by rapid turnover rates, the microbial pool is exceptionally sensitive to environmental fluctuations and anthropogenic disturbances. Consequently, monitoring changes in microbial biomass carbon and microbial biomass nitrogen provides a highly responsive diagnostic tool for evaluating ecosystem responses to climate change (Insam, 1990), tillage practices (Carter, 1991; Lynch & Panting, 1980), crop rotations (Anderson & Domsch, 1989; Campbell *et al.*, 1991), and pollution stress. Furthermore, MBC has been widely accepted as a reliable indicator of baseline microbial status and overall soil quality. When compared against total organic carbon and total nitrogen pools, MBC and MBN serve as effective measures for assessing microbial metabolic efficiency and broader soil functionality during ecosystem succession (Bastida *et al.*, 2008; Srivastava *et al.*, 2016; Wardle & Ghani, 1995).

In recent years, global research has increasingly focused on how land use and agricultural management practices govern the long-term storage of soil organic carbon (SOC) (Liu *et al.*, 2016). As a fundamental component of the global carbon cycle, SOC underpins ecosystem health, climate regulation, and sustainable land management worldwide (Jaya *et al.*, 2026). In terrestrial ecosystems, where microbial activity centralizes the regulation of nutrient availability, ecosystem functioning is potentially dependent on the intrinsic relationships between soil microbial diversity and biomass (Sile *et al.*, 2025). However, understanding how land cover and seasonal variations influence these microbial communities remains a critical hurdle for sustainable land management (Rakotonindrina *et al.*, 2025). These challenges are compounded by multiple global change drivers; for instance, understanding the combined effects of warming (W) and nitrogen (N) fertilization is critical for accurately predicting ecosystem responses to climate change (Pandey *et al.*, 2026). These escalating climate effects have elicited a worldwide search for strategies to mitigate C and N emissions from agricultural soils (Shirale *et al.*, 2025), alongside organic fertilizer applications designed to reduce SOC loss and achieve agricultural sustainability (Yang *et al.*, 2026).

Land-use type stands out as a primary parameter dictating soil physical, chemical, and biological properties, directly shaping microbial community compositions and plant nutrient status (Zhao *et al.*, 2025, Baligh *et al.*, 2025). Prior research indicates that land-use change exerts a profound influence on soil carbon pools and significantly enhances soil CO₂ efflux (Srivastava *et al.*, 2016); yet, the precise underlying mechanisms and exact soil attributes involved remain incompletely understood (Qi *et al.*, 2018). It is well established that converting natural forests to alternative systems such as plantation or agricultural lands in humid tropical regions frequently leads to significant reductions in SOC stocks, compromising the carbon sequestration potential of the soil (Zhou *et al.*, 2017; Jaya *et al.*, 2026). Intensive cropping systems, heavy nutrient inputs, and altered residue management practices disrupt baseline C and N cycling, thereby accelerating nutrient losses and altering sequestration capacities (Sahoo *et al.*, 2023). Despite these overarching trends, the precise impacts of localized climatic and edaphic conditions, alongside specific land-use transitions, on soil carbon pools and microbial biomass properties remain unclear on a regional scale (Tiwari *et al.*, 2026; Raghuvanshi *et al.*, 2026).

This knowledge gap is particularly acute in the tropical forest soils of India, where limited studies have tracked the dynamics of MBC and N transformation rates consequent to heavy cultivation (Tripathi & Singh, 2013). Research indicates a significant decrease in MBC and N following land-use conversion across the subcontinent (Manral *et al.*, 2022). The

Northeast Region (NER) of India, despite being an area of immense biodiversity, is facing severe ecological pressures driven by rapid economic development (Jamir *et al.*, 2015). In this region, the widespread conversion of natural forests into agricultural fields and traditional jhum (shifting) cultivation plots has significantly altered soil processes and degraded inherent soil properties (Celik, 2005; Dawson *et al.*, 2007). These landscape transitions disrupt essential microbial functions by modulating the key biogeochemical processes that regulate C and N cycling (Sousa *et al.*, 2012).

To date, no baseline research on the dynamics of microbial biomass carbon and total nitrogen has been conducted within the critically vulnerable Indo-Myanmar Biodiversity Hotspot. This region is currently experiencing intense human interference driven by severe socio-ecological pressures, including hunting and unauthorized tree felling. Local livelihoods depend almost entirely on subsistence agriculture and traditional jhum cultivation, accelerating rapid, unregulated land-use transitions across the natural forest landscape. These dynamics are further compounded by the unique land tenure systems of the region, where the vast majority of forest land is held under village jurisdiction and customary tribal control rather than state governance. Given these compounding socio-ecological pressures and the widespread conversion of native forests, urgent concerns have emerged regarding the long-term ecological sustainability and progressive soil degradation of the area. To address these critical uncertainties, the present study evaluates the distinct effects of land-use types on the dynamics of MBC, MBN, and associated soil physicochemical properties within the Indo-Myanmar Biodiversity Hotspot. By quantifying these shifts, we aim to elucidate the mechanisms driving microbial responses to anthropogenic stress and provide foundational data to guide sustainable land management and conservation strategies in this ecologically sensitive landscape.

METHODOLOGY

Description of the study area

The study was conducted from 2023 to 2025 in the Phek district of Nagaland, India, situated within the Indo-Myanmar biodiversity hotspot. Four distinct land-use types were selected for investigation: natural forest, permanent agriculture, horticulture, and shifting cultivation (*jhum*). The region experiences a typical subtropical climate characterized by pronounced seasonal temperature variations and heavy rainfall concentrated during the monsoon period; no significant long-term climatic trends were observed during the study timeframe. Meteorological data recorded throughout the study period are illustrated in Fig. 2. The sampling sites span a prominent elevational gradient across different administrative units (Fig. 1). The forest study site features Chida Lake (also historically referred to as Loho Lake, translating to "Collection of Water"). This natural water body sits at an elevation of 1,870 m above sea level, is located 3.8 km from Khezhakeno Village, and forms a natural border with the state of Manipur to the south. The study region is predominantly located at high elevations, with all land-use sites situated above 2000 m a.s.l. Agriculture is the primary livelihood activity of local communities, who have relied on farming for more than two decades with minimal use of chemical fertilizers. Shifting cultivation (*jhum*) is the dominant land-management practice in the region, although horticultural crops are also cultivated in some areas. The traditional *jhum* system involves a sequence of forest clearing, biomass burning, crop sowing, and harvesting. In the study area, the cultivation phase typically lasts 1–2 years and is followed by a fallow period of 8–10 years to allow vegetation regeneration and soil fertility recovery. The duration and frequency of these cultivation–fallow cycles are

adjusted by local farmers based on previous crop productivity and observed soil conditions, enabling them to sustain approximately 70 % of the expected crop yield.

Fig. 1: Land Use Land Cover (LULC) classification map of the study area in Phek, Nagaland, indicating the specific locations of the sampling points.

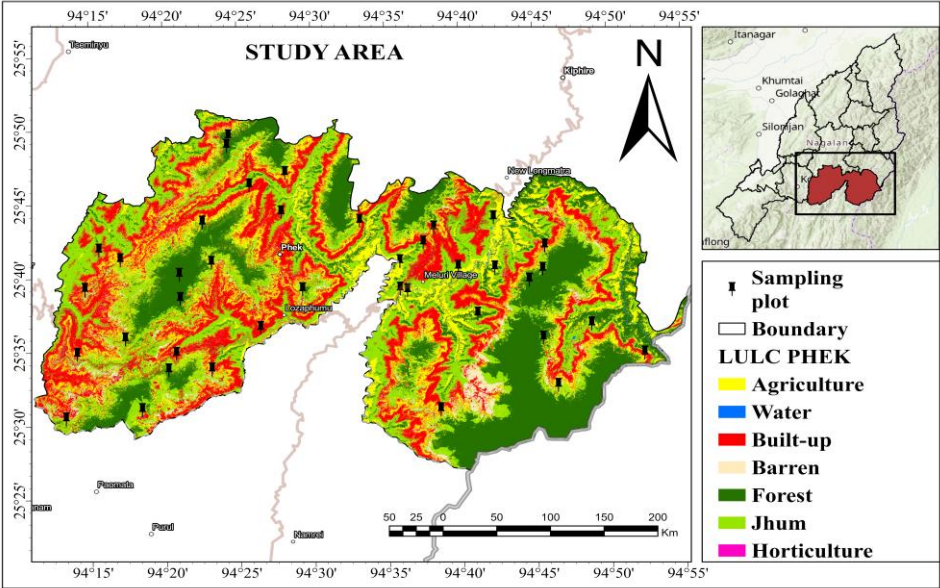
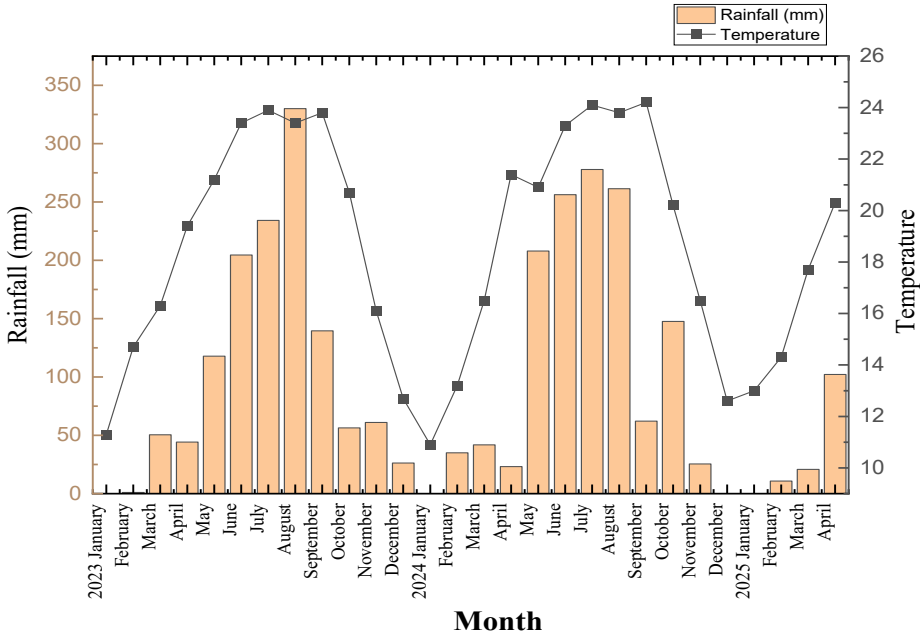


Fig. 2: Meteorological data of Phek from the period of 2023–2025 (April).



Experimental design

The sample collection was carried out in four land use; primary forest, agriculture, horticulture and jhum cultivation land and collected seasonally namely pre-monsoon (feb-april), monsoon(may-july), post monsoon(aug-oct) and winter(nov-jan) for two consecutive years. At each sampling site, soil cores were collected from five locations (four corners and one central point) using a 4-cm diameter steel corer. The subsamples from each site were pooled to form a single composite sample. Composite soil samples were collected from three depth intervals: 0–10 cm, 10–20 cm, and 20–30 cm. The upper two layers were selected to capture the influence of organic matter inputs and active biological processes, whereas the 20–30 cm layer represented relatively stabilized soil conditions.

The sampling design therefore consisted of four land-use types, 10 independent site replicates per land-use type, four seasonal sampling periods, three soil depths, and two years of observation. Consequently, each land-use $\times$ season $\times$ depth combination was represented by ten independent site replicates. In total, 960 composite soil samples were collected and for statistical analyses and graphical presentation, measurements from the two sampling years were averaged, resulting in an effective sample size of 480 observations (4 land-use types $\times$ 10 sites $\times$ 4 seasons $\times$ 3 depths).

Soil physicochemical properties

Soil TN was measured following Kjeldahl method (Allen *et al.*, 1974). MBC was determined by chloroform fumigation-extraction method (Vance *et al.*, 1987). Further soil parameters were carried out to compared with the MBC and TN correlation. Soil moisture was conducted using the gravimetric method (Allen *et al.*, 1974) and bulk density was carried out using the method describe by Anderson and Ingram (Anderson & Ingram, 1993). pH was measured following 1:5 soil distilled water suspension method using an auto digital pH meter (Allen *et al.*, 1974). The water holding capacity (WHC) was determined following the protocol proposed by Mishra (1968). Soil temperature in field was measured using a soil thermometer. Soil organic carbon (SOC) was calculated following Walkley & Black (1934). The Tinsley (1950) fast titration method was used to measure soil inorganic carbon (SIC) (Bremner & Jenkinson, 1960).

Statistical analysis

The present study utilized Sentinel-2 satellite imagery dated 26 February 2025, obtained from the Copernicus browser. The selection of imagery was guided by data quality, with priority given to scenes exhibiting minimal or no cloud cover. LULC classification was conducted in Google Earth Engine (GEE) using Sentinel-2 data at a spatial resolution of 10 m. Accuracy assessment of the classification was carried out using the Cohen's kappa (κ) and overall accuracy (OA) and calculated from the following equations

$$OA = \frac{P_c}{P_n} \times 100 \quad \text{Eq. (1)}$$

Where P_c is the number of pixels classified correctly and P_n is the total number of pixels.

$$\kappa = \frac{N \sum_{i=1}^r x_{ii} - \sum_{i=1}^r (x_i + x_{+i})}{N^2 \sum_{i=1}^r (x_i + x_{+i})} \quad \text{Eq. (2)}$$

where;

where r = the number of rows and columns in the error matrix, x_{ii} = the number of observations in row i and column i , x_{i+} = the marginal total of row i , x_{+i} = the marginal total of column i , and N = the total number of observations. The magnitude ranges from -1 to $+1$. It agrees well with the categorization if the value is larger than $+0.5$ (Thomas *et al.*, 2004). If

the number is 0, it means that the agreement is just a coincidence. Negative values of κ can be understood as the amount of agreement that could only happen by chance (Brennan *et al.*, 1992). The overall best performance is selected for further classification of images and integrated to study the spatiotemporal changes. The overall accuracy shows 0.89.

The data analysis was carried out using XLSTAT. Tukey's honestly significant difference (HSD) test was used to compare the means of soil parameters, microbial biomass quotient of different land-use types. Two-way ANOVA was used to measure the relationship between the soil, depth, season and land use. Pearson's multiple correlation was used to determine the relationship of MBC and TN with other soil parameters and environmental covariant in different land use. Multivariate relationships and data patterns were explored through Principal Component Analysis (PCA) using R Commander. To account for varying scales of measurement, soil attributes were standardized via z-scores. Principal components with Eigenvalues > 1.0 were retained to identify the primary drivers of variance. The resulting biplots were used to visualize the spatial clustering of land-use types and the directional influence of microbial and physicochemical variables on soil quality. Additionally, a Scree Plot was used to visually confirm the "elbow" point, ensuring that the retained PCs captured a significant cumulative percentage (typically $> 70\%$) of the total variance in the soil-microbial system. Graphs were prepared using Origin 2021 and ArcGIS pro was used to generate maps.

RESULTS

Soil properties

The physical and chemical properties of the studied soils were dynamically modulated by the main effects and interactive combinations of land use, seasonal variation, and soil depth (Table 1). The interaction between land use and season exerted a highly significant influence ($P < 0.001$) on nearly all measured parameters, except SIC, showing no significant response. Soil pH values remained consistently and strongly acidic across all sampling sites.

Table 1: Two-way ANOVAs showing significant differences in soil characteristics.

Source	pH (%)	WHC %	BD %	SM %	SIC %	SOC (mg.ha ⁻¹)	MBC (μg.g ⁻¹)	TN (mg.ha ⁻¹)
Land use and season								
Land use	57.1***	51.2***	34.6***	25.1***	2.1 ^{NS}	1142.9***	47.1***	35***
Season	294.1***	149.9***	11.6***	58.6***	3.8*	12.1***	10.8***	156.2***
Land use x season	90.3***	56.9***	8.4***	12.8***	7.9 ^{NS}	34.5***	18.2***	18.1***
Soil depth and land use								
Soil depth	338.8***	669.2***	54.3***	158.6***	0.1 ^{NS}	629.1***	117.9***	1.75***
Land use	84.4***	1010.5***	110.2***	373.9***	13.5***	1972.7***	916.7***	0.88***
Soil depth x land use	14.5***	117.8***	8.4***	106.5***	0.5 ^{NS}	67.6***	266.1***	0.69***

Values represent F values. In each panel, * denotes $P < 0.05$, ** denotes $P < 0.01$, and *** denotes $P < 0.001$.

WHC water holding capacity, BD bulk density, SM soil moisture, SIC soil inorganic carbon, SOC soil organic carbon stock, MBC microbial biomass carbon, TN total nitrogen.

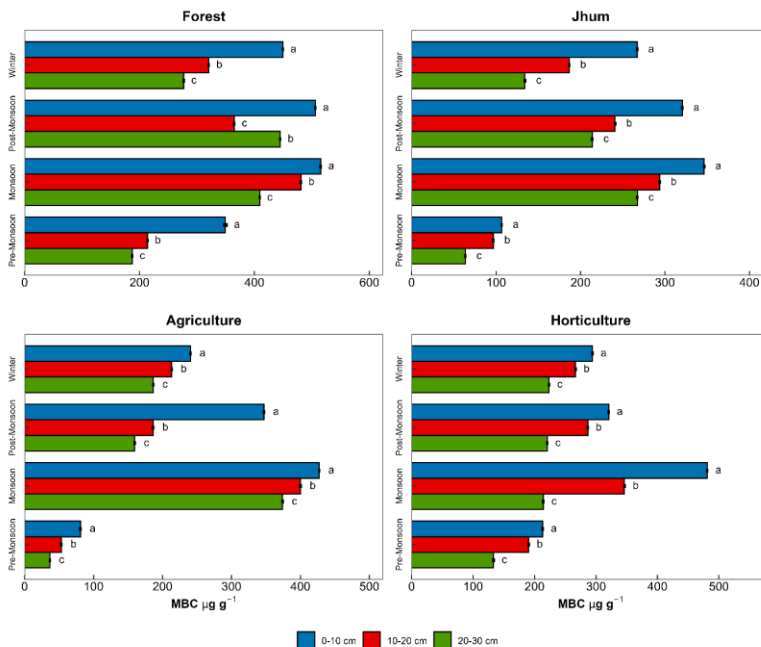
Land use independently and strongly altered bulk density ($F = 34.6$, $P < 0.001$); while undisturbed forest soils maintained uniformly low BD horizons, agricultural and Jhum systems exhibited elevated subsurface compaction ($1.0\text{--}1.5\text{ g cm}^{-3}$). WHC peaked in the forest ecosystem, which also displayed the most pronounced depth-dependent stratification ($F = 669.2$) across all land use. Furthermore, the interaction between soil depth and land use were significant ($P < 0.001$) for pH, WHC, BD, SM, SOC, MBC, and TN. The interaction between soil depth and land use was highly significant ($p < 0.001$) for pH, WHC, BD, SM, SOC, MBC, and TN, demonstrating that the impact of land use changes varies distinctively across the soil profile. In contrast, SIC dynamics were independent of soil depth ($F = 0.1$, NS) and showed no significant depth and land use interaction ($F = 0.5$, NS). Instead, SIC variations in the profile were strictly driven by the main effect of land use ($F = 13.5$, $p < 0.001$).

Microbial Biomass Carbon and Total Nitrogen

Distinct seasonal and depth-dependent dynamics of MBC and TN were observed across different land-use systems, revealing novel patterns of nutrient-microbe interactions. From Figs. 3 and 4 we can observed that in forest soils, MBC activity decreases with soil depth, contrasting with a consistent decline in TN. The highest MBC was recorded in the forest land-use system, reaching approximately $520\text{ }\mu\text{g g}^{-1}$ in the 0–10 cm layer during the post-monsoon season. Comparable but slightly lower values were observed in horticultural soils ($480\text{ }\mu\text{g g}^{-1}$) and Jhum lands ($350\text{ }\mu\text{g g}^{-1}$). The lowest MBC occurred in agricultural soils, in the 20–30 cm layer during the pre-monsoon season, where values declined to approximately $40\text{--}50\text{ }\mu\text{g g}^{-1}$ (Fig. 3).

Fig. 3: Seasonal variation of soil MBC $\mu\text{g g}^{-1}$ at three depths in four land use in Phek, India.

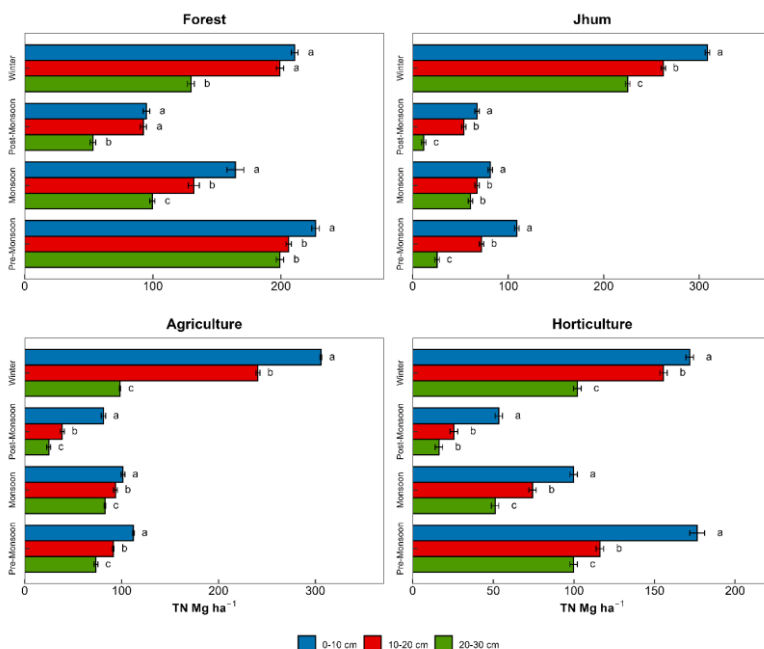
Different letters denote significant differences ($P < 0.05$) among depths, determined by multiple comparisons with the Tukey HSD test.



Across all seasons and depths (Fig. 4), Jhum exhibited the highest TN values, in the soil surface soil, where TN reached its maximum during winter (310 Mg ha⁻¹). The lowest TN values were consistently recorded in the agricultural system in the deeper soil layer (20–30 cm) during the post-monsoon season (25–30 Mg ha⁻¹). Forest and horticultural systems maintained intermediate TN levels, with values generally decreasing with soil depth.

Fig. 4: Seasonal variation of TN Mg.ha⁻¹ at three depths in four land use in Phek, India.

Different letters denote significant differences ($P < 0.05$) among depths, determined by multiple comparisons with the Tukey HSD test.



Effects of Season and Soil Depth on Soil MBC and TN within Different Land-use Systems

The two-way ANOVA revealed significant effects of season, soil depth, and their interaction on both MBC and TN within all land-use systems ($p < 0.001$; Table 2). In forest soils, significant season $\times$ depth interactions were observed for MBC ($F = 17.14$) and TN ($F = 39.5$), with the interaction effect being more pronounced for TN. In Jhum soils, soil depth exerted the strongest influence on MBC ($F = 133.3$, $p < 0.001$) among the studied land-use systems, while season remained a significant source of variation for both MBC and TN. Agricultural soils also showed significant effects of season, depth, and their interaction on both parameters. In horticultural soils, both MBC and TN were strongly influenced by season and soil depth; notably, TN exhibited the highest season $\times$ depth interaction among all land-use systems ($F = 308.2$, $p < 0.001$). These results indicate that seasonal fluctuations and vertical soil stratification jointly regulate microbial biomass carbon and total nitrogen dynamics across different land-use systems.

Table 2: Two-way ANOVA on the effect of seasons and soil depth on soil MBC and TN at different land use.

LULC	Parameters	Factors	DF	F value	Significance (p)
Forest	MBC	Season	3	348.4	<0.001
		Depth	2	13.9	<0.001
		Season x Depth	6	17.14	<0.001
	TN	Season	3	1551.5	<0.001
		Depth	2	502.9	<0.001
		Season x Depth	6	39.5	<0.001
Jhum	MBC	Season	3	329	<0.001
		Depth	2	133.3	<0.001
		Season x Depth	6	12.4	<0.001
	TN	Season	3	345.1	<0.001
		Depth	2	33.2	<0.001
		Season x Depth	6	29.2	<0.001
Agriculture	MBC	Season	3	884.7	<0.001
		Depth	2	16.7	<0.001
		Season x Depth	6	29.9	<0.001
	TN	Season	3	718.8	<0.001
		Depth	2	12.2	<0.001
		Season x Depth	6	45.6	<0.001
Horticulture	MBC	Season	3	539	<0.001
		Depth	2	47.5	<0.001
		Season x Depth	6	21.5	<0.001
	TN	Season	3	2428.8	<0.001
		Depth	2	1042.9	<0.001
		Season x Depth	6	308.2	<0.001

Correlation matrix of MBC and TN with soil properties

The correlation matrix between soil MBC and environmental variables and soil parameters across various land-use types (Table 3) demonstrated a positive correlation with BD ($r = 0.56$) and WHC ($r = 0.339$) with significance at $p < 0.001$, while parameters such as SM, SIC and RF shows a moderate negative correlation with microbial activity.

Table 3: Correlation table of Pearson coefficient between MBC and soil properties and climatic variables.

	MBC	SM	WHC	BD	pH	SOC	SIC	ST	RF	RH
MBC	1									
SM	-0.409*	1								
WHC	0.339*	-0.132 ^{NS}	1							
BD	0.560*	0.008 ^{NS}	0.072 ^{NS}	1						
pH	-0.285 ^{NS}	0.401*	0.329*	-0.434*	1					
SOC	0.125 ^{NS}	0.341*	0.547*	-0.386*	0.886**	1				
SIC	-0.304*	0.056 ^{NS}	0.303*	-0.524*	0.602**	0.564*	1			
ST	-0.152 ^{NS}	0.222 ^{NS}	-0.057 ^{NS}	0.530*	-0.284 ^{NS}	-0.218 ^{NS}	0.015 ^{NS}	1		
RF	-0.369*	0.414*	0.331*	-0.146 ^{NS}	0.566*	0.676**	0.448*	0.451*	1	
RH	-0.078 ^{NS}	-0.036 ^{NS}	0.279 ^{NS}	-0.423*	0.722**	0.609**	0.538*	-0.243 ^{NS}	0.506*	1

MBC microbial biomass carbon, SM moisture, WHC water holding capacity, BD bulk density, pH soil pH, SOC soil organic carbon, SIC soil inorganic carbon, ST soil temperature, RH relative humidity, RF rainfall

*Significance at $p < 0.01$, **significant at $p < 0.001$, NS non-significant

TN exhibited several significant correlations with key soil parameters, reflecting its central role in regulating soil fertility and microbial functioning across land-use systems (Table 4). TN showed a positive correlation with WHC ($r = 0.426$) and RH ($r = 0.311$) reveals that greater moisture-retention capacity and rainfall regimes tend to accumulate more nitrogen.

Table 4: Correlation table of Pearson coefficient between TN and soil properties and climatic variables.

	TN	SM	WHC	BD	pH	SOC	SIC	ST	RF	RH
TN	1									
SM	-0.316 *	1								
WHC	0.426 *	-0.132 ^{NS}	1							
BD	0.030 ^{NS}	0.008 ^{NS}	0.072 ^{NS}	1						
pH	0.170 ^{NS}	0.401 *	0.329 *	-0.434 *	1					
SOC	0.131 ^{NS}	0.263 ^{NS}	0.276 ^{NS}	0.114 ^{NS}	0.244 ^{NS}	1				
SIC	-0.017 ^{NS}	0.056 ^{NS}	0.303 *	-0.524 *	0.602 **	0.433 *	1			
ST	-0.670 **	0.222 ^{NS}	-0.057 ^{NS}	0.530 *	-0.284 ^{NS}	0.245 ^{NS}	0.015 ^{NS}	1		
RF	-0.332 *	0.414 *	0.331 *	-0.146 ^{NS}	0.566 *	0.317 *	0.448 *	0.451 *	1	
RH	0.311 *	-0.036 ^{NS}	0.279 ^{NS}	-0.423 *	0.722 **	-0.062 ^{NS}	0.538 *	-0.243 ^{NS}	0.506 *	1

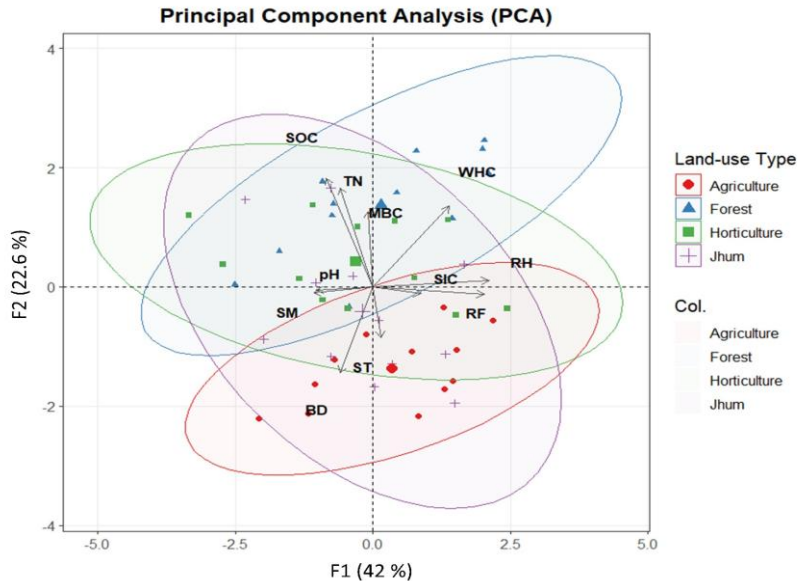
TN microbial biomass carbon, SM moisture, WHC water holding capacity, BD bulk density, pH soil pH, SOC soil organic carbon, SIC soil inorganic carbon, ST soil temperature, RH relative humidity, RF rainfall

*Significance at $p < 0.01$, **significant at $p < 0.001$, NS non-significant

However, it shows moderate negative correlation with SM ($r = -0.316$), ST ($r = -0.670$) emphasizing that excessively high SM and high ST conditions may lead to nitrogen losses through leaching or denitrification. Although correlations with SOC ($r = 0.131$) and SIC ($r = -0.017$) were not statistically significant, the slight positive trend with SOC implies that organic matter contributes partially to nitrogen retention through microbial immobilization. No significant relationships were found between TN and BD ($r = 0.030$) or pH ($r = 0.170$), indicating that nitrogen content is less influenced by compaction or acidity within the land use region.

The PCA coordinates (Fig. 5) captured 64.6 % of the total variance, with PC1 and PC2 contributing 42.0 % and 22.6 %, respectively. The ordination shows distinct associations among soil properties and land-use systems. SOC, TN, MBC, and WHC were grouped within the positive region of PC2, indicating strong positive relationships among these variables. In contrast, BD and ST were positioned in the negative region of PC2 and were negatively associated with SOC, TN, MBC, and WHC. Relative humidity (RH), rainfall (RF), and SIC were aligned primarily along the positive side of PC1, contributing substantially to the separation of samples along this axis. Forest sites were associated with higher SOC, TN, MBC, and WHC and were primarily distributed along the positive PC2 axis, whereas agricultural sites were associated with higher BD and ST and occurred mainly along the negative PC2 axis. Horticultural and Jhum systems occupied intermediate positions and showed substantial overlap, indicating similar soil characteristics. Overall, variation in SOC, TN, MBC, WHC, BD, and ST was the main factor differentiating land-use types along PC2.

Fig. 5: Principal component analysis (PCA) of soil parameters in four different land use in Phek, Nagaland, India.



DISCUSSION

The results of the present study revealed that the soil physical (SM, WHC, BD, and pH) and chemical (SOC, SIC, and TN) properties shows a significant variation in different land use. Similarly significant variations were also observed by Evangelou *et al.* (2021). This underscores the profound impacts of LULC transformations across these fragile mountainous landscapes (Gashu *et al.*, 2026). The baseline soil pH remained strongly acidic (4.0-6.0) with minimal variation across land uses, seasons, and soil depths, save for a slight post-monsoon increase (Fig. S1 & S2). This consistent acidity reflects inherent parent material weathering and high-rainfall leaching characteristic of the region, though minor spikes in forest topsoils during post-monsoon intervals match observations by Buruso *et al.* (2023), who noted higher relative pH values in natural forests than cultivated systems due to alkaline base cation cycling within undisturbed organic layers. Forest soils consistently exhibited the highest WHC, SM, and SOC, followed closely by traditional Jhum systems (Fig. S1). The settled agricultural and horticultural land showed comparatively lower values. This pattern reflects long-term structural degradation driven by vegetation removal and tillage intensification. The elevated SOC and nutrient status of undisturbed forests are tied directly to sustained, diverse litterfall and dense root biomass networks (Mgelwa *et al.*, 2025). These natural inputs are disrupted during agricultural conversion, accelerating the mineralization of labile carbon fractions and triggering topsoil erosion, an observation aligning with Kebebew *et al.* (2022).

The vertical distribution of soil properties revealed strong stratification across all land-use systems ($P < 0.05$). This depth-dependent decline was particularly pronounced for SOC and TN, indicating that topsoil is highly sensitive to land-use change and management practices. Similar observations were reported by Gong *et al.* (2022), who found significant reductions in active carbon and nitrogen pools with increasing soil depth. The concentration of carbon and nitrogen in surface horizons is largely driven by greater litter deposition, root biomass, and microbial activity, whereas lower organic inputs, reduced aeration, and increased bulk density in deeper layers restrict biological and biochemical processes (Sahoo *et al.*, 2023; Grüneberg *et al.*, 2014; Zhao *et al.*, 2014; Francaviglia *et al.*, 2017). Forest soils maintained substantially higher baseline concentrations than managed systems, highlighting their role as important reservoirs of carbon and nitrogen. In contrast, conversion to agriculture and horticulture resulted in significant carbon depletion throughout the soil profile. These findings are consistent with Padbhushan *et al.* (2022), who reported losses of total carbon (21 %), labile carbon (25 %), non-labile carbon (32 %), microbial biomass carbon (26 %), and SOC stocks (41.2 %) following forest conversion to cultivated land. Similar trends were reported by Buruso *et al.* (2023), who documented significantly greater nutrient retention in natural forests than in cultivated ecosystems.

The depletion of organic matter following land-use conversion had important implications for soil physical quality. Lower SOC levels in cultivated soils were accompanied by reduced WHC and SM, highlighting the role of organic matter in regulating soil water storage. Similar conclusions were drawn by Chen *et al.* (2022), who identified SOC and TN as the dominant regulators of soil quality following land-use transitions. Likewise, Ma *et al.* (2025) reported substantially greater SOC concentrations and aggregate stability in forest ecosystems than in agricultural lands, while Torres *et al.* (2024) and Amoakwah *et al.* (2022) highlighted the widespread loss of soil carbon following forest-to-cropland conversion. The deterioration of soil structure following cultivation was further evident from BD patterns. Forest soils maintained uniformly low BD values, whereas agricultural and Jhum systems exhibited elevated subsurface BD ($1.0\text{--}1.5\text{ g cm}^{-3}$), indicating soil compaction and structural degradation caused by repeated tillage, reduced root penetration, and rainfall impact on

exposed soils. Similar increases in BD following land-use conversion have been reported by Özdemir *et al.* (2022) and Buruso *et al.* (2023), who observed significantly higher compaction levels in cultivated soils than in undisturbed forests. In contrast, SIC remained consistently low (<0.7) across all land-use systems and showed limited seasonal and depth-related variation, suggesting that carbon storage in these humid subtropical soils is predominantly governed by organic rather than inorganic carbon pools.

Land-use conversion substantially altered MBC and TN, highlighting the close linkage between soil biological activity and nutrient cycling (Figs. S3a and S3b). The MBC and TN show the highest in forest following agriculture, horticulture and jhum. Forest soils maintained the highest MBC and TN because continuous litterfall, root turnover, and minimal disturbance create favorable microclimatic conditions that promote microbial activity, nutrient retention, and long-term carbon stabilization. Similar findings have been reported by Karimzadeh *et al.* (2024), who observed significantly greater microbial biomass carbon and nitrogen in forest soils than in agricultural systems. Likewise, Liu *et al.* (2023) reported the highest topsoil MBC values in forest ecosystems and the lowest values in croplands. Pan *et al.* 2024 has reported that the conversion of natural forest increases MBC activities. Agricultural soils exhibited a marked reduction in MBC, likely resulting from SOC depletion, soil disturbance, and reduced organic matter inputs. Similar declines have been reported by Paddhushan *et al.* (2022), Díaz-Vallejo *et al.* (2021), and Kara & Bolat (2008). Interestingly, despite lower MBC, agricultural soils maintained relatively higher TN concentrations. This pattern may reflect enhanced nitrogen mineralization and reduced microbial immobilization, resulting in the accumulation of readily available nitrogen forms. Although Jhum retained relatively higher SOC and TN than permanent agriculture, repeated slash-and-burn practices and shortened fallow periods can accelerate nutrient losses and reduce microbial stability over time. The decline in TN with depth in Jhum soils may be associated with downward movement of soluble nitrogen following intense monsoon rainfall and erosion on steep slopes, which promotes nitrogen redistribution beyond the biologically active surface layer. Similar observations have been reported for shifting cultivation systems where nutrient availability is initially enhanced by ash deposition but declines with continued cultivation and reduced fallow periods (Chen *et al.*, 2022; Dahmani *et al.*, 2025). In contrast, horticultural soils exhibited relatively higher MBC but lower TN concentrations. This inverse relationship suggests greater microbial immobilization of nitrogen, whereby active microbial communities assimilate available nitrogen into microbial biomass, thereby reducing the measurable soil nitrogen pool. Similar interactions between microbial biomass and nitrogen cycling have been described by George *et al.* (2013), Malik *et al.* (2018), Soleimani *et al.* (2019), and Chen *et al.* (2022). Collectively, these findings indicate that agricultural systems are dominated by mineralization-driven nutrient cycling, whereas horticultural systems retain a greater proportion of nitrogen within microbial biomass. The response of Jhum soils was intermediate between forest and agricultural systems.

Seasonal variability strongly influenced MBC and TN dynamics. MBC peaked during the monsoon season and declined during the pre-monsoon period (Figs. S3c), reflecting the strong dependence of microbial activity on soil moisture availability. Favorable temperature and moisture conditions during the rainy season stimulate decomposition, substrate turnover, and microbial growth, resulting in increased microbial biomass. Similar seasonal peaks in microbial biomass have been reported by Singh *et al.* (2021), and Rawat *et al.* (2021), all of whom demonstrated strong positive relationships between microbial biomass and soil moisture in tropical ecosystems. In contrast, TN peaked during winter and declined during the post-monsoon period (Fig. S3d). Reduced rainfall during winter may limit nitrogen leaching losses and promote the accumulation of mineralized nitrogen within the soil profile,

while lower plant nutrient demand further enhances nitrogen retention. The pronounced decline in TN during the post-monsoon season is likely associated with nitrogen losses through leaching and surface runoff following prolonged monsoon rainfall, particularly in steep mountainous landscapes where nutrient retention is limited. Enhanced plant uptake and microbial assimilation following the rainy season may further contribute to the reduction in measurable soil nitrogen. Similar seasonal patterns have been reported by Sahoo *et al.* (2023), Buruso *et al.* (2023) and Liu *et al.* (2018) who highlighted the influence of rainfall, mineralization, and nutrient transport processes on seasonal nitrogen dynamics. Seasonal fluctuations were most pronounced in Jhum and agricultural systems, whereas forest and horticultural systems displayed comparatively stable profiles, suggesting that land-use intensification increases temporal variability in microbial activity and nutrient cycling, thereby reducing ecosystem resilience.

Soil depth exerted a significant influence on most measured variables. Parameters like WHC, SOC declined consistently with increasing depth (Figs. S3e and S3f), reflecting the concentration of organic matter, litter inputs, and fine root biomass in surface horizons. Similar depth-dependent reductions have been reported by Sahoo *et al.* (2023), Gong *et al.* (2022), and Lepcha *et al.* (2020). Forest soils maintained comparatively high SOC and TN even at deeper layers, indicating more efficient carbon stabilization and nutrient retention. Although both MBC and TN decreased with depth (Figs. S3e and S3f), MBC exhibited a slower rate of decline than TN, suggesting that active microbial communities persist in subsurface horizons despite reduced nutrient availability. Similar observations were reported by Gong *et al.* (2022), who demonstrated strong relationships between MBC, SOC, and TN across soil profiles. The increase in bulk density with depth further reflects reduced organic matter content and greater compaction in lower horizons, as previously documented by Grüneberg *et al.* (2014), Zhao *et al.* (2014), and Francaviglia *et al.* (2017).

The PCA results demonstrated that soil variation among land-use systems was governed primarily by a fertility–degradation gradient. SOC, TN, MBC, and WHC clustered closely together, indicating that soil organic matter is the central regulator of nutrient cycling, microbial activity, and hydrological functioning. Forest sites were strongly associated with these positive soil quality indicators, highlighting the role of continuous organic matter inputs and minimal disturbance in maintaining ecosystem stability. Conversely, agricultural sites were associated with higher bulk density and soil temperature, reflecting structural degradation and reduced biological functioning. Jhum and horticultural systems occupied intermediate positions, suggesting transitional ecological states where both conservation-driven and disturbance-driven processes operate simultaneously. Similar interpretations have been reported by Chen *et al.* (2022) and Mbibueh *et al.* (2025), who identified soil organic matter as the principal determinant of soil resilience and ecosystem functioning following land-use change.

CONCLUSION

The results of the present study revealed that land use, season, and soil depth significantly influence the physical and chemical properties of soil and significantly alter the biogeochemical coupling of MBC and TN. Natural forests serve as critical ecological stabilizers, maintaining high microbial biomass and nutrient retention through continuous organic inputs and minimal disturbance. Conversely, intensive agriculture and shifting cultivation trigger significant vertical nutrient depletion and structural degradation, as evidenced by increased bulk density and reduced MBC. The seasonal decoupling of MBC

and TN suggests that microbial communities are highly sensitive to moisture and temperature-driven shifts in substrate availability. Our results indicate that current land-management practices are accelerating soil degradation in Nagaland due to highly practise of jhum cultivation. To ensure long-term ecosystem sustainability, regional management must prioritize the preservation of soil organic matter and the implementation of conservation-based agricultural practices to support microbial resilience and nutrient conservation.

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CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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SUPPLEMENTARY FILE

Fig. S1: Comprehensive evaluation of soil physicochemical and biological properties across a matrix of LULC types and seasonal periods.

Vertical columns correspond to distinct management systems (Forest, Jhum, Agriculture, and Horticulture), while horizontal rows display individual parameters ((pH, water holding capacity [WHC], bulk density [BD], soil moisture [SM], soil organic carbon [SOC] and soil inorganic carbon [SIC])), each optimized on its native scale. Vertical grouped bars represent the calculated mean values ($n = 3$), color-coded explicitly by seasonal transitions (Monsoon = green, Post-Monsoon = orange, Winter = purple, Pre-Monsoon = pink). Dashed trendlines connect seasonal data nodes to illustrate temporal trajectories and cyclical fluctuations within each ecosystem.



Fig. S2: Interactive effects LULC transitions and soil profile depth on soil properties.

Individual panels represent a matrix grid of measured parameters (pH, water holding capacity [WHC], bulk density [BD], soil moisture [SM], soil organic carbon [SOC] and soil inorganic carbon [SIC]), across four land management types (Forest, Jhum, Agriculture, and Horticulture). Bars represent the calculated mean values of three independent biological replicates ($n = 3$), color-coded explicitly by soil depth layers (0–10 cm = blue, 10–20 cm = orange, 20–30 cm = red). Dashed lines delineate the directional trend of vertical nutrient attenuation and physical profile stratification. All parameters are scaled independently on the y-axes to optimize visual resolution across varying data bounds.

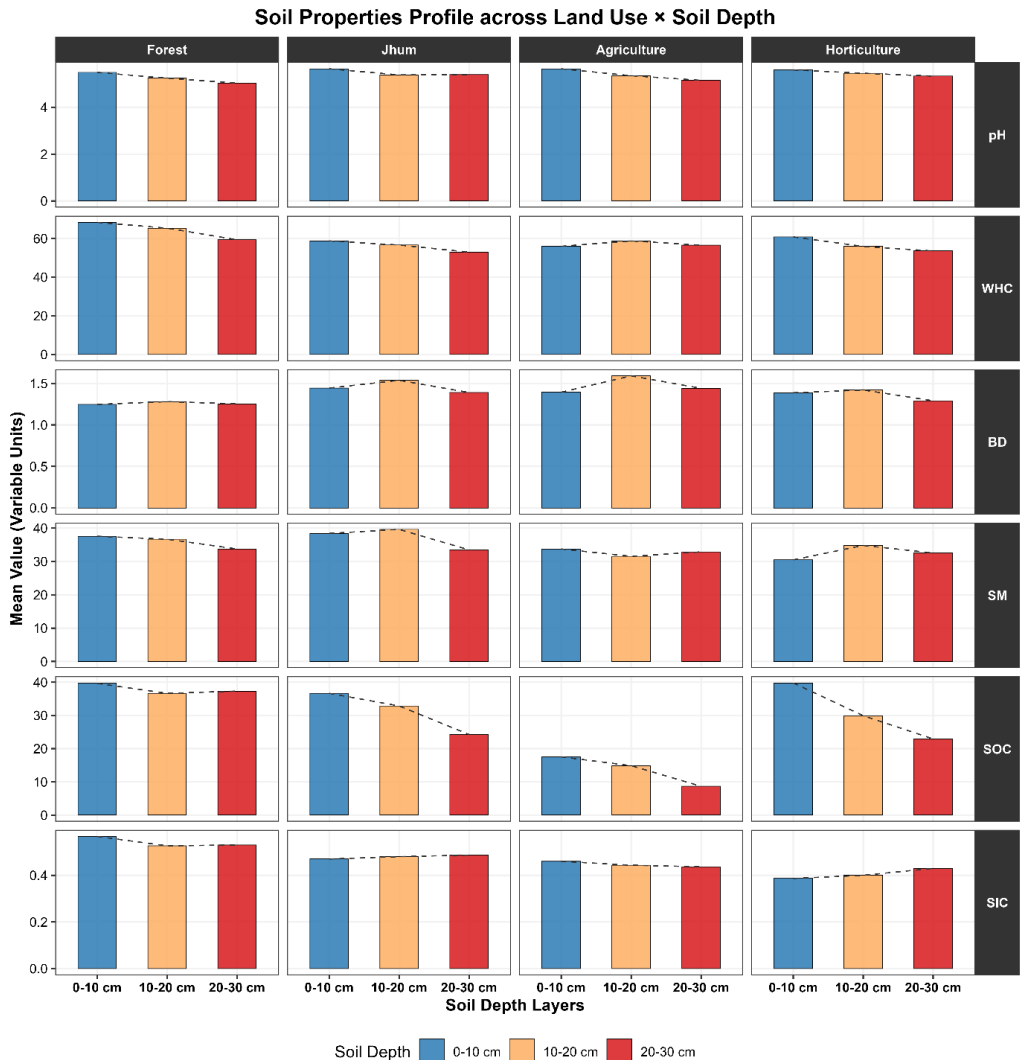


Fig. S3: Variance of MBC and TN content across different land use type, seasonal variations and soil depth.

Mean value indicated by different letters case in different soil depth indicates their significance $p<0.05$ according to Tukey's HSD test

