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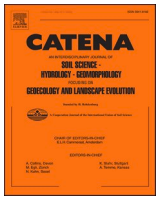

Impact of seasonality, moss cover, and forest types on soil microbial biomass and enzymatic activity: An environmental prospective from the Himalaya

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ABSTRACT

Soil microbial biomass (SMB) is a key storehouse of carbon and nitrogen, driving biogeochemical cycles. Understanding soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN), and soil enzymes is crucial for global nutrient cycling. Soil biochemistry is linked to seasonal and vegetation-related soil changes, but little is known about how season, moss cover, and forest types collectively affect SMB and enzymes. In this context, our study examined five temperate forest types (*Pinus roxburghii, Quercus leucotrichophora, Q. floribunda, Q. semecarpifolia, and Cupressus torulosa*) and two ground cover types (moss-covered and bare soil) to assess their impacts on SMBC, SMBN, and enzymatic activity in the Indian Central Himalayas during the rainy and winter seasons. SMBC and SMBN were quantified using the chloroform fumigation-extraction method, while enzymatic activity was assessed using established protocols. Forest types, ground cover, and seasons significantly influenced SMBC and enzymatic activity ($p < 0.01$). Forest and ground cover had substantial effects on SMBN ($p < 0.01$), while seasons had negligible effects ($p > 0.05$). Biochemical properties showcased higher values under moss-covered soil in the rainy season and bare soil in winter. *C. torulosa* forests, followed by *Quercus*-dominated forests, exhibited superior SMB and enzymatic activities compared to *P. roxburghii* forests. SMBC and SMBN varied across forest types, ranging from 58.54 to 1913.75 μg/g and 16.77 to 137.81 μg/g, respectively. Soil organic matter and moisture were key abiotic factors influencing soil biochemical properties. The results indicate that moss-covered soil in *C. torulosa* and *Quercus*-dominated forests appears promising for maintaining SMB and enzymatic activity, and should be preferred in forest management plans to improve microbial diversity and soil quality. Overall, this study deepens our understanding of soil enzymatic activity and microbial biomass dynamics in carbon and nitrogen cycling, and highlights the importance of moss ground cover as hotspots for ecosystem functioning.

1. Introduction

Soil microbes are important drivers of energy flow and wield significant influence over ecosystem productivity, playing a crucial role in controlling key terrestrial processes such as nutrient cycling, soil carbon sequestration, organic matter decomposition, nitrogen mineralization, and soil formation (Li et al., 2019; Manral et al., 2022; Wang et al., 2023). Among these processes, soil microbial biomass (SMB) constitutes about 1–5 % of the soil organic matter (SOM) and emerges as a critical labile pool of carbon and other nutrients (Sun et al., 2011; Bargali et al., 2018). In forest ecosystems, SMB significantly governs ecological processes and functioning (Xu et al., 2013; Xue et al., 2014; Rawat et al., 2021). Central components of SMB encompass soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) (Singh and Gupta, 2018; Chen et al., 2021). Soil microbial biomass serves as a key biological indicator for soil fertility, ecosystem functioning (Jhariya and Singh, 2021a, 2021b; Manral et al., 2022), vegetation composition (Borga et al., 1994), and the ongoing impacts of climate change (Schindlbacher et al., 2011), as it responds rapidly to soil properties such as pH, moisture, temperature, nutrients, organic matter type and quantity, oxygen, and redox status (Diaz-Ravina et al., 1995; Zalman et al., 2018). The fluctuations in microbial biomass can significantly influence the response of biogeochemical cycling to environmental warming (Tian et al., 2023). Moreover, soil microbial biomass stands as

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an effective environmental management tool and a pivotal parameter for assessing soil functional status (Bargali et al., 2018; Karki et al., 2021).

Soil microbes also produce extracellular enzymes that serve as primary regulators of soil biological activities. Soil enzymes are critical for mineralization of carbon, nitrogen, phosphorus, and sulphur, thus controlling nutrient availability in soil. For instance, β-glucosidase facilitates carbon acquisition (Ghiloufi et al., 2019), urease is central to nitrogen cycling (Adetunji et al., 2017), phosphatase propels phosphorus mineralization (Schaub et al., 2019), and arylsulfatase supports sulphur mineralization (Piutti et al., 2015). Estimates of microbial biomass and enzymatic activity offer insights into soil fertility and soil functional status (Meena and Rao, 2021; Shankar and Garkoti, 2023). The ability of extracellular enzymes to adapt swiftly to soil environment changes serves as an indicator to assess nutrient limitations in forest ecosystems (Allison et al., 2007; Zhang et al., 2023). Thus, the dynamics of microbiological properties and the flux of carbon and nutrients within microbial biomass hold functional significance in soil ecosystems.

Himalayan ecosystems showcase a spectrum of soil types and vegetation, varying substantially in biogeochemical traits (Bargali et al., 2019; Joshi and Garkoti, 2023). The heterogeneity across mountain ranges, slopes, and altitudes leads to rapid shifts in vegetation types, resulting in diverse microclimates throughout the landscape (Manish and Pandit, 2018). Soil microorganisms respond concurrently to environmental changes (Liu et al., 2016; Agnihotri et al., 2023), soil qualities (Yao et al., 2017), and vegetation types (Bargali et al., 2018). Vegetation cover exerts an influence on soil quality indicators and microbial community composition, thereby impacting soil microbial biomass, enzymatic activity, and microbial efficiency in carbon utilization (Bargali et al., 2018). Forest composition shapes microbial processes within carbon and nitrogen cycles due to alterations in soil physical and chemical properties, quality and quantity of litter and root exudates, and decomposition processes (Bargali et al., 2015; Salunkhe et al., 2018; Manral et al., 2022).

In the Indian Central Himalayan Region (ICH), the temperate forests thrive within a multifaceted ecosystem marked by varying topography, climate, soil conditions (Rawat et al., 2021), and seasonality (Bargali et al., 2018). Notably seasonal, these ecosystems bear profound implications for functioning and biodiversity (Williams et al., 2017; Rawat et al., 2021). However, information concerning seasonal variations in SMBC, SMBN, and enzymatic activity remains scarce within the temperate forests of ICH (Bargali et al., 2018; Rawat et al., 2021; Siwach et al., 2021).

Although vascular plants provide substantial insights into how primary producers shape ecosystems, non-vascular plants like mosses wield their own ecological influence (Slate et al., 2019). Despite their small size, mosses play significant ecological functions, particularly in temperate ecosystems (Gall et al., 2023), providing vital ecosystem services that have, until recently, gone unnoticed (Ladrón de Guevara and Maestre, 2022). Mosses are poikilohydrous, meaning they desiccate during the dry season and rehydrate in ambient moisture conditions. These seasonal morphological changes significantly influence soil properties and key soil processes (Gornall et al., 2007; Slate et al., 2019). Mosses perform important ecological functions such as increasing carbon and nitrogen fixation, regulating microhabitat conditions (nutrient availability, soil moisture, and temperature), impacting soil microbial biomass and composition, and organic matter accumulation (Delgado-Baquerizo et al., 2018; Bao et al., 2019; Xiao et al., 2023). Additionally, mosses harbour diverse microbiota (Permin et al., 2022), impacting colonization and performance (Su et al., 2020; Cheng et al., 2021). Notably, mosses often enhance soil enzymatic activity, thereby improving soil fertility and regulating carbon and nitrogen cycling (Miralles et al., 2012a, 2012b; Xu et al., 2022; Xiao et al., 2023). The intricate role of mosses in ecosystem functioning, while occasionally enigmatic (Chamizo et al., 2016; Dollery et al., 2022), remains entirely unexplored in India, despite the country hosting approximately 27.5 % of the world's mosses (Banerjee, 1978; Saxena et al., 2006). The distribution of SMBC and SMBN is believed to be influenced by soil properties, ground cover, and forest composition; however, the relative importance of these factors remains unknown. In this sense, this study will improve the understanding of ecological functions of mosses in the temperate forest ecosystems of the Himalayas. The acquired new understanding of SMB and enzymatic activity will provide benchmark carbon and nitrogen dynamics in temperate ecosystems. Thus, the present study will help in facilitating an optimal choice of forest type and ground cover to promote soil microbial health and opting for a sustainable forest management strategy for the Himalayas to counteract climate change.

In this study, we hypothesize that there will be seasonal fluctuations in SMBC, SMBN, and soil enzymatic activity under the impact of moss cover and forest composition. The scientific exploration of the interaction between SMBC, SMBN, enzymatic activity, and other soil properties is lacking. Here we investigate the potential role of SMB and soil enzymes as indicators of soil fertility in future soil monitoring programs with the following research questions:

1) What are the differences in SMBC, SMBN, and soil enzymes among selected Central Himalayan forest types?

2) How do SMBC, SMBN, and enzymatic activity under two ground cover conditions including soil with moss

cover (moss-covered soil) and soil without moss cover (bare soil) change?

3) How do SMBC, SMBN, and soil enzymes vary seasonally and annually under moss cover in different Central

Himalayan forest types?

4) What is the relationship between SMBC, SMBN, and soil enzymes with soil physico-chemical properties?

2. Materials and methods

2.1. Study area

The study was carried out in the Kumaun Himalayan region, situated within the Nainital district of Uttarakhand, India (Fig. 1). Five distinct forest types were carefully chosen for investigation: Chir-pine (*Pinus roxburghii* Sarg.) – PRF, Banj-Oak (*Quercus leucotrichophora* A. Camus) – QLF, Moru-Oak (*Quercus floribunda* Lindl. ex A. Camus) – QFF, Kharsu-Oak (*Quercus semecarpifolia* Sm.) – QSF, and Cypress forest (*Cupressus torulosa* D. Don ex Lamb.) – CSF. These forest types span an elevation range from 1700 m to 2600 m (Siwach et al., 2023). The classification of these forest types adhered to Champion and Seth (1968) forest type classification of India.

The selected study sites are situated in the geological context of the Lesser Himalayan zone, characterized by a prevalence of sedimentary rocks as well as Proterozoic to Palaeozoic crystalline nappe/klippe structures (Panwar and Kumar, 2022). Within this zone, a mixture of sedimentary, igneous, and low-grade transformed rocks, constituting the Krol series, can be observed (Valdiya, 1980; Manral et al., 2022). The Krol series encompasses a sequence of diverse rock types, including limestones, siltstones, as well as shades of grey and greenish-grey, alongside purple slates. Notably, the upper portion of this series, which follows the Blaini formation, features extensive dolomite formations. The Blaini rock layer itself is characterized by the presence of conglomerates and siltstones (Medlicott, 1864). The soil of the region belongs to the mountain or forest soil type and majorly entisols according to Indian and USDA system of soil taxonomic classification, respectively (Mishra, 2020). Soil texture is predominantly sandy loam (Siwach et al., 2023).

The climate of the region exhibits three distinct seasons: winter (November to February), summer (March to May), and the rainy season (June to October). In addition, there is a brief spring period that falls between winter and summer (March), and an autumn phase experienced between the rainy and winter months (November) (Bargali et al., 2018).

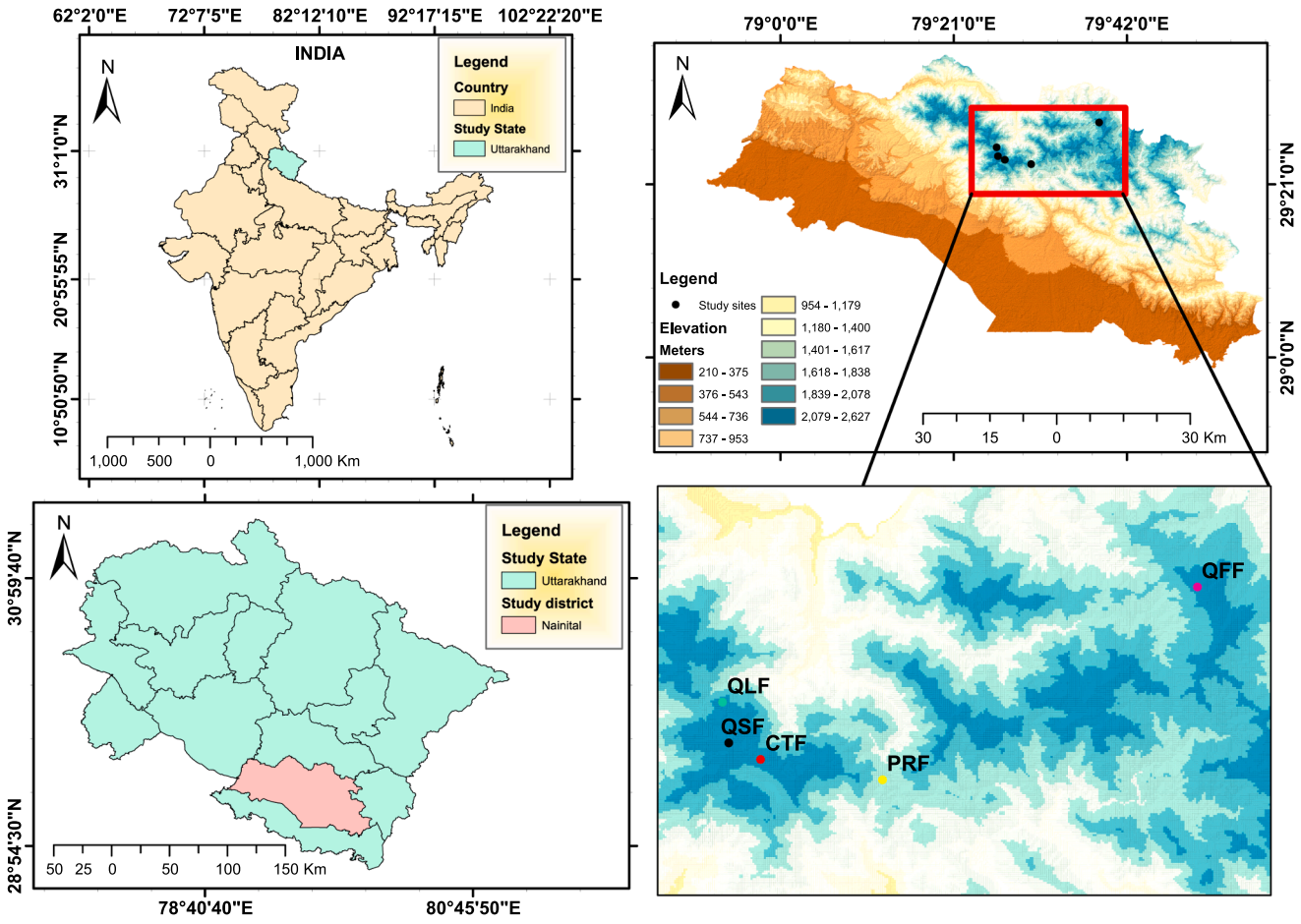

Fig. 1. Map showing study sites in the Nainital district of Uttarakhand, India.

The region receives an annual rainfall of 2095 mm, with the mean monthly precipitation varying from 22 mm in December to 597.33 mm in July. The mean monthly minimum temperature ranges from 3.85 °C to 19.50 °C, while the mean monthly maximum temperature fluctuates between 12.78 °C and 25.86 °C (Fig. 2).

2.2. Soil sampling

Soil samples were collected in a random manner from each of the five forest types under two distinct ground cover conditions: forest soil with moss cover (referred to as "moss-covered soil") and forest soil without moss cover (referred to as "bare soil") (Siwach et al., 2023). Mosses usually cover the forest floor by forming dense and green moss mats which we considered as moss cover and the area of the forest floor where mosses were absent was considered as bare soil. This sampling was carried out over the course of two consecutive years, specifically in 2021 and 2022. The soil sampling took place during the peak time of two different seasons: the rainy (mid July – mid August) and winter (late December – early January). In each forest type, a total of ten random samples were collected for each ground cover type during each season. For a single forest type in each season, 20 samples were collected which represent 10 samples each for moss-covered and bare-soil, hence a total of 40 samples for both seasons from each forest type were collected. 10 samples from the same ground cover in each season and each forest type were thoroughly homogenized to form a composite sample (Bargali et al., 2018, Cheng et al., 2021; Chen et al., 2022). As a result, a total of 40 composite soil samples were collected, which comprised a combination of 400 individual samples (5 forest types × 2 ground covers × 2 seasons × 10 replicates × 2 years). This comprehensive set of samples was designed to represent the five forest types, two different ground covers, and two distinct seasons. It is important to note that the depth of soil sampling was confined to the top 5 cm of soil. This decision is rooted in the understanding that the impact of mosses on soil characteristics is most pronounced in the surface layer (Zhang et al., 2022). To mitigate the potential influence of spatial heterogeneity, the distance between sampling points for the two types of ground covers was maintained at a minimum i.e. about 5 cm. The soil samples obtained were packaged carefully in airtight zip-lock bags to ensure their preservation and

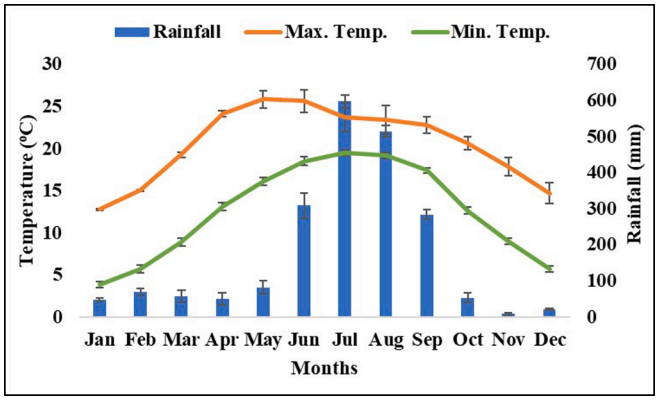

Fig. 2. Monthly variation in rainfall and temperature in the study sites. The values are average for all the study sites and represent a 20-year data average (1999–2019). The data was obtained from: https://en.climate-data. org/asia/india/uttarakhand-763/.

transported to the laboratory for subsequent analysis. Upon arrival at the laboratory, the field-moist soil samples were sieved through a 2 mm sieve and stored at 4 °C for determination of SMBC, SMBN, and soil enzyme activities. From each composite, analyses were carried out in three replicates (40 composites × 3 replicates).

2.3. Soil biochemical properties

2.3.1. Soil microbial biomass carbon and soil microbial biomass nitrogen

The SMBC and SMBN were quantified using the chloroform fumigation-extraction method (Brookes et al., 1985; Vance et al., 1987; Wu et al., 1990). In this approach, ten grams (g) of freshly sieved 2 mm soil were placed within a vacuum desiccator. To this soil, 25 ml of chloroform-free ethanol was added. Subsequently, the samples in the vacuum desiccator were positioned within a Biological Oxygen Demand (BOD) incubator, and allowed to fumigate at 25 °C in dark conditions for 24 h. Simultaneously, an additional 10 g of soil was retained without chloroform, ensuring it remained in a non-fumigated state. After 24 h, the fumigated desiccator was evacuated with a vacuum pump. The fumigated and non-fumigated soil samples were then extracted with 40 ml of 0.5 M K_2SO_4 solution. The resulting filtrate was utilized in the determination of total organic carbon content using a Liqui TOC II Analyzer (Elementar Analysis Systems GmbH, Germany). The quantification of microbial biomass carbon was derived from this analysis. To determine SMBN, the total nitrogen content was determined using a Kjeldahl digestion-distillation unit, (UDK19, VELP Scientifica, Italy) and titrated against 0.2 N HCl. The calculations for SMBC and SMBN were as follows:

$SMBC = E_C/0.45$.

$SMBN = E_N/0.54$.

Where, EC is the difference between C of fumigated soil – C of non-fumigated soil,

and EN is the difference between N of fumigated soil – N of non-fumigated soil.

Soil Microbial Quotients, specifically Soil microbial biomass carbon/Soil organic carbon (SMBC/SOC) and Soil microbial biomass nitrogen/Total Kjeldahl Nitrogen (SMBN/TKN), were computed to assess the microbial efficiency in relation to soil organic carbon and nitrogen content, respectively.

2.3.2. Soil enzymatic activity

Soil dehydrogenase activity (DHA) (μg TPF gDW^{-1} hr^{-1}) was assessed by measuring the reduction of 2,3,5 triphenyltetrazolium chloride (TTC) as per the method outlined by Casida et al. (1964). Six grams (g) of soil were placed in a glass tube and mixed with 0.06 g of $CaCO_3$, 2.5 ml of deionized water, and 1 ml of 3 % TTC solution. The tubes were tightly sealed, agitated to ensure thorough mixing, and subsequently incubated in darkness at 37 °C for 24 h. After incubation, soil samples were rinsed with methanol, and the red methanolic extract of tri-phenyl formazan (TPF) was measured spectrophotometrically at 485 nm.

Soil β-glucosidase activity (GLU) (mg PNP gDW^{-1} hr^{-1}) was assessed by employing p-Nitrophenyl-β-D-glucoside (PNPG) as a substrate following Eivazi and Tabatabai (1988). One gram (g) of fresh soil was mixed with 250 μl of toluene, 4 ml of modified universal buffer (MUB) (pH 6.0), and 1 ml of 25 mM PNPG solution. The resulting mixture was then subjected to incubation in the dark at 37 °C for one hour. Following the incubation, 1 ml of 0.5 M $CaCl_2$ and 4 ml of 0.1 M tris-hydroxymethyl aminomethane (THAM) buffer (pH-12.0), were introduced to the mixture. Subsequently, the intensity of the yellow-coloured p-nitrophenol released as a result of the enzymatic reaction was measured spectrophotometrically at 400 nm.

Soil Phosphatase Activity (PH) (mg PNP gDW^{-1} hr^{-1}) was determined using p-nitrophenyl phosphate (PNPP) as a substrate following Tabatabai and Bremner (1969). One gram (g) of fresh soil was incubated with 4 ml of MUB (pH-6.5), 0.25 ml of toluene, and 1 ml of PNPP solution in a BOD at 37 °C for 1 h. Following incubation, 1 ml of 0.5 M $CaCl_2$ and 4 ml of 0.5 M NaOH were added, and the intensity of yellow-colored p-nitrophenol released was measured at 400 nm.

Arylsulfatase Activity (AS) (mg PNP gDW^{-1} hr^{-1}) was assayed colorimetrically by estimating p-nitrophenol (PNP) released after the addition of substrate p-Nitrophenyl sulfate (PNPS) into the soil (Tabatabai and Bremner, 1970). One gram (g) of soil was mixed with 4 ml of 0.5 M acetate buffer (pH-5.8), 250 μl toluene, and 1 ml PNPS, and incubated at 37 °C for 1 h. After incubation, 1 ml of 0.5 M $CaCl_2$ and 4 ml of 0.5 M NaOH were added, and the absorbance of the filtrate was measured at 400 nm.

Phenol Oxidase Activity (PO) (μM $ABTS^+$ gDW^{-1} min^{-1}) was estimated using ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)) assay (Floch et al., 2007). In this process, 0.1 g fresh soil was mixed with 10 ml of MUB solution (pH-2.0) and 200 μl of 0.1 M ABTS solution. The mixture was then incubated for 5 min at 30 °C in a water bath and later centrifuged at 12,000 rpm at 4 °C for 2 min. The supernatant was transferred to a fresh tube, and the oxidation rate of ABTS to $ABTS^+$ was determined at 420 nm.

Soil Urease Activity (UR) (μg NH_4^+-N gDW^{-1} hr^{-1}) was assayed using urea as the substrate following Tabatabai and Bremner (1972). Fresh soil (5 g) was incubated at 37 °C for 2 h with 0.2 ml toluene, 9 ml THAM, and 1 ml of 0.2 M urea solution. Following incubation, samples were extracted using KCl-Ag_2SO_4 solution, and Ammonium Nitrogen (NH_4^+-N) in the filtered soil samples was estimated by carrying out steam distillation using a Kjeldahl digestion-distillation unit (UDK19, VELP Scientifica, Italy).

2.4. Statistical analysis

The normality and homoscedasticity of the data were assessed through Shapiro and Levene's tests. To determine significant distinctions between two ground covers during both seasons, a multiple unpaired sample *t*-test was conducted utilizing GraphPad Prism software (Ver. 9.5.1). Pearson's correlation analysis was performed to identify significant correlations between soil physico-chemical and biochemical properties studied. Principal Component Analysis (PCA) was used to further examine the correlation patterns. Pearson and PCA analysis were conducted using PAST software (PAST ver.4.09). All the data in figures and tables were expressed as mean of the three replicates ± Standard Deviation (S.D.).

3. Results

3.1. SMBC and SMBN variation

Soil microbial biomass carbon (SMBC) and soil microbial biomass nitrogen (SMBN) were found to be influenced by both seasons and forest types (Fig. 3). Across the various forest types, the range of SMBC values spanned from 58.54 to 1913.75 μg/g, whereas for SMBN, the range was from 16.77 to 137.81 μg/g. Notably, both SMBC and SMBN exhibited their highest concentrations during the rainy season, while the lowest concentrations were observed during the winter season. Specifically, the QFF exhibited the highest SMBC value (1913.75 μg/g) and the lowest value (58.45 μg/g) within the same forest type. Similarly, for SMBN, CSF had the highest value (137.81 μg/g), whereas the lowest value (16.77 μg/g) was observed in the same forest type. Throughout both years, the concentrations of SMBC and SMBN were consistently higher in *Quercus*-dominated forests compared to PRF.

3.2. Effects of ground cover on SMBC and SMBN over the season

Soil microbial biomass carbon (SMBC) and nitrogen (SMBN) values varied significantly under different ground covers during different seasons (Fig. 3). Moss-covered soil exhibited greater SMBC and SMBN during the rainy season, while bare soil had higher SMBC and SMBN during the winter. In the rainy season, the highest SMBC value (1913.75

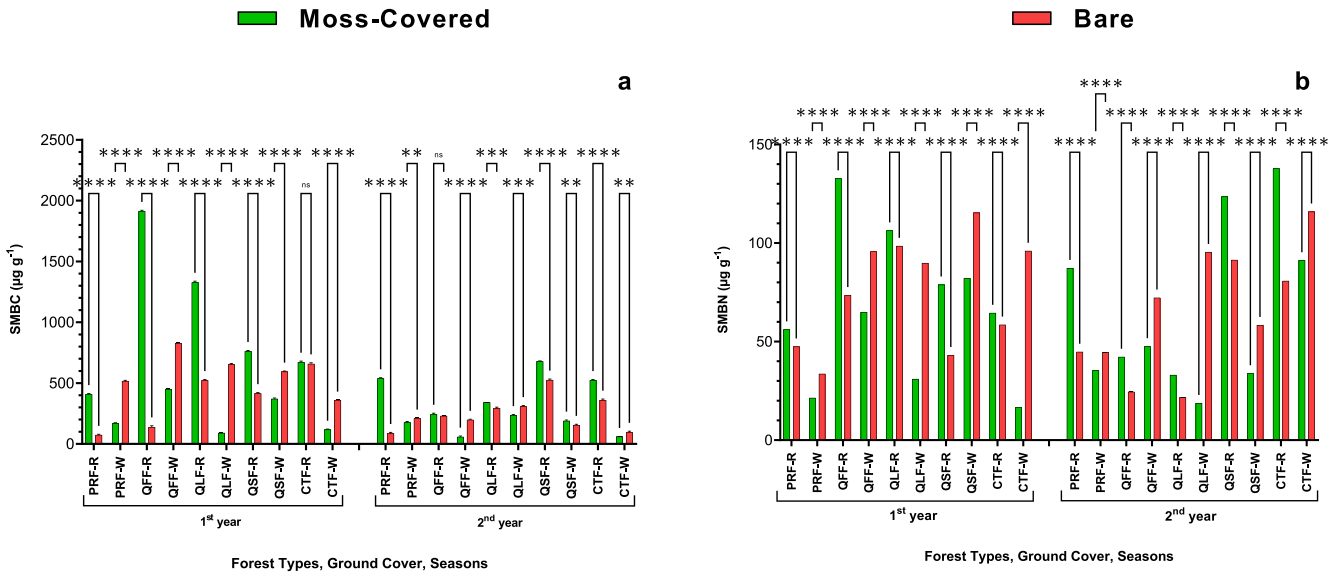

Fig. 3. Mean seasonal variations in Soil microbial biomass carbon (a), and soil microbial biomass nitrogen (b) content under moss-covered and bare soil in different forest types. PRF=*Pinus roxburghii* forest; QFF=*Q. floribunda* forest; QLF=*Q. leucotrichophora* forest; QSF=*Q. semecarpifolia* forest, and CTF=*Cupressus torulosa* forest. R=Rainy season, and W=Winter season.

µg/g) was observed in the moss-covered soil of QFF, and the highest SMBN value (137.81 µg/g) was recorded in the moss-covered soil of CSF. During winter, the highest SMBC (828.63 µg/g) and SMBN (115.95 µg/g) values were found in the bare soil of QFF and CSF, respectively (Fig. 3).

3.3. Soil microbial biomass quotient

During the rainy season, SMBC/SOC values spanned from 0.18 to 5.25, while during the winter, they ranged from 0.056 to 0.97. The lowest SMBC/SOC value (0.056) was observed in the bare soil of CSF during the winter season. Conversely, the highest SMBC/SOC value (5.25) was recorded in the moss-covered soil of QFF during the rainy season. The SMBN/TKN exhibited a range of variability from 0.43 to

Table 1
Soil Microbial Quotient (SMBC/SOC and SMBN/TKN), and SMBC/SMBN ratios for the two ground covers in different forest types in rainy and winter season (Values in parenthesis represent standard deviation).

Forest types	Ground cover	SMBC/SOC				SMBN/TKN				SMBC/SMBN			
		1st year		2nd year		1st year		2nd year		1st year		2nd year	
		Rainy	Winter	Rainy	Winter	Rainy	Winter	Rainy	Winter	Rainy	Winter	Rainy	Winter
PRF	Moss-Covered	1.02 (0.06)	0.48 (0.01)	0.92 (0.01)	0.27 (0.02)	2.68 (0.09)	0.39 (0.01)	2.67 (0.12)	0.62 (0.05)	7.29 (0.07)	7.91 (0.15)	6.17 (0.13)	4.93 (0.06)
	Bare	0.44 (0.01)	0.84 (0.03)	0.18 (0.01)	0.32 (0.00)	1.41 (0.02)	0.59 (0.01)	1.92 (0.02)	0.71 (0.00)	1.55 (0.05)	15.37 (0.19)	1.98 (0.03)	4.72 (0.08)
QFF	Moss-Covered	5.26 (0.19)	0.82 (0.09)	0.29 (0.05)	0.07 (0.00)	4.12 (0.05)	1.25 (0.01)	0.79 (0.01)	0.78 (0.02)	14.41 (0.11)	6.94 (0.06)	5.76 (0.02)	1.23 (0.01)
	Bare	0.93 (0.05)	0.97 (0.08)	0.29 (0.01)	0.19 (0.00)	3.09 (0.04)	1.49 (0.01)	0.53 (0.00)	0.77 (0.01)	1.89 (0.00)	8.65 (0.12)	9.40 (0.16)	2.75 (0.08)
QLF	Moss-Covered	1.40 (0.02)	0.20 (0.00)	0.31 (0.01)	0.28 (0.00)	1.70 (0.03)	0.67 (0.01)	0.45 (0.01)	0.28 (0.00)	12.48 (0.13)	2.90 (0.02)	10.35 (0.09)	12.61 (0.11)
	Bare	1.13 (0.04)	0.45 (0.03)	0.40 (0.02)	0.27 (0.01)	2.76 (0.02)	1.09 (0.01)	0.43 (0.01)	1.16 (0.02)	5.30 (0.02)	7.27 (0.05)	13.49 (0.08)	3.24 (0.01)
QSF	Moss-Covered	0.80 (0.02)	0.89 (0.04)	0.59 (0.02)	0.19 (0.00)	1.06 (0.01)	1.68 (0.00)	1.55 (0.01)	0.39 (0.00)	9.66 (0.10)	4.52 (0.09)	5.49 (0.03)	5.62 (0.05)
	Bare	1.07 (0.07)	0.70 (0.03)	0.64 (0.01)	0.13 (0.00)	1.28 (0.01)	1.73 (0.03)	1.40 (0.01)	0.64 (0.01)	9.61 (0.13)	5.15 (0.02)	5.75 (0.02)	2.65 (0.01)
CTF	Moss-Covered	0.30 (0.01)	0.15 (0.00)	0.34 (0.01)	0.07 (0.00)	0.57 (0.00)	0.26 (0.00)	1.27 (0.01)	1.41 (0.02)	10.40 (0.17)	7.04 (0.03)	3.80 (0.01)	0.67 (0.01)
	Bare	0.73 (0.02)	0.22 (0.00)	0.32 (0.01)	0.05 (0.00)	0.82 (0.01)	1.01 (0.02)	0.91 (0.01)	1.22 (0.01)	11.23 (0.10)	3.74 (0.03)	4.45 (0.03)	0.82 (0.00)

Here, SMBC=Soil Microbial Biomass Carbon; SOC=Soil Organic Carbon; SMBN=Soil Microbial Biomass Nitrogen; TKN=Total Kjeldahl Nitrogen; PRF=*Pinus roxburgii* forest; QFF=*Quercus floribunda* forest; QLF=*Quercus leucotrichophora* forest; QSF=*Quercus semecarpifolia* forest; and CTF=*Cupressus torulosa* forest.

4.12 during the rainy season and 0.26 to 1.74 during the winter. The lowest SMBN/TKN value (0.26) was observed in CSF during the winter season. On the other hand, the highest SMBN/TKN value (4.12) was recorded in the moss-covered soil of QFF during the rainy season (Table 1).

3.4. SMBC/SMBN ratios in different seasons, forest types and ground cover

In our study, the SMBC/SMBN ratios exhibited a range from 1.55 to 14.41 during the rainy season and 0.67 to 15.37 during the winter. Generally, these ratios were higher in the rainy season than in the winter. The lowest SMBC/SMBN ratio was observed in the CSF, whereas the highest ratio was found in PRF. Specifically, within the moss-covered soil, the SMBC/SMBN ratio ranged from 0.67 to 14.41. Meanwhile, within the bare soil, the SMBC/SMBN ratio varied from 0.82 to 15.37 (Table 1).

3.5. Enzyme activities in different seasons and forest types

Except for acid phosphatase, which was not affected by the seasons, all other enzyme activities were significantly impacted by both forest types and seasons (Fig. 4). Most enzyme activities exhibited highest values during the rainy season and their lowest values during the winter.

Dehydrogenase (DHA) activity ranged from 172.75 to 1686.09 μg TPF gDW^{-1} hr^{-1}, with the highest observed value occurring in CSF during the rainy season. β-glucosidase (GLU) activity reached its highest value in CSF during the rainy season, ranging from 0.94 to 5.59 mg PNP gDW^{-1} hr^{-1}. Phosphatase (PH) activity showcased variability between 0.53 and 18.36 mg PNP gDW^{-1} hr^{-1}, with the highest recorded value in QSF during the rainy season. Arylsulfatase (AS) activity spanned from 0.24 to 2.95 mg PNP gDW^{-1} hr^{-1}, with the maximum observed in QFF during the winter season. Phenol oxidase (PO) activity attained its highest value QSF forest during the rainy season, ranging from 972.53 to 9133.05 μM $ABTS^{+}$ gDW^{-1} min^{-1}. Urease (UR) activity demonstrated its highest values in CSF during the rainy season, with a range of 21.96 to 516.08 μg NH_4^+-N gDW^{-1} hr^{-1}. On average, the enzyme activity was found to be highest in the CSF and lowest in the PRF.

3.6. Effects of ground cover on enzyme activities

Enzyme activities also demonstrated significant differences under the influence of ground cover (Fig. 4). Enzyme activities exhibited higher values under moss-covered soil during the rainy season and in bare soil during the winter. Specifically, the highest values of DHA, GLU, PH, AS, PO, and UR activities recorded in moss-covered soil during the rainy season were 1686.09 μg TPF gDW^{-1} hr^{-1}, 5.59 mg PNP gDW^{-1} hr^{-1}, 18.36 mg PNP gDW^{-1} hr^{-1}, 2.79 mg PNP gDW^{-1} hr^{-1}, 9133.05 μM $ABTS^{+}$ gDW^{-1} min^{-1}, and 516.08 μg NH_4^+-N gDW^{-1} hr^{-1}, respectively (Fig. 4). Conversely, within bare soil during the winter season, the highest values of DHA, GLU, PH, AS, PO, and UR activities were measured at 1192.17 μg TPF gDW^{-1} hr^{-1}, 4.81 mg PNP gDW^{-1} hr^{-1}, 13.01 mg PNP gDW^{-1} hr^{-1}, 2.95 mg PNP gDW^{-1} hr^{-1}, 4417.36 μM $ABTS^{+}$ gDW^{-1} min^{-1}, and 238.02 μg NH_4^+-N gDW^{-1} hr^{-1}, respectively (Fig. 4).

3.7. Pearson correlation

SMBC displayed a significant positive correlation with soil moisture ($r = 0.51$, $p < 0.05$), SOM ($r = 0.40$, $p < 0.05$), and a weak positive correlation with SOC ($r = 0.25$, $p > 0.05$). On the other hand, SMBN exhibited a strong positive correlation with SOM ($r = 0.38$, $p < 0.05$), SOC ($r = 0.33$, $p < 0.05$), SMBC ($r = 0.41$, $p < 0.05$), and a weak positive correlation with soil moisture ($r = 0.21$, $p > 0.05$), and TKN ($r = 0.27$, $p > 0.05$). Among enzymes, DHA and GLU showed a significant positive correlation with SOC ($r = 0.60$, $p < 0.05$), ($r = 0.70$, $p < 0.05$), respectively; PH a weak negative correlation with available phosphorus ($r = -0.10$, $p > 0.05$); AS a weak positive correlation with sulphur ($r = 0.11$, $p > 0.05$); PO a weak positive correlation with SOC ($r = 0.23$, $p > 0.05$); and UR a weak positive correlation with TKN ($r = 0.11$, $p > 0.05$) (Fig. 5).

3.8. Principal Component analysis (PCA)

Four principal components (PCs) with Eigenvalues greater than 1 collectively explained 76.89 % of the variance in the dataset. PC1 was responsible for capturing 40.28 % of the variance, while PC2 accounted for 19.14 % of the total variance (Fig. 6).

3.8.1. Loading correlations for PCs

In PC1, the most significant loading correlations were observed with β-glucosidase (GLU) (0.931), soil organic matter (SOM) (0.895), aryl-sulfatase (AS) (0.872), soil organic carbon (SOC) (0.849), total Kjeldahl nitrogen (TKN) (0.789), and phosphatase (PH) (0.753). This indicates that PC1 is strongly influenced by these variables. On the other hand, PC2 exhibited the strongest loading correlations with soil temperature (ST) (0.813), soil moisture (SM) (0.688), urease (UR) (0.611), soil microbial biomass carbon (SMBC) (0.584), and available phosphorus (AP) (0.414) (Table 2). These loading correlations highlight the key factors that contribute to the variation captured by PC2.

3.8.2. Biplot interpretation

The biplot analysis reveals that most enzyme activities are closely correlated with PC1, signifying a strong connection among them. Meanwhile, soil moisture (SM) and soil temperature (ST) correlate with PC2, implying a significant interplay between these two abiotic factors. Among the abiotic factors, soil organic matter (SOM) stands out as the primary influencer on all the biochemical properties within the dataset (Fig. 6).

4. Discussion

Our findings suggest that SMBC, SMBN, and enzymatic activity exhibit significant variations across different forest types, ground covers, and seasons (Fig. 6). Both biotic and abiotic factors play a crucial role in elucidating how vegetation types impact soil microbial biomass and enzymatic activity. Variations in substrate inputs (organic carbon and nitrogen) due to alterations in plant litter and root types, along with related nutrient composition and status, are fundamental drivers of soil microbial biomass and enzymatic activity (Feng et al., 2009; Jin et al., 2010; Bargali et al., 2018).

Soil microbial biomass and enzymatic activity are tightly linked to the availability of soil organic matter (SOM) as a substrate (Amador et al., 1997; Baldrian and Šťursová, 2011), and a decline in SOC leads to reductions in both SMB and enzymatic activity (Chen et al., 2005; Sedia and Ehrenfeld, 2006). This relationship is evident from the correlations (Fig. 5), which reveal a significant positive correlation between SOM and SMBC ($r = 0.40$, $p < 0.05$). Also, PCA analysis (Fig. 6), shows that SOM is the major abiotic factor which influences the biochemical properties.

4.1. Soil microbial biomass

Biochemical properties including enzymatic activity and SMB exhibited higher levels in forests dominated by *Quercus* sp. and *C. torulosa* in comparison to PRF. The increase in biochemical properties in CSF may be attributed to higher litter input, faster decomposition, and a more favourable microclimate characterized by higher SOM and moisture content. This aligns with several studies (Islam et al., 2000; Baldrian et al., 2010; Brockett et al., 2012) which reported higher amount of SMB with increased soil moisture and reduced SMB with decreased soil moisture. Our findings also highlight significant positive correlations

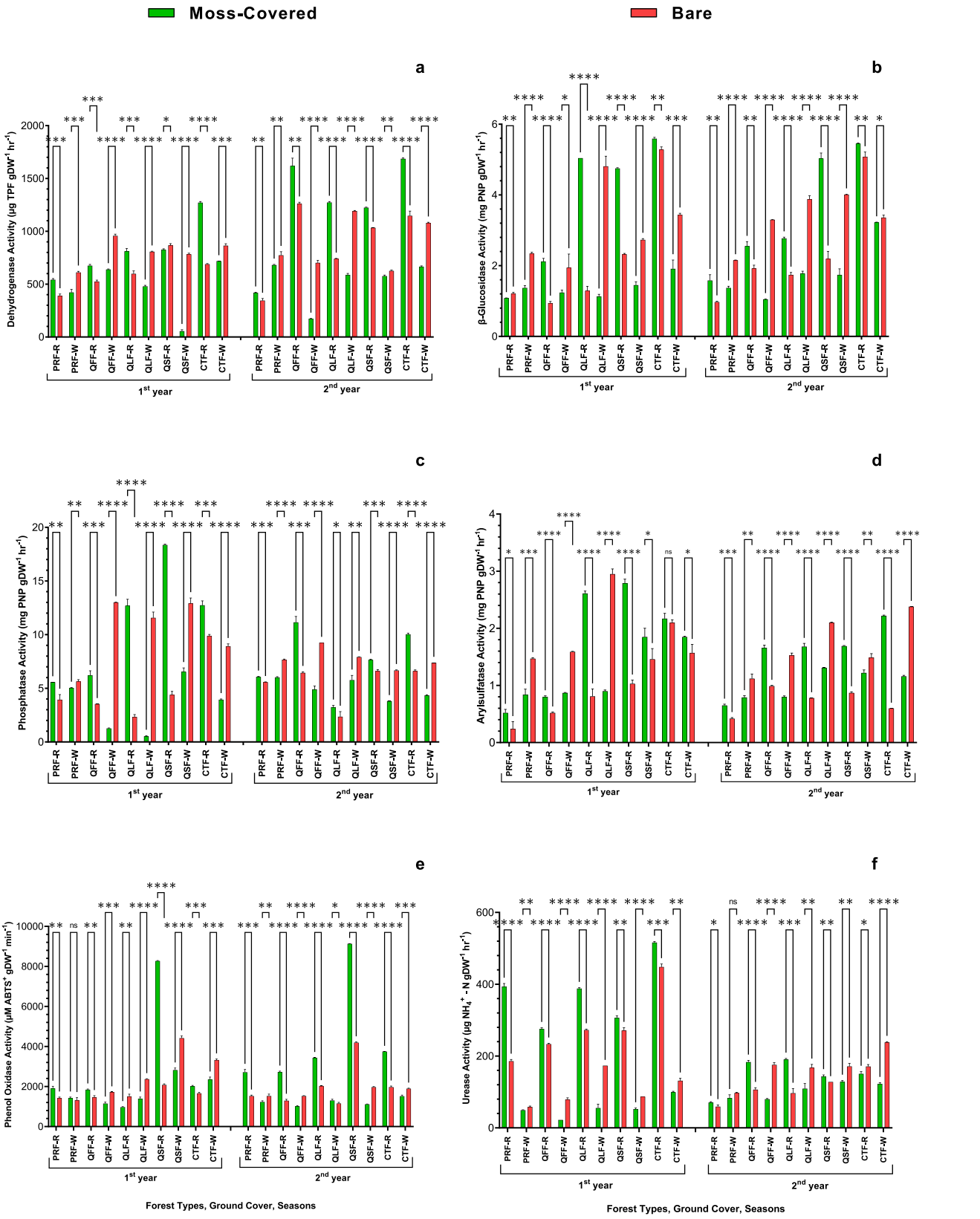

Fig. 4. Mean seasonal variations in Dehydrogenase activity (a), β-Glucosidase activity (b), Acid Phosphatase activity (c), Arylsulfatase activity (d), Phenol Oxidase activity (e), and Urease activity (f) under moss-covered and bare soil in different forest types. PRF=*Pinus roxburghii* forest; QFF=*Q. floribunda* forest; QLF=*Q. leucotrichophora* forest; QSF=*Q. semecarpifolia* forest, and CTF=*Cupressus torulosa* forest. R=Rainy season, and W=Winter season.

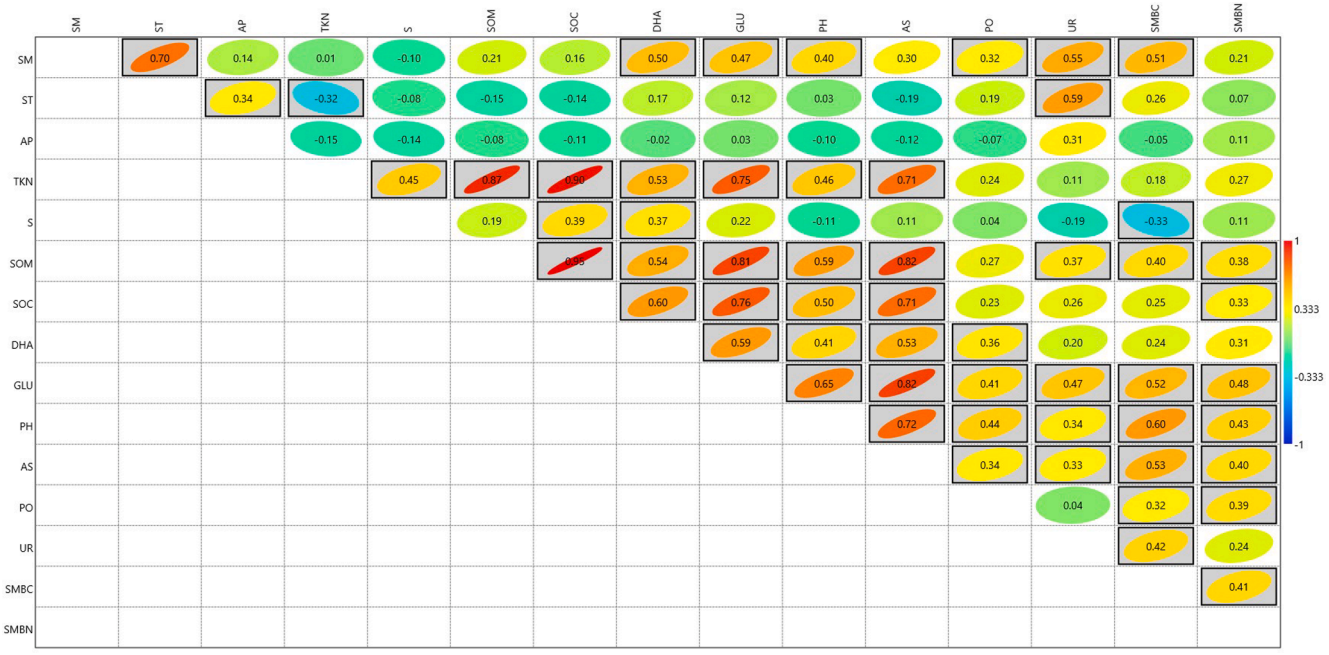

Fig. 5. Pearson correlation matrix between mean values of different physico-chemical and biochemical properties. SM=Soil moisture; ST=Soil temperature; AP=Available phosphorus; TKN=Total kjeldahl nitrogen; S=Total Sulphur; SOM=Soil Organic Matter; SOC=Soil Organic Carbon; DHA=Dehydrogenase activity; GLU=β-Glucosidase activity; PH=Acid Phosphatase activity; AS=Arylsulfatase activity; PO=Phenol Oxidase activity, and UR=Urease activity.

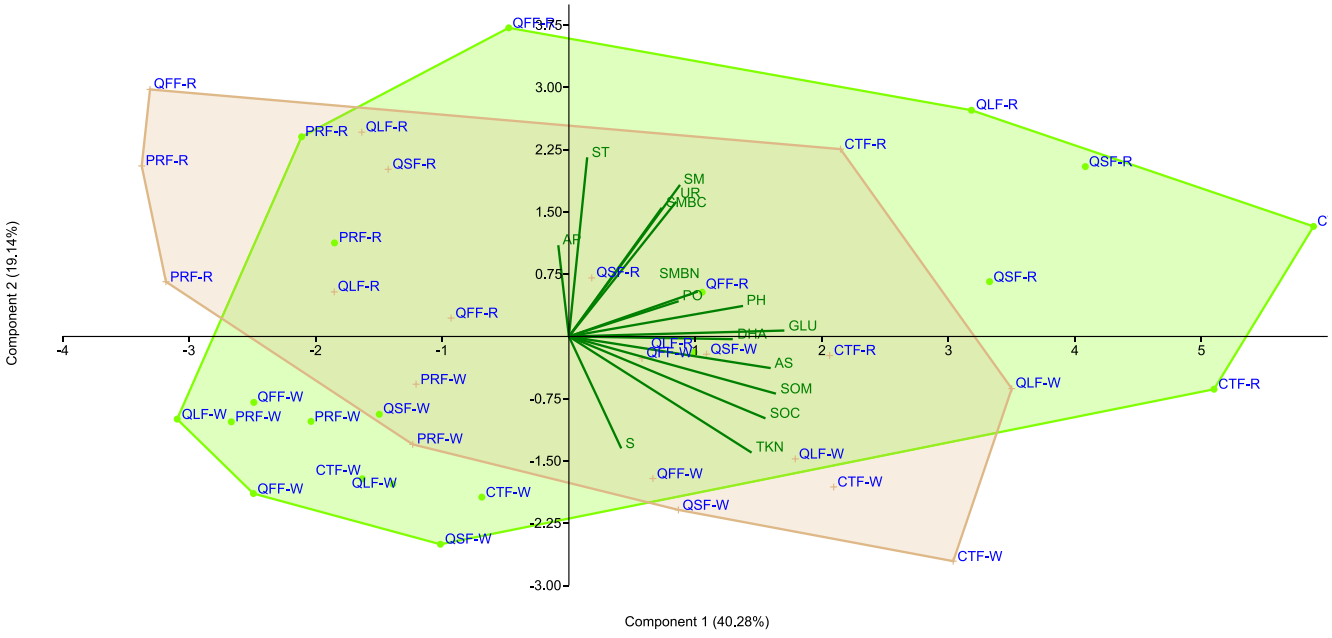

Fig. 6. Biplot from Principal Component Analysis of physico-chemical and biochemical properties of soil in different forest types. SM=Soil moisture; ST=Soil temperature; AP=Available phosphorus; TKN=Total kjeldahl nitrogen; S=Total Sulphur; SOM=Soil Organic Matter; SOC=Soil Organic Carbon; DHA=Dehydrogenase activity; GLU=β-Glucosidase activity; PH=Acid Phosphatase activity; AS=Arylsulfatase activity; PO=Phenol Oxidase activity, and UR=Urease activity.

between soil moisture and both SMBC ($r = 0.51$, $p < 0.05$) and SMBN ($r = 0.21$, $p > 0.05$).

The slow litter decomposition observed in PRF could be attributed to poor litter quality and the presence of recalcitrant compounds that hinder the decomposition process (Usman et al., 2000; Manral et al., 2022). Higher SMB values in *Quercus*-dominated forests likely stem from greater litter input, both above and below-ground biomass, higher soil moisture content, and increased soil organic carbon and nitrogen content, along with denser canopy cover (Sheikh et al., 2020; Kumar et al., 2021; Rawat et al., 2022; Joshi and Garkoti, 2023). The SMBC values (58.54 to 1913.75 μg/g) reported in our study align with the ranges reported by Bargali et al. (2018) (416 – 763 μg/g), and Rawat et al. (2021) (192 – 6210 μg/g) for Central Himalayan forest types. Our observed SMBN values ranged from 16.77 to 137.81 μg/g, and is consistent with previous research. Reported range for Central Himalayan forest types is 8.61 to 229 μg/g (Rawat et al., 2021).

Table 2
Correlation loading values of different biochemical properties on four principal components having Eigenvalues greater than 1.

Principalcomponents	SM	ST	AP	TKN	S	SOM	SOC	DHA	GLU	PH	AS	PO	UR	SMBC	SMBN
PC 1	0.480	0.079	−0.046	0.790	0.226	0.895	0.850	0.708	0.931	0.753	0.872	0.474	0.464	0.401	0.557
PC 2	0.688	0.813	0.414	−0.527	−0.508	−0.260	−0.372	−0.012	0.027	0.139	−0.144	0.160	0.612	0.584	0.204
PC 3	0.221	0.456	0.392	0.106	0.576	0.005	0.170	0.333	0.067	−0.367	−0.202	−0.159	0.195	−0.493	−0.270
PC 4	0.193	0.151	−0.408	−0.122	0.363	−0.259	−0.151	0.317	−0.069	0.005	−0.135	0.606	−0.426	0.040	0.177

Here, SM=Soil Moisture; ST=Soil Temperature; AP=Available Phosphorus; TKN=Total Kjeldahl Nitrogen; S=Total Sulphur; SOM=Soil Organic Matter; SOC=Soil Organic Carbon; DHA=Soil Dehydrogenase activity; GLU=β-Glucosidase activity; PH=Phosphatase activity; AS=Arylsulfatase activity; PO=Phenol Oxidase activity; UR=Urease activity, SMBC=Soil Microbial Biomass Carbon; SMBN=Soil Microbial Biomass Nitrogen; and PC=Principal Component.

4.2. Soil microbial biomass quotient

The soil microbial biomass quotient, represented by SMBC/SOC and SMBN/TKN, offers insight into the status of soil carbon and whether it is accumulating, decreasing, or reaching equilibrium. The literature reports a wide range in soil microbial quotient, ranging from 0.27 to 7.0 (Anderson and Domsch, 1989; Bargali et al., 2018). In our study, microbial quotient values ranged from 0.056 to 5.25 % for SMBC/SOC, while 0.26 to 4.12 % for SMBN/TKN. Variations in microbial quotient ratios resulted from differences in vegetation, soil nutrient status, management practices, sampling time, and analytical methods. These ratios were found to be lowest in CSF during the winter and highest in QFF during the rainy season. Lower SMBC/SOC and SMBN/TN ratios reflect the microbial community's restriction of organic substrate consumption and contribute to microbial immobilization inhibition (Singh et al., 2021). Higher ratios, on the other hand, are associated with greater C immobilization (Bargali et al., 2018).

4.3. SMBC/SMBN ratio

SMBC/SMBN ratio can act as ecosystem recovery indicator and be used to define state and structure of microbial community (Arunachalam and Pandey, 2003; Singh et al., 2021). Lower SMBC/SMBN ratios indicate bacterial community dominance, while higher ratios indicate fungal community dominance in soils (Rawat et al., 2021; Singh et al., 2021). For example, the SMBC/SMBN range for bacteria was 3–5, and for fungi, it was 4–15 (Recous and Mary, 1990). In our study, the SMBC/SMBN ratio ranged from 0.67 to 15.36 and was lowest in the CSF, indicating bacterial community dominance in this forest type. Lower values indicate more available carbon sources and short time to build up the microbial population (Manral et al., 2023). The fungal community was dominant in *Quercus* sp. forests and PRF, but there were seasonal variations.

4.4. Soil enzymatic activity

An increase in enzymatic activity is primarily related to increased organic matter and metabolic activity of microorganisms (Shankar and Garkoti, 2023). In our study, we observed significant positive correlations between SOM and the following enzymes: DHA ($r = 0.54$, $p < 0.05$), GLU ($r = 0.81$, $p < 0.05$), PH ($r = 0.59$, $p < 0.05$), AS ($r = 0.82$, $p < 0.05$), PO ($r = 0.27$, $p < 0.05$), and UR ($r = 0.37$, $p < 0.05$). This indicates that CSF with higher SOM and SMBC content exhibited higher enzymatic activity, followed by forests dominated by *Quercus* sp., and the lowest activity was observed in PRF.

Many studies have also found a significant correlation between soil enzymes and organic carbon as a substrate (Zhang et al., 2010; Spohn et al., 2018; Zhang et al., 2018; Singh et al., 2021). DHA, an intracellular enzyme, and an indicator of microbial activity in general (Nannipieri et al., 1990), showed a positive correlation with SMBC. DHA is involved in the biological oxidation of organic matter, and increasing the amount of organic carbon can enhance DHA activity, thereby improving soil oxidative activity (Zhang et al., 2010).

Soil β-glucosidase activity (GLU), an extracellular hydrolase, catalyzes the conversion of complex cellulose compounds into simple sugars (Esen, 1993), and its activity is proportional to the amount of organic matter in the soil (Sinsabaugh et al., 2008). Similarly, PO, a group of extracellular enzymes, oxidizes lignin and phenolic compounds in soil organic matter (Sinsabaugh, 2010; Sanchez-Julia and Turner, 2021) and is mainly secreted by saprotrophic and ectomycorrhizal fungi (Faure et al., 1994). Both GLU and PO showed positive correlations with SOM in our study.

Phosphatase (PH) and Arylsulfatase (AS) are also extracellular enzymes that catalyze the hydrolysis of organic phosphorus compounds and aryl sulphates to free phosphates and sulphates, respectively (Roberge, 1978). The findings indicated that PH had a non-significant

negative correlation with available phosphorus (r = -0.10, p > 0.05), and AS had a non-significant positive correlation with sulphur (r = 0.11; p > 0.05). Increased available phosphorus content can reduce PH activity due to lesser secretion of these enzymes by microbes (Olander and Vitousek, 2000; Hamman et al., 2008).

Urease (UR) is an aminohydrolase enzyme that decomposes amide nitrogen, catalyzing the hydrolysis of peptide bonds in organic matter and producing ammonium ions, which can improve soil nitrogen content (Roberge, 1978). UR showed a non-significant positive correlation with TKN (r = 0.11, p > 0.05) and SOM (r = 0.37; p < 0.05). The enzyme activity was closely related to organic matter, available nitrogen content, and the number of microorganisms (Błońska et al., 2017; Lu et al., 2022).

In general, soil moisture is a limiting factor for most enzyme activity (Brockett et al., 2012). We discovered a positive correlation between soil moisture and enzymatic activity, which is consistent with previous findings (Kompała-Bąba et al., 2021; Singh et al., 2021; Siwach et al., 2021; Shankar and Garkoti, 2023). Additionally, soil moisture (SM) showed a strong positive correlation with DHA (r = 0.50, p < 0.05), GLU (r = 0.47, p < 0.05), PH (r = 0.40, p < 0.05), PO (r = 0.32, p < 0.05), and UR (r = 0.55, p < 0.05), and weak positive correlation with AS (r = 0.30, p > 0.05). Enzymes also showed a strong correlation within the enzymes themselves, possibly due to the dependence of enzymatic activity on soil moisture and organic matter content (Fig. 6).

4.5. Effects of seasons on SMB and enzymatic activity

Aside from forest types and ground cover, seasonal variations also significantly impacted SMB and enzymatic activity (Fig. 3, and Fig. 4). On average, SMB and enzymatic activity peaked during the rainy season and dropped during the winter. Higher values of biochemical properties during the rainy season are due to favourable climatic conditions for microbial activity, which accelerates the litter decomposition process (Rawat et al., 2021). These findings are consistent with those of Devi and Yadava (2006), Baldrian et al. (2008), Bargali et al. (2018), and Siwach et al. (2021).

Lower biochemical properties during the winter may be attributed to the lower activity of microorganisms and a slower litter decomposition rate during dry and cool periods (Manral et al., 2023). Seasonal variations in SMB indicate the degree of mineralization and immobilization of soil carbon and nitrogen. An increase in SMB may result in nutrient immobilization, while a decrease in SMB may result in nutrient mineralization (Yang et al., 2010).

In the PCA biplot, QLF, QSF, and CTF for the rainy season ordinate in the top right corner, indicating maximum enzymatic activity and adequate SM, ST, and SMB. Meanwhile, PRF, QFF, QLF, QSF, and CTF for the winter ordinate in the lower-left corner of the PCA biplot, indicating the least enzymatic activity and subsequently deficient in SM, ST, and SMB. Also, SM, ST, SMBC, UR and S are the main drivers for distinguishing different properties during both seasons (Fig. 6).

4.6. Effects of ground covers on SMB and enzymatic activity

SMB and enzymatic activities exhibit distinct patterns in the rainy and winter seasons under two different ground covers. Mosses covering the soils exhibited a clear effect on biochemical properties. During the rainy season, biochemical properties were higher under moss cover, whereas, during the winter, they were higher under bare soil. Results from Pearson's correlation (Fig. 5) and PCA (Fig. 6) have shown that soil organic matter and soil moisture are the two major factors responsible for the seasonal changes in SMB and enzyme activities under two ground covers. Moss cover influences the biogeochemistry of the underlying soil by buffering soil moisture and temperature (Sedia and Ehrenfeld, 2006). They increase soil surface water sorption capacity and create an ideal environment for microbial growth (Xiao et al., 2016). Higher microbial activity favours extracellular enzymatic activity, suggesting that moss cover significantly contributes to nutrient cycling (Xu et al., 2022). Moss covered soils have higher organic matter content that provide abundant carbon sources for microbes, which can increase microbial biomass and enzymatic activity (Permin et al., 2022; Zhang et al., 2022). Soil dehydrogenase, β-glucosidase, and urease which are of crucial importance for soil C and N metabolism, have higher values under moss cover during the rainy season (Fig. 4). Moss ground cover exhibited higher values of hydrolytic enzymes, indicating stimulatory role of mosses on microbial production of these enzymes. This may be due to the positive effect of moss layer on soil moisture or the leaching of labile substrates from mosses (Koranda and Michelsen, 2021). Mosses efficiently sequester nutrients all over their surface from atmospheric deposition, throughfall and litter leaches (Turetsky, 2003), and hence function as a filter layer that retains absorbed nutrients for a longer period of time (Gundale et al., 2011; Rousk et al., 2014). Soil organic carbon, and soil nutrients, particularly total nitrogen, and available phosphorus, are observed to be higher in soil beneath moss cover than in bare soil. Nutrient retention, appropriate microclimate, higher microbial activity and greater species composition under mosses attributes to higher microbial biomass underneath moss ground cover (Yang et al., 2018a, 2018b), as illustrated in Fig. 3. Several other studies have emphasized the importance of moss cover for improving soil biochemical properties (Joshi and Garkoti, 2023; Shankar and Garkoti, 2023; Siwach et al., 2023). Several authors (Miralles et al., 2012a, 2012b; Liu et al., 2014; Zhang et al., 2022) have shown that enzymatic activities in soil under moss cover are greater than in bare soil. Cheng et al. (2021) demonstrated the importance of moss crusts in the ecological restoration of karst rocky desertification due to their positive effects on soil microbial richness and nutrients.

During the winter, the biochemical properties of moss-covered soil are lower than those of bare soil. Slow moss growth during winter owing to lower temperatures and precipitation reduces their ability to trap moisture, consequently lowering microbial and enzymatic activity (Liu et al., 2014). Thus, our findings indicate that full-grown moss cover is beneficial to the growth and reproduction of the underlying soil microbial community.

In addition, the long term effects of mosses on soil properties should be further studied for temporal consistency and predictability of these findings so that they can be incorporated in degraded ecosystem restoration and climate change studies. Also, our study did not focus on soil microbial diversity and composition under the two ground covers, which can further be studied in the Himalayan forest ecosystems.

5. Conclusions

Forest type, ground cover, and seasons significantly influenced soil microbial biomass carbon, soil microbial biomass nitrogen, and enzymatic activity. Forests dominated by *Quercus* sp. and *C. torulosa* exhibited a higher proportion of SMB and enzymes compared to the PRF, indicating that these forest types harbour an abundant and diverse soil microbial community that is more efficient at utilizing substrates, thus maintaining higher soil quality. Additionally, an increase in organic matter and moisture levels in the soil promoted greater microbial biomass and enzymatic activity. Seasonality also played a crucial role in shaping biochemical properties, with higher activity observed during the rainy season. The presence of higher SMBC and SMBN during the rainy season indicates a nutrient conservation strategy, while lower SMBC and SMBN amounts during winters suggest C immobilization. The biochemical properties of the two ground cover also differed significantly. Soil with moss cover exhibited higher SMB and enzymatic activity compared to bare soil. The presence of mosses enhanced the nutrient status and moisture content of soils, resulting in an increase in the number and diversity of microorganisms present.

The study's findings emphasize the importance of SMB and enzymatic activity as vital indicators of soil health, biomonitoring and environmental sustainability. SMB, being a key biological driver of ecosystem function, proves to be a sensitive indicator of soil fertility.

This research addresses gaps in our understanding of soil biochemical processes and sheds light on the ecological functions of mosses in various Central Himalayan forest types. As a result of this study, lower plants such as mosses should be prioritized in forest management practices across various ecosystems, particularly in response to climate change. Furthermore, the nutrient-rich and microbe-diverse *Quercus* sp. forests show potential for afforestation in degraded lands. For future research, more sophisticated molecular techniques and fluorescent probes can be employed to delve deeper into the underlying mechanisms governing soil community composition, structure, and enzymatic activity in diverse and climate-sensitive Himalayan forest ecosystems.

Author contributions

RB and AS planned and designed this study. AS collected the field samples and data analysis. AS performed the experiments, analysed the results, and wrote the original draft. RB and QZ reviewed, edited and improved the English language of the manuscript. RB supervised this study and made funding acquisition. All authors have read and approved the final version of this manuscript.

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CRediT authorship contribution statement

Anshu Siwach: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Qianlai Zhuang:** Writing – review & editing, Methodology. **Ratul Baishya:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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