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Seasonal dynamics of soil Inorganic N and N-mineralization in sub-tropical Sal forest in Central Himalaya, India

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Abstract: **Seasonal variation in inorganic N-pool and Net N-mineralization rate was investigated in relation to site characteristics in sub-tropical Sal forest in Central Himalaya, India. Two sites, viz. Fatehpur (FP) located at a latitude of 29°19'23.69''N and longitude of 79°18'05.34''E at 430 m asl and Ranibagh (RB) at a latitude of 29°17'10.03''N and longitude of 79°32'49.19''E at 580m asl were established. Ammonification, nitrification and N-mineralization rates were significantly ($p<0.05$) affected by site, season, soil depth and their interactions. Total inorganic -N and N-mineralization rates were significantly higher in FP site as compared to RB site. Higher mineralization rates were reported during the summer (7.30±0.17 µg g^{-1} $month^{-1}$ and 6.17±0.27 µg g^{-1} $month^{-1}$ in FP and RB site, respectively) and lowest rates during the winter season (2.10±0.17 µg g^{-1} $month^{-1}$) in FP and (1.78±0.18 µg g^{-1} $month^{-1}$ in RB site). The variability in mineralization rates may be due to the ecological differences among the sites. Seasons and soil nitrogen content showed positive correlation with N-mineralization rates while site, clay content and C/N ratio showed negative correlation. The soil N-mineralization affects the N release and availability of inorganic-N for supporting the plant growth, thus regulates the N- cycling in forest ecosystems.**

Index Terms: **Ammonification, N-cycling, Nitrification, N-mineralization, Sal forest.**

I. INTRODUCTION

Nitrogen mineralization is a crucial process in which organic N is transformed to inorganic forms, such as NH_4^+ and NO_3^- that can be taken up by plants through roots. Thus, N mineralization is one of the most important processes for plant growth, facilitates the nitrogen supply in terrestrial ecosystems, regulates the plant growth and productivity and determines availability and losses of nitrogen within the ecosystems (Arslan et al. 2010; Kautsar et al. 2022). In the forest ecosystems, several biotic and abiotic factors influence the N- mineralization rates. Among the abiotic factors, precipitation and temperature have a vital role in leaching of nutrients, microbial transformation mechanisms by regulating enzyme activities (Cregger et al. 2014). In subtropical forests, the precipitation pattern alters the abundance of microbes and nutrient content in microbial biomass thus affect the nitrification and N- mineralization rates (Chen et al. 2017).

Soil characteristics such as soil moisture content, C and N ratios and organic matter content also govern the N cycling (Yokobe et al. 2018; Yang et al. 2022). The management regimes followed in the forests changes the soil properties and soil fertility and thus, regulates the nitrogen dynamics (Padalia et al. 2022; Raj and Jhariya 2021a, b). Soil organic matter content, decomposition patterns of litter and organic matter also have a direct impact on N-transformation mechanisms (Urakawa et al. 2016; Jhariya and Singh 2021). The vegetational composition and climatic variables of a region determines the physical and chemical constituents

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of the litter which in turn influence the N-mineralization rates (Ono et al. 2013).

In the Central Himalayan region, sub- tropical moist deciduous Sal (*Shorea robusta* Roxb. ex Gaertner f.) forests distributed in foothills and Bhabhar belt are characterized by seasonality and variation in plant species diversity. These forests have great economic and ecological significance. Chen and Mulder (2007) reported that the sub-tropical forests have higher N pools, nitrification and net mineralization rates in comparison to temperate forests. The overall objective of this study was to examine how site characteristics affect inorganic N pool and N mineralization in sub-tropical Sal forest of Central Himalaya India. The study would provide an insight to understand these processes in sub-tropical Sal forests and in planning management regimes for the sites for maintaining the sustainability among forest ecosystems.

II. MATERIAL AND METHODS

A. *Site description*

The study was carried out in sub- tropical Sal forest in Nainital district of Uttarakhand state, India. Two sites were established at Fatehpur (FP) and Ranibagh (RB) (Fig.1) within the elevation range from 430m - 580m. Site FP was located between 29°19'23.69"N latitude and 79°18'05.34"E longitude and site RB was located between 29°17'10.03"N latitude and 79°32'49.19"E longitude. *S. robusta* was the dominant tree species in both the sites with *G. velutinum* (FP) and *H. pubsescens* (RB) as co-dominant species (Table I). The total tree density of the forest ranged from 620 ind. ha^{-1} (FP) to 810 ind. ha^{-1} (RB) and total basal area was 25.50 m^{2} ha^{-1} (FP) to 25.63m^{2} ha^{-1} (RB).

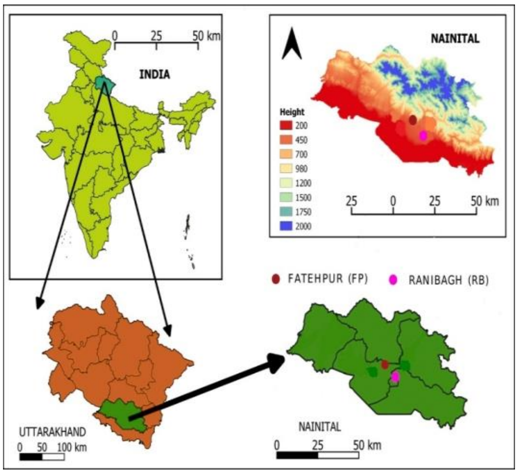

Fig. 1. Map of the study area

B. *Climate*

The climate of the study sites showed distinct seasonal patterns with warm humid rainy season, followed by dry and cold winter season and hot and dry summer season (Fig. 2). The mean minimum temperature ranged between 9ºC (January) and 23ºC (August) whereas the mean maximum temperature ranged from 21ºC (January) to 38ºC (June) and the annual rainfall ranged in between 0 mm (October) and 577.6 mm (July).

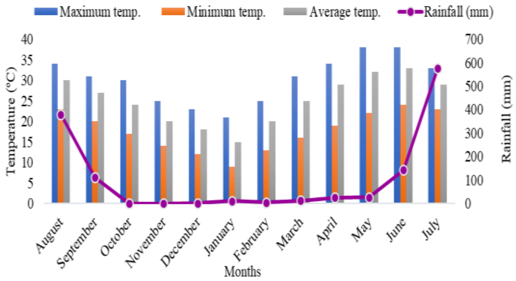

Fig. 2. Climatic data during the study period (August 2017- August 2018)

C. Methodology

Permanent plots of 200×200 m were established in the respective forest sites and soil samples were collected seasonally (rainy, winter and summer) from each site from three soil depths (0-20 cm, 20-40 cm, 40-60 cm) with the help of a soil corer. Soil texture (Indian Standard, 1965), Soil moisture content (Misra, 1968), Soil pH (Jackson, 1958) bulk density (Black, 1965), water holding capacity (Piper, 1950), Porosity (Kumar, 2000) were determined. Soil organic carbon (Walkley and Black, 1934) and soil total nitrogen (Subbiah and Asija, 1956) were also determined.

D. N-mineralization

Short- term field incubation method (Eno, 1960) was used for the estimation of N- mineralization. The soil samples were collected randomly from the respective sites at monthly interval in triplicates from each depth. The coarse debris were removed from the samples and sterile air free polyethylene bags were used to pack the samples, the sealed bags were again inserted into their respective depths and collected every month. Fresh soil samples from the same depths were also brought to the laboratory, sieved and stored for further analysis. The incubated bags were collected from all the soil depths of respective sites after one month incubation period. Phenol disulphonic acid method (Jackson 1958) and the method of Wetzel and Lickens (1979) were used to determine the concentration of Nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N), respectively in the soil samples. Subtracting the initial ammonium and nitrate concentration from the respective final concentration provided the final concentration of ammonia and nitrogen in the samples.

E. Statistical analysis

SPSS 26 (Windows statistical software), PAST3 statistical package (Paleontological statistics software for Education and Data Analysis) was used for performing statistical tests on the data.

III. RESULTS

A. Soil characteristics

The soil characteristics are displayed in Table II. The textural analysis of the soil across the soil depths revealed that soil type varied between loam and clayey loam in FP and clay loam in RB site. Soil moisture content, bulk density and water holding capacity showed increasing trend with increasing soil depth, while soil organic carbon and soil nitrogen decreased with increasing soil depth (Table II). The soil moisture content (10.68 %) and water holding capacity (46.11%) were comparatively higher in site RB than site FP (SMC- 9.95%, WHC- 44.91%). The bulk density was higher in site FP (1.33 gcm^{-3}) than site RB (1.32 gcm^{-3}), while porosity showed reverse trend than bulk density as it was higher in site RB (49.02%) than site FP (48.80%). The pH value was slightly more basic in site RB (7.49) than site FP (7.06). Soil organic carbon (1.78%) and nitrogen values (0.22%) reported from site FP were more than site RB {SOC (1.51%), TN (0.20%}. Higher C: N ratio was observed in site FP (7.98) than site RB (7.71).

Table I. Description of the selected study sites

Sites	**Forest type**	**Vegetative composition**		
		Trees	**Shrubs**	**Herbs**
FP	Dense canopied Sal forest	*Shorea robusta* Roxb. ex Gaertner f., *Glochidion velutinum* Wight, *Mallotus philippensis* (Lam.) Muell-Arg, *Dalbergia sissoo* Roxb., *Syzygium cumini* (L.) Skeels, *Toona ciliata* Roem., *Grewia asiatica* L.	*Asparagus adscendens* Buch-Ham. Ex Roxb., *Cassia occidentalis* L., *Cassia tora* L., *Clerodendrum viscosum* Ventenat., *Desmodium caudatum* (Thumb.) DC., *Lantana camara* L., *Murraya koenigii* (L.) Sprengel, *Randia uliginosa* DC.	*Achyranthes aspera* L., *Ageratum conyzoides* L., *Asparagus racemosus* Willd., *Chenopodium album* L., *Cynoglossum lanceolatum* Forsk., *Cyperus kyllingia* Endl., *Cyperus nutans* Vahl., *Cyperus rotundus* L., *Desmodium triflorum* (L.) DC., *Digitaria granularis* (Trinius) Henard, *Oxalis corniculata* L., *Parthenium hysterophorus* L., *Polygonum barbatum* L., *Setaria glauca* (L.) P. Beauv., *Sida cordata* (Burm. f.) *Borss. Waalk.*, *Sida rhombifolia* L.
RB	Sal mixed dense canopy forest	*Shorea robusta* Roxb. ex Gaertner f., *Holarrhena pubescens* Wall. ex G. Don, *Mallotus philippensis* (Lam.) Muell-Arg, *Syzygium cumini* (L.) Skeels, *Grewia optiva* Drumm. ex Burret, *Careya arborea* Roxb, *Randia dumetorum* (Retz.) Poir. *Phyllanthus emblica* L., *Terminalia chebula* Retz., *Cassia fistula* L. *Malva parviflora* L., *Ficus hispida* L., *Lannea coromandelica* (Houtt.) Merr.	*Asparagus adscendens* Buch-Ham. Ex Roxb., *Calotropis procera (*Aiton) Dryander, *Clerodendrum viscosum* Vent., *Colebrookea oppositifolia* Smith., *Desmodium pulchellum* (L.) Benth., *Lantana camara* L., *Murraya koenigii* (L.) Sprengel, *Randia uliginosa* DC., *Rubus ellipticus* Smith, *Pogostemon benghalensis* (Burm. f.) Kuntze, *Woodfordia fruticosa* (L.) Kurz	*Achyranthes aspera* L., *Ageratum conyzoides* L., *Ageratina adenophora* L., *Alternanthera sessilis* (L.) DC., *Artemisia nilagirica* Clarke, *Bidens biternata* (Lour.) Merrill & Sherff, *Corchorus aestuans* L. *Commelina benghalensis* L., *Cynaglossum lanceolatum* Forsk., *Cynotis cristata* (L.) D. Don, *Cyperus rotundus* L., *Desmodium heterocarpon* (L.) DC., *Desmodium triflorum* (L.) DC., *Mimosa pudica* L., *Ophioglossum reticulatum* L., *Oxalis corniculata* L., *Parthenium hysterophorus* L., *Scutellaria spp.*, *Sida cordata* (Burm. f.) Borss. Waalk., *Sida acuta* Burm F., *Sida cordifolia* L., *Sigesbeckia orientalis* L., *Stellaria media* (L.) Vill., *Smilax macrophylla* L.

B. Available N-pool

The maximum available N-pool was observed in the rainy season in the uppermost soil depth which declined with the increase in soil depth across the sites. The inorganic ammonium pool was higher than nitrate pool among both the sites. During winter season highest available N-pool was reported in the site FP (15.20 µg g^{-1} month^{-1}) in 0-20 cm soil depth and lowest in the site RB (8.68 µg g^{-1} month^{-1}) 20-40 soil depth (Table III).

C. N-mineralization rates

Significant variations were observed in both the sites with respect to soil depth, season and site ($p<0.05$). Ammonification ranged from 1.47-4.15 µg g^{-1} month^{-1} in site FP to 0.87-3.60 µg g^{-1} month^{-1} in site RB. Nitrification rates varied from 1.93-4.60 µg g^{-1} month^{-1} in site FP to 1.17-2.87 µg g^{-1} month^{-1} in site FP. N-mineralization rates varied between 4.07 and 7.30 µg g^{-1} month^{-1} in site FP, 2.64 and 6.17 µg g^{-1} month^{-1} in site RB (Table IV). The highest N- mineralization rates were observed in the 40-60 cm soil depth of site FP (7.30 µg g^{-1} month^{-1}), while minimium in 20-40 cm soil depth of site RB (2.64 µg g^{-1} month^{-1}).

Table II. Soil physical and chemical properties across the studied sites

Sites	**Soil Depth (cm)**	**Texture Class**	**SMC (%)**	**WHC (%)**	**bD (gcm^{-3})**	**Po (%)**	**pH**	**SOC (%)**	**TN (%)**	**C:N Ratio**
FP	**0-20**	Loam	8.36 ±1.02	44.79 ±0.97	1.21 ±0.03	53.40 ±0.02	7.10 ±0.02	2.11 ±0.05	0.24 ±0.01	8.93 ±0.56
	20-40	Clay loam	9.65 ±1.46	43.36 ±1.65	1.34 ±0.02	48.31 ±0.02	7.15 ±0.04	1.89 ±0.02	0.22 ±0.01	8.71 ±1.24
	40-60	Loam	11.83 ±1.73	46.58 ±2.62	1.44 ±0.05	44.69 ±0.03	6.92 ±0.06	1.35 ±0.04	0.21 ±0.01	6.31 ±0.87
Mean±SD			9.95 ±1.40	44.91 ±1.75	1.33 ±0.03	48.80 ±0.02	7.06 ±0.04	1.78 ±0.04	0.22 ±0.01	7.98 ±0.89
RB	**0-20**	Clay loam	9.46 ±1.02	43.81 ±1.15	1.26 ±0.02	51.57 ±0.81	7.40 ±0.03	1.78 ±0.05	0.19 ±0.01	9.37 ±1.62
	20-40	Clay loam	9.04 ±1.46	51.42 ±2.20	1.30 ±0.02	49.83 ±0.79	7.41 ±0.02	1.65 ±0.04	0.20 ±0.01	8.23 ±1.37
	40-60	Clay loam	14.07 ±1.73	43.11 ±0.40	1.41 ±0.03	45.65 ±1.09	7.66 ±0.02	1.09 ±0.04	0.20 ±0.01	5.53 ±0.74
Mean±SD			10.68 ±1.40	46.11 ±1.25	1.32 ±0.02	49.02 ±0.90	7.49 ±0.02	1.51 ±0.04	0.20 ±0.01	7.71 ±1.24

Table III. Seasonal variations in mineral-N content (µg g^{-1} month^{-1}) across the study sites in sub-tropical Sal forest

Sites	**Soil depth (cm)**	**Rainy**			**Winter**			**Summer**		
		NH_4^+–N	**NO_3^-–N**	**Total Inorganic-N**	**NH_4^+–N**	**NO_3^-–N**	**Total Inorganic-N**	**NH_4^+–N**	**NO_3^-–N**	**Total Inorganic-N**
FP	**0-20**	8.63 ±1.58	7.33 ±0.42	15.96 ±1.97	6.80 ±1.02	5.53 ±0.86	12.33 ±1.21	7.37 ±0.96	7.50 ±0.79	14.87 ±1.29
	20-40	7.40 ±0.95	5.60 ±0.77	13.00 ±0.75	8.58 ±0.73	5.50 ±0.72	14.08 ±0.92	7.23 ±0.75	5.63 ±0.85	12.87 ±0.85
	40-60	6.57 ±0.91	6.37 ±0.56	12.93 ±0.96	6.53 ±0.76	5.70 ±0.82	12.23 ±1.62	6.57 ±1.07	8.13 ±0.72	14.71 ±1.32
Mean±SD		7.53 ±1.15	6.43 ±0.58	13.96 ±1.23	7.30 ±0.84	5.58 ±0.80	12.88 ±1.25	7.06 ±0.93	7.09 ±0.79	14.15 ±1.15
RB	**0-20**	6.17 ±0.63	3.60 ±0.63	9.77 ±0.73	6.60 ±0.66	3.37 ±00.74	9.97 ±0.66	5.33 ±0.59	4.57 ±0.67	9.90 ±0.69
	20-40	7.10 ±0.82	3.43 ±0.59	10.53 ±0.92	5.50 ±0.67	3.18 ±0.69	8.68 ±0.59	5.77 ±0.63	4.10 ±0.68	9.87 ±0.78
	40-60	6.67 ±0.57	3.30 ±0.61	9.97 ±0.77	6.40 ±0.42	3.49 ±0.68	9.89 ±0.48	5.70 ±0.59	4.40 ±0.59	10.10 ±0.92
Mean±SD		6.65 ±0.67	3.44 ±0.61	10.09 ±0.81	6.17 ±0.58	3.35 ±0.70	9.51 ±0.58	5.60 ±0.60	4.36 ±0.65	9.96 ±0.80

Table IV. Seasonal variations in N transformation rates (µg g^{-1} $month^{-1}$) across the study sites in sub-tropical Sal forest

Sites	Soil depth (cm)	Rainy			Winter			Summer		
		AM	NI	NM	AM	NI	NM	AM	NI	NM
FP	**0-20**	1.47 ±0.18	4.30 ±0.46	5.77 ±0.58	2.33 ±0.83	3.17 ±0.19	5.50 ±0.65	2.17 ±0.03	4.03 ±0.09	6.20 ±0.10
	20-40	2.27 ±0.03	3.00 ±0.31	5.27 ±0.33	4.15 ±0.19	2.10 ±0.17	6.25 ±0.16	2.13 ±0.12	1.93 ±0.18	4.07 ±0.15
	40-60	1.97 ±0.15	4.10± 0.30	6.07 ±0.44	2.03 ±0.22	2.43 ±0.13	4.47 ±0.32	2.70 ±0.15	4.60 ±0.25	7.30 ±0.17
Mean±SD		1.90 ±0.12	3.80 ±0.36	5.70 ±0.45	2.84 ±0.41	2.57 ±0.16	5.41 ±0.38	2.33 ±0.10	3.52 ±0.17	5.86 ±0.14
RB	**0-20**	1.87 ±0.03	1.17 ±0.03	3.03 ±0.03	1.23 ±0.09	1.97 ±0.12	3.20 ±0.06	3.20 ±0.15	2.87 ±0.37	6.07 ±0.52
	20-40	1.67 ±0.13	2.00± 0.36	3.67 ±0.49	0.87 ±0.19	1.78 ±0.18	2.64 ±0.08	3.60 ±0.10	2.37 ±0.21	5.97 ±0.22
	40-60	2.17 ±0.23	1.93 ±0.03	4.10 ±0.21	2.00 ±0.32	2.19 ±0.11	4.19 ±0.42	3.37 ±0.12	2.80 ±0.15	6.17 ±0.27
Mean±SD		1.90 ±0.13	1.70 ±0.14	3.60 ±0.24	1.37 ±0.20	1.98 ±0.14	3.34 ±0.19	3.39 ±0.12	2.68 ±0.24	6.07 ±0.34

AM=Ammonification, NI=Nitrification, NM=N-mineralization

IV. DISCUSSION

A. *N-transformation rates in sub-tropical sal forest*

Net N mineralization rates that are measured by relatively long-term incubation (30 days) are considered to provide a useful index of plant N availability (Schimel and Bennett, 2004) because these rates indicate the residual inorganic N subtracted by the consumption of soil microbes. In this study, ammonification, nitrification and N-mineralization rates were significantly affected by site, season, soil depth and their interactions (Table V). The average net N mineralization, ammonification and nitrification rates in the Sal forest soils were 3.34±0.19- 6.07±0.34 µg g^{-1} $month^{-1}$, 1.37±0.20- 3.39±0.12 µg g^{-1} $month^{-1}$ and 1.70±0.14- 3.80±0.36 µg g^{-1} $month^{-1}$, respectively. The average rates obtained in this study were similar to the values reported by Mylliemngap et al. (2015) for ammonification (0.51 to 2.99 µg g^{-1} $month^{-1}$), nitrification (0.39–4.42 µg g^{-1} $month^{-1}$) and net N mineralization (2.12 to 7.41 µg g^{-1} $month^{-1}$)) from sub-tropical broadleaved forest of India**.** Net N mineralization showed strong positive correlation with nitrification (r^2 = 0.928) and ammonification (r^2 = 0.759) rates in site RB and with nitrification in site FP (r^2 = 0.5123) (Fig. 3). These relationships suggest that N demands for soil microbes were sufficient (Schimel and Bennett, 2004) and thus, nitrification was dominant form of N-transformation as compared to ammonification in the sub-tropical Sal forest soils.

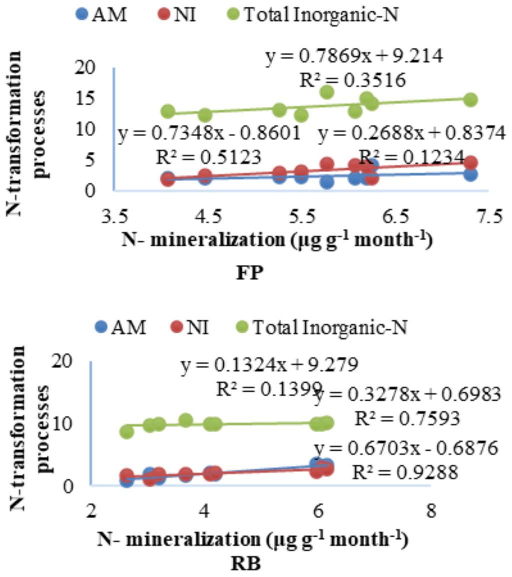

Fig. 3. Relationship between N-transformation processes and N-mineralization rates

At RB site highest concentration of mineral-N (NH_4^+ - N+ NO_3- N) in the soil occurred during the summer period while the lowest concentrations were recorded for winter period. In dry tropical ecosystems Jha et al. (1996) and Singh and Kashyap (2007) also reported maximum mineral-N during dry season and suggested that concentration of mineral-N during the dry period may reflect low vegetation demand for the nutrients and increase in supply due to microbial cell death (Jaramillo and Sanford 1985). On the other hand, high mineral-N during the rainy season at site FP may be due to high decomposition rate due to favourable conditions for microbial activity.

B. Seasonal variability in N-transformation rates

Nitrification, ammonification and net N-mineralization rates were significantly ($p<0.05$) affected by season and their interaction with sites and soil depth (Table V). The highest N-mineralization rates were observed in summer season in both the sites (5.86 µg g^{-1} $month^{-1}$ at FP and 6.07 µg g^{-1} $month^{-1}$at RB), while lowest values were reported during winter season (5.41 µg g^{-1} $month^{-1}$ at FP and 3.34 µg g^{-1} $month^{-1}$ at RB) (Fig. 4). The observed rates were similar to N-mineralization rates (2.12 to 7.41 µg g^{-1} $month^{-1}$) reported by Mylliemngap et al. (2015) in sub-tropical forests of North-east India. The rates reported in the present study were comparatively lower than the rates (17.15–22.02 µg g^{-1} $month^{-1}$) reported by Verma and Sagar (2020) in tropical regions of Indo Gangetic Basin.

Higher values of N- mineralization parameters were observed during the summer and rainy season due to the abundant moisture content and temperature regimes for the proper functioning of microbes. Bhuyan et al. (2014) and Karki et al. (2021a, 2021b) also reported similar findings from the Eastern Himalayan region and agroforestry systems of Kumaun Himalaya, respectively. Manral et al. (2020) also observed that the elevated temperature during the summer season increases the metabolic activities in the microbes responsible for the higher N- mineralization rates in the season. Jongen et al. (2013) and Omara et al. (2022) observed that the rainfall frequency and quantity influence the leaching of nutrients and physiological activities of microbial communities thus effects the nitrification and N-mineralization rates. Yokobe et al. (2018) observed that soil microbial organisms accumulate huge fractions of N during the dry season and at the onset of rainy season their physiological activities are enhanced by the precipitation effect resulting in higher N-mineralization rates.

Low mineralization rates during winter season correspond to the decreased microbial activities and higher immobilization of inorganic nitrogen due to low temperature. Garkoti et al. (2003) also reported that the mineralization rates slow down during the winter season due to low temperature. Karhu et al. (2010) observed that the increased soil temperature improves the efficiency of microbial communities that results in faster decomposition and mineralization rates. Groffman et al. (2009) and Contosta et al. (2011) observed highest N-fluxes in summer and lowest during the coldest parts of the year.

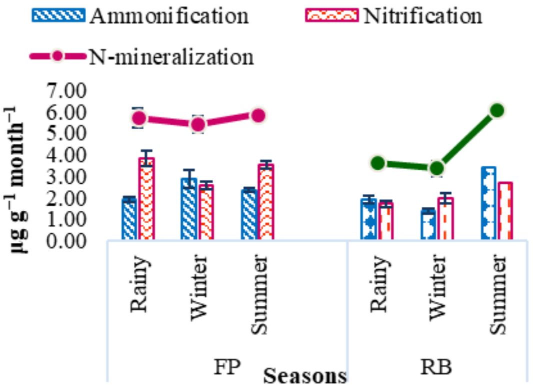

Fig. 4. Seasonal variability in ammonification, nitrification and Net N-mineralization across the sites

C. Spatial variation in N-mineralization rates

In the present study, ammonification, nitrification and N-mineralization rates were significantly influenced by soil depth ($p < 0.05$) (Table V). In the present study, the N-mineralization rates were comparatively higher in deeper soil depths (Fig. 5). This may be attributed to the percolation of nutrients in higher concentrations to the deeper depths due to higher rainfall or other anthropogenic and climatic pressures as heavy rains or other catastrophes result in heavy losses of N through leaching and runoff from the surface layer of soil resulting in low N-mineralization rates in upper layers of soil. About 31.51-34.32% of N- mineralization was confined to the uppermost soil depth (0-20 cm), 30.63-31.45% to the sub surface layer (20-40 cm), while 35.05-37.04% to the deepest soil depth (40-60 cm).

Iversen et al. (2011) also reported similar results from *Liquidambar styraciflua L.* plantations in forests due to the decreased microbial competition in deeper soil depths and high root proliferation while Chen et al. (2005) and Karki et al. (2021b) observed a significant decline in N-mineralization rates with increasing soil depth in planted pine and in Kumaun Himalayan agro-ecosystems, respectively. Dessureault-Rompre et al. (2016) and Paul et al. (2001) also observed that soil mineralizable N pools generally decreased with increasing soil depth and out of the total N-mineralization, 35-90% is contributed by the surface layer. Fu-sheng et al. (2005) reported that more than 50% of N-mineralization rates are confined to the uppermost soil layer (0-15cm) in Pine plantations of China.

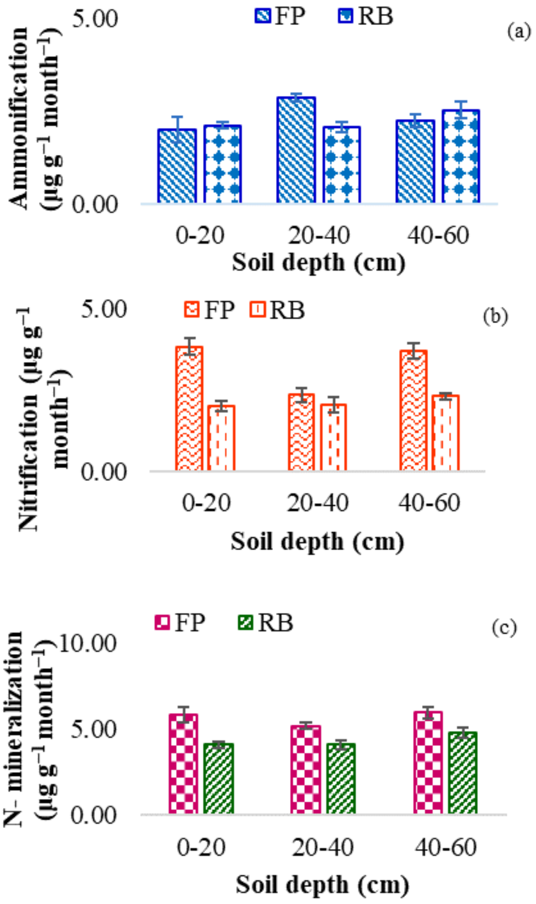

Fig. 5. Spatial variability in ammonification (a), nitrification (b) and Net N-mineralization (c) across the sites

D. Site variation in N-mineralization rates

N-mineralization rate was significantly ($p < 0.05$) affected by sites (Table V). The net N-mineralization rates varied from 4.07-7.3µg g^{-1} $month^{-1}$ to 2.67-6.17 µg g^{-1} $month^{-1}$ (Fig. 6). Sun et al. (2013) suggested that in forest ecosystems, litter can be the major source of SOM, and changes in dominant plant species can affect the quality and quantity of litter input, SOM decomposition process, and nutrient cycling. Therefore, site characteristics have complex effects on SOM decomposition by affecting soil temperature, moisture, nutrient availability, and microbial community.

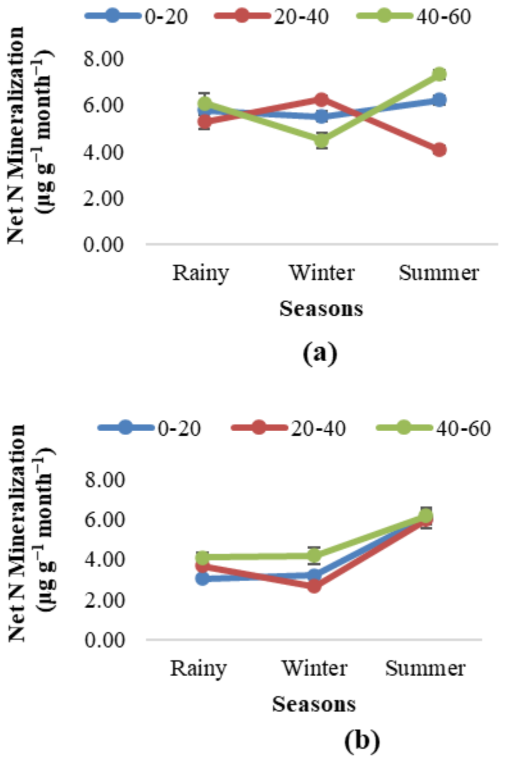

Fig. 6. Effect of soil depth and seasons on Net N-mineralization in the two experimental sites: (a)=FP and (b)=RB

In this study, RB site showed significantly lower organic-C (1.51%) and total-N (0.20%) content as compared to FP site as most organic matter input in forest soil is in the form of litter fall (Singh and Singh, 1993) these differences were suggested to be caused by differences in the amount, chemical properties and decomposition processes of the organic layer (Ono et al. 2013). The higher nutrient availability (soil carbon and nitrogen contents) in the FP site enhances microbial activity, as a result greater input of carbon and nitrogen occurs in the soil via higher decomposition rate. Soil organic matter improves aeration of the soil and facilitates the functioning of microorganism in soil. Thus, higher organic-C in the soil of FP forest site may be attributed to higher N-mineralization and nitrification rate than the RB site. This study recorded significant interaction between site and season indicating that the action of season across the study site was different and may be related to topographic characteristic of each site, including vegetational cover, quality and quantity of soil organic matter, organic-N, N-mineralization and nitrification rates.

Higher concentration of mineral-N (N - NH_4^++N- NO_3^-) in the soil occurred in FP (5.66±0.32 μg g^{-1} $month^{-1}$) site while the lower concentration recorded for RB (4.34±0.26 μg g^{-1} $month^{-1}$) as well as higher Inorganic N content was also observed in site FP (13.66±1.21 μg g^{-1} $month^{-1}$) in comparison to site RB (9.85±0.73 μg g^{-1} $month^{-1}$) (Table VI). The N- mineralization pattern and Inorganic N content is dependent on the amount of litter and quality of litter which is determined by the vegetational composition of the region as the species have varying fractions of easily degradable and recalcitrant compounds in their plant parts that influences the decomposition rates (Bargali et al. 1993, 2015). The higher N-mineralization rates in FP as compared to RB site may be due to vegetational communities with large fractions of easily degradable litter supplemented with adequate abiotic and biotic factors. Wang et al. (2018) reported that N- transformation mechanisms are also controlled by diversity among plant species as different plant species have differential litter quality and decomposition rates that provide a constant supply of nitrogen in wide time frames that affects the nitrification and N-mineralization rates within sites.

Quan et al. (2014) and Zha et al. (2022) observed that the carbon and nitrogen contents and C:N ratio of the soil have coupling effects on decomposition patterns of soil organic matter and mineralization patterns. Gan et al. (2020) documented that the ecological differences among forests in association with the management regimes followed results in differential selection of the plant communities which significantly influences the organic matter, available nutrients and N-mineralization mechanisms. Jerabkova et al. (2006) reported that nutrient release rates of carbon and nitrogen were higher in mineral soil of deciduous forests in comparison to coniferous forests resulting in higher N-mineralization rates.

E. Relationship between soil characteristics and N-transformation rates

The Himalayan ecosystems are quite diverse and have frequent variations in topography, vegetation composition and climatic conditions within short distances which are responsible for the extensive variability in soil characteristics (Bargali K et al. 2018 and Bargali et al. 2019). Pearson's correlation matrix revealed that soil properties significantly ($p<0.05$) affected N- mineralization rates in the Sal forest (Fig. 7). Primo et al. (2021) also reported that the soil parameters have direct or indirect effect on the N-mineralization rates of an ecosystem.

N-mineralization rates recorded strong positive correlations ($p<0.05$) with season and soil nitrogen while negative correlations were recorded with sites, clay content and C/N ratio (Fig.7). Bhuyan et al. (2014) also reported that coarse textured soil with higher sand and soil organic carbon content positively influence the N- mineralization rates whereas soil with higher clay content showed lower N- mineralization rates because the fine clay particles protect the organic matter from decomposition by microbes.

Masunga et al. (2016) also observed that high N supply and lower C:N ratio increased the N-mineralization rates. Soil organic carbon was negatively correlated with sites, seasons and soil depth while soil nitrogen varied significantly with seasons and sites. Bulk density showed strong positive correlation with soil depth while porosity was negatively correlated. C/N ratio was negatively correlated with soil depth, seasons, bulk density, soil moisture content, soil nitrogen (Fig. 7).

Singh and Kashyap (2007) and Karki et al. (2021c) also reported that the vegetational composition, carbon and nitrogen content of the soil determine the N- mineralization rates of a region.

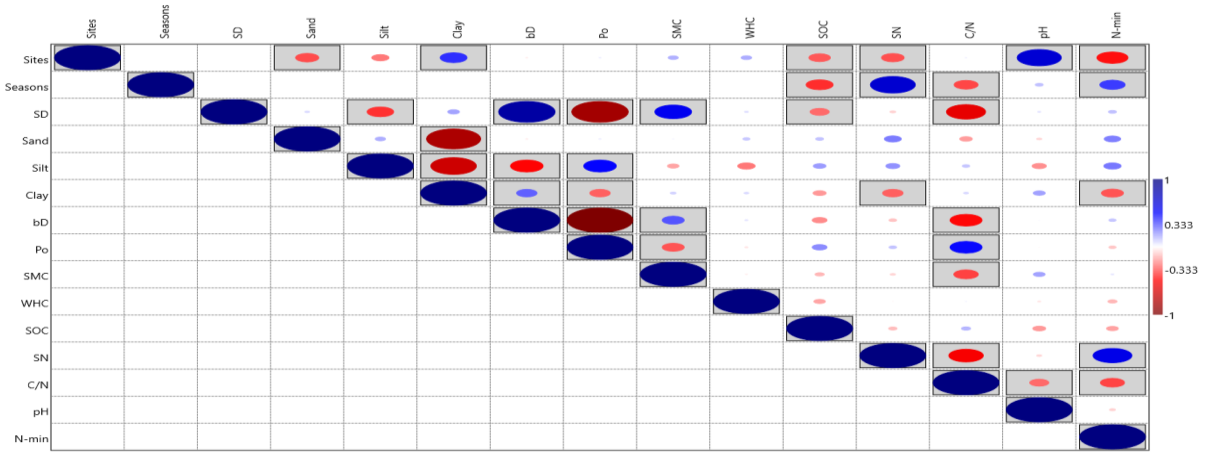

Fig.7. Correlation matrix of the soil and Nitrogen mineralization; more visible circles showed higher correlation among variables; bluish color indicated positive correlation while reddish color indicated negative correlation. SD- Soil depth, bd-bulk density, Po-Porosity, SMC- Soil moisture content, WHC-Water holding capacity, SOC-soil organic carbon, SN-Soil nitrogen, C/N-Carbon and Nitrogen ratio, N-min- Nitrogen mineralization [Boxes show significant values ($p<0.05$)].

Table V. Multivariate analysis of variance for different N- mineralization parameters verses sites, seasons and soil depth among the studied sites (µg g^{-1} $month^{-1}$)

Parameters	**Ammonification**	**Nitrification**	**Net N-mineralization**
Sites (SI)	1.37*	115.74*	66.59*
Seasons (SE)	24.38*	19.26*	36.84*
Soil depth (SD)	4.36*	22.00*	7.00*
SI* SE	38.28*	18.19*	22.45*
SI*SD	8.08*	17.51*	1.58*
SE*SD	1.16*	4.90*	4.21*
SI * SE* SD	8.57*	3.99*	11.03*

Table VI. Available mineral N and mineralization rates (mean± SE) in soils of sub-tropical Sal forest in Central Himalaya, India

Soil N parameters	**Sites**	
	FP	**RB**
NH_4-N (µg g^{-1})	7.30±0.97	6.14±0.62
NO_3-N (µg g^{-1})	6.37±0.72	3.72±0.65
NH_4-N:NO_3-N	1.15±0.03	1.65±0.09
Total Inorganic N (µg g^{-1})	13.66±1.21	9.85±0.73
Ammonification (µg g^{-1}month^{-1})	2.36±0.21	2.22±0.15
Nitrification (µg g^{-1}month^{-1})	3.30±0.23	2.12±0.17
Ammonification: Nitrification	0.72±0.09	1.05±0.08
N-mineralization (µg g^{-1}month^{-1})	5.66±0.32	4.34±0.26

CONCLUSION

In this study, the floristic composition along with soil properties, like clay content, bulk density, soil carbon and nitrogen content significantly affected N mineralization rates in the subtropical Sal forest of Central Himalayan region. The soil physical as well as chemical characteristics regulate the soil health which directly influenced the N-mineralization patterns. The higher mineralization rates observed during the summer season reflects the appropriate temperature regimes in association with other biotic and abiotic factors for better physiological activities of microbial communities to support the growth and development of plant species. The reduced temperature during winter season slowed down the N transformation mechanisms involved in the process of N-mineralization. The distinct rates of N-mineralization among the sites demonstrated species specific control on soil nutrient and plant community dynamics. The results would help in conceptualizing better management regimes for sub- tropical Sal forests for improved N cycling.

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REFERENCES

Arslan, H., Guleryuz G. and Kirmizi, S. (2010). Nitrogen mineralization in the soil of indigenous oak and pine plantation forests in a Mediterranean environment. European Journal of Soil Biology 46, 11-17. http://dx.doi.org/10.1016/j.ejsobi.2009.08.002 .

Bargali, K., Manral, V., Padalia, K., Bargali, K. and Upadhyay, V.P. (2018). Effect of vegetation type and season on microbial biomass carbon in Central Himalayan forest soils. India. Catena, 171, 125–135. https://doi.org/10.1016/j.catena.2018.07.001.

Bargali, S.S., Padalia, K. and Bargali, K. (2019). Effects of tree fostering on soil health and microbial biomass under different land use systems in central Himalaya. Land Degradation and Development, 30(16), 1984–1998. https://doi.org/10.1002/ldr.3394.

Bargali, S.S., Shukla, K., Singh, L. and Ghosh, L. (2015). Leaf litter decomposition and nutrient dynamics in four tree species of dry deciduous forest. Tropical Ecology, 56(2), 57–66.

Bargali, S.S., Singh, S.P. and Singh, R.P. (1993). Pattern of weight loss and nutrient release in decomposing leaf litter in an age series of eucalypt plantations. Soil Biology and Biochemistry, 25, 1731–1738.

Bhuyan, S.I., Tripathi, O.P. and Khan, M.L. (2014). Effect of season, soil and land use pattern on soil N-mineralization, ammonification and nitrification: A study in Arunachal Pradesh, Eastern Himalaya. International Journal of Environmental Sciences, 5(1), 88-97. https://doi.org/10.6088/ijes.2014050100008.

Black, C.A. (1965). Methods of soil analysis. Academic Press Inc., New York, pp 369.

Chen, J., Xiao, G., Kuzyakov, Y., Jenerette, G.D., Ma, Y., Liu, W., Wang, Z. and Shen, W. (2017). Soil nitrogen transformation responses to seasonal precipitation changes are regulated by changes in functional microbial abundance in a subtropical forest. Biogeosciences, 14, 2513–2525. https://doi.org/10.5194/bg-14-2513-2017.

Chen, X. and Mulder, J. (2007). Indicators for nitrogen status and leaching in subtropical forest ecosystems, South China. Biogeochemistry, 82(2), 165-180. http://dx.doi.org/10.1007/s10533-006-9061-3.

Contosta, A.R., Frey, S.D. and Cooper, A.B. (2011). Seasonal dynamics of soil respiration and N mineralization in chronically warmed and fertilized soils. Ecosphere, 2(3), 1-21. https://doi.org/10.1890/ES10-00133.1.

Cregger, M.A., McDowell, N.G., Pangle, R.E., Pockman, W.T. and Classen, A.T. (2014). The impact of precipitation changes on nitrogen cycling in a semi-arid ecosystem. Functional Ecology, 28(6), 1534–1544. https://doi.org/10.1111/1365-2435.12282.

Dessureault-Rompre, J., Zebarth, B.J., Burton, D.L. and Grant, C.A. (2016). Depth distribution of mineralizable nitrogen pools in contrasting soils in a semi-arid climate. Canadian Journal of Soil Science, 96(1), 1-11. https://doi.org/10.1139/cjss-2015-0048.

Eno, C.F. (1960). Nitrate production in the field by incubating soil in polyethylene bags. Soil Science Society of American Proceedings 24, 277-279. https://doi.org/10.2136/sssaj1960.03615995002400040019x.

Fu-Sheng, C., De-Hui, Z., Singh, A.N. and Guang-sheng, C. (2005). Effects of soil moisture and soil depth on nitrogen mineralization process under Mongolian pine plantations in Zhanggutai sandy land, P. R. China. Journal of Forestry Research, 16, 101-104. http://dx.doi.org/10.1007/BF02857899.

Gan Huei, Y., Schoning, I., Schall, P., Ammer, C. and Schrumpf, M. (2020). Soil Organic Matter Mineralization as Driven by Nutrient Stoichiometry in Soils Under Differently Managed Forest Stands. Frontiers in Forests and Global Change, 3, 99. https://doi.org/10.3389/ffgc.2020.00099.

Garkoti, S.C., Zobel, D.B. and Singh, S.P. (2003). Variation in drought response of Sal (*Shorea robusta*) seedlings. Tree Physiology, 23(15), 1021–1030. http://dx.doi.org/10.1093/treephys/23.15.1021.

Groffman, P.M., Hardy, J.P., Fisk, M.C., Fahey, T.J., and Driscoll, C.T. (2009). Climate variation and soil carbon and nitrogen processes in a northern hardwood forest. Ecosystems, 12(6), 927– 943. http://dx.doi.org/10.1007/s10021-009-9268-y.

Indian Standard (1965). Part IV: grain size analysis. Indian Standard Institute, New Delhi, pp 2720.

Iversen, C.M., Hookerm, T.D., Classen, A.T. and Norby, R.J. (2011). Net mineralization of N at deeper soil depths as a potential mechanism for sustained forest production under elevated [CO2]. Global Change Biology, 17(2), 1130–1139. http://dx.doi.org/10.1111/j.1365-2486.2010.02240.x.

Jackson, M.L. (1958). Soil Chemical Analysis. Verlag: Prentice Hall, Inc. Englewood Clift, NJ, pp 498. https://doi.org/10.1002/jpln.19590850311.

Jaramillo, V.J. and Sanford, R.L.J.R. (1985). Nutrient cycling in tropical deciduous forests. In: S.H. Bullock, H.A. Mooney & E.O. Medina (eds.) Seasonally Dry Tropical Forests. Academic Press Inc, London, pp 347-362.

Jerabkova, L., Prescott, C.E. and Kishchuk, B.E. (2006). Nitrogen availability in soil and forest floor of contrasting types of boreal mixedwood forests. Canadian Journal of Forest Research, 36, 112–122. https://doi.org/10.1139/x05-220.

Jha, P.B., Singh, J.S. and Kashyap, A.K. (1996). Dynamics of viable nitrifier community and nutrient availability in dry tropical forest habitat as affected by cultivation and soil texture. Plant and Soil, 180, 277–285. https://doi.org/10.1007/BF00015311.

Jhariya, M.K. and Singh, L. (2021). Effect of fire severity on soil properties in a seasonally dry forest ecosystem of Central India. International Journal of Environmental Science and Technology, 18(12), 3967-3978. https://doi.org/10.1007/s13762-020-03062-8.

Jongen, M., Lecomte, X., Unger, S., Fangueiro, D. and Pereira, J.S. (2013). Precipitation variability does not affect soil respiration and nitrogen dynamics in the understorey of a Mediterranean oak woodland. Plant and Soil, 372, 235–251. http://dx.doi.org/10.1007/s11104-013-1728-7.

Karhu, K., Fritze, H., Tuomi, M., Vanhala, P., Spetz, P., Kitunen, V. and Liski, J. (2010). Temperature sensitivity of organic matter decomposition in two Boreal forest soil profiles. Soil Biology and Biochemistry, 42, 72-82. http://dx.doi.org/10.14214/df.107.

Karki, H., Bargali, K. and Bargali, S.S. (2021a). Spatial and Seasonal Pattern of Fine Root Biomass and Turnover Rate in Different Land Use Systems in Central Himalaya, India. Russian Journal of Ecology, 52(1), 36-48. http://dx.doi.org/10.1134/S1067413621010070.

Karki, H., Bargali, K. and Bargali, S.S. (2021b). Spatial and temporal trends in soil N-mineralization rates under the agroforestry systems in Bhabhar belt of Kumaun Himalaya, India. Agroforestry Systems, https://doi.org/10.1007/s10457-021-00669-9.

Karki, H., Bargali, K. and Bargali, S.S., (2021c) Nitrogen mineralization patterns in Populus deltoids and Tectona grandis based agrisilvicultural practices in Central Himalaya, India. *Vegetos*, 34(1), 86-93. http://dx.doi.org/10.1007/s42535-021-00195-0.

Kautsar, V., Tang, S., Kimani, S.M., Tawaraya, Wu, J., Toriyama, K., Kobayashi, K. and Cheng, W. (2022). Carbon decomposition and nitrogen mineralization of foxtail and milk vetch incorporated into paddy soils for different durations of organic farming. Soil Science and Plant Nutrition, 68, 1, 158-166. https://doi.org/10.1080/00380768.2021.2024424.

Kumar, B.M. (2000). *Ailanthus triphysa* in the homegardens of Kerala, India: occurrence, basal area, average standing stock of wood and diameter structure. Indian Journal of Agroforestry, 2(1-2), 49-52.

Manral, V., Bargali, K., Bargali, S.S. and Shahi, C. (2020). Changes in soil biochemical properties following replacement of Banj oak forest with Chir pine in Central Himalaya, India. Ecological Processes, 9, 30. https://doi.org/10.1186/s13717-020-00235-8.

Masunga, R.H., Uzokwe, V.N., Mlay, P.D., Odeh, I., Singh, A., Buchan, D. and De Neve, S. (2016). Nitrogen mineralization dynamics of different valuable organic amendments commonly used in agriculture. Applied Soil Ecology. 101: 185-193. https://doi.org/10.1016/j.apsoil.2016.01.006.

Misra, R. (1968). Ecology Work Book. Oxford and IBH publishing Company, Calcutta, pp 244.

Mylliemngap, W., Nath, D. and Barik, S.K. (2015). Changes in vegetation and nitrogen mineralization during recovery of a montane subtropical broadleaved forest in North-eastern India following anthropogenic disturbance. Ecological Research, 31(1), 21–38. http://dx.doi.org/10.1007/s11284-015-1309-8.

Omara, P., Aula, L., Otim, F., Obia, A., Souza, J.L.B. and Arnall, D.B. (2022). Biochar Applied with Inorganic Nitrogen Improves Soil Carbon, Nitrate and Ammonium Content of a Sandy Loam Temperate Soil. Nitrogen 3, 90-100. https://doi.org/10.3390/nitrogen3010007.

Ono, K., Hiradate, S., Morita, S. and Hirai, K. (2013). Fate of organic carbon during decomposition of different litter types in Japan. Biogeochemistry, 112, 7–21. https://doi.org/10.1007/s10533-011-9682-z.

Padalia, K., Bargali, S.S., Bargali, K. and Manral, V. (2022). Soil microbial biomass phosphorus under different land use systems of Central Himalaya. Tropical Ecology, 63(1), 30–48. http://dx.doi.org/10.1007/s42965-021-00184-z.

Paul, K.I., Black, A.S. and Conyers, M.K. (2001). Effect of plant residue return on development of surface soil pH gradient. Soil Biology and Biochemistry, 33(1), 75–82. http://dx.doi.org/10.1007/s003740000293.

Piper, C.S. (1950). Soil and Plant Analysis. The University of Adelaide. Adelaide press, Australia, pp 368.

Primo, A.A., Araujo, M.D.M., Silva, K.F., Silva, L.A., Pereira, G.A., Fernandes, F.E.P., Pompeu, R.C.F.F., Natale, W. and Henrique, A.S. (2021). Litter production and nutrient deposition from native woody species in the Brazilian semi-arid region. Agroforestry Systems, 95(8), 1459-1464 https://doi.org/10.1007/s10457-021-00652-4.

Quan, Q., Wang, C., He, N., Zhang, Z., Wen, X., Su, H., Wang, Q. and Xue, J. (2014). Forest type affects the coupled relationships of soil C and N mineralization in the temperate forests of northern China. Scientific Reports, 4, 6584. https://doi.org/10.1038/srep06584.

Raj, A. and Jhariya, M.K. (2021a). Site quality and vegetation biomass in the tropical Sal mixed deciduous forest of Central India. Landscape and Ecological Engineering, 17(3), 387-399. https://doi.org/10.1007/s11355-021-00450-1.

Raj, A. and Jhariya, M.K. (2021b). Carbon storage, flux and mitigation potential of tropical Sal mixed deciduous forest ecosystem in Chhattisgarh, India. Journal of Environmental Management 293(1), 112829. https://doi.org/10.1016/j.jenvman.2021.112829.

Schimel, J.P. and Bennett, J. (2004). Nitrogen mineralization: challenges of a changing paradigm. Ecology, 85(3), 591–602. https://doi.org/10.1890/03-8002.

Singh, J.S. and Kashyap, A.K. (2007). Variations in soil N-mineralization and nitrification in seasonally dry tropical forest and savanna ecosystems in Vindhyan region. India. Tropical Ecology, 48(1), 27–35.

Subbiah, B.V. and Asija, G.L. (1956). A rapid procedure for the determination of available nitrogen in soil. Current Science, 25, 259–260.

Sun, S.H., Liu, J.J. and Chang, S.X. (2013). Temperature sensitivity of soil carbon and nitrogen mineralization: impacts of nitrogen species and land use type. Plant and Soil, 372(1-2), 597–608. http://dx.doi.org/10.1007/s11104-013-1758-1.

Urakawa, R., Ohte, N., Shibata, H., Isobe, K., Tateno, R., Oda, T., Hishi, T., Fukushima, K., Inagaki, Y., Hirai, K., Oyanagi, N., Nakata, M., Toda, H., Kenta, T., Kuroiwa, M., Watanabe, T., Fukuzawa, K., Tokuchi, N., Ugawa, S., Enoki, T., Nakanishi, A., Saigusa, N., Yamao, Y. and Kotani, A. (2016). Factors contributing to soil nitrogen mineralization and nitrification rates of forest soils in the Japanese archipelago. Forest Ecology and Management, 361, 382-396. http://dx.doi.org/10.1016/j.foreco.2015.11.033.

Verma, P. and Sagar, R. (2020). Effect of nitrogen (N) deposition on soil-N processes: a holistic approach. Scientific Reports, 10, 10470. https://doi.org/10.1038/s41598-020-67368-w.

Walkley, A. and Black, I.A. (1934). An examination of Degtjareff method for determining soil organic matter and the proposed modification of the chromic acid titration method. Soil Science, 37(1), 29-38. https:// doi.org/10.1097/00010694-193401000-00003.

Wang, Q., Li, F., Rong, X. and Fan, Z. (2018). Plant-Soil Properties Associated with Nitrogen Mineralization: Effect of Conversion of Natural Secondary Forests to Larch Plantations in a Headwater Catchment in Northeast China. Forests, 9(7), 386. https://doi.org/10.3390/f9070386.

Wetzel, R.G. and Lickens, G.E. (1979). Limnological Analyses, W.B. Saunders Co., Philadeplphia, pp 357. https://doi.org/10.1007/978-1-4757-3250-4.

Yang, R, Liu, K., Harrison, M.T., Fahad, S., Wang, Z., Zhou, M. and Wang, X. (2022). How Does Crop Rotation Influence Soil Moisture, Mineral Nitrogen, and Nitrogen Use Efficiency? Frontiers in Plant Science 13, 854731. https://doi.org/10.3389/fpls.2022.854731.

Yokobe, T., Hyodo, F. and Tokuchi, N. (2018). Seasonal effects on microbial community structure and nitrogen dynamics in temperate forest soil. Forests, 9(3), 153. https://doi.org/10.3390/f9030153.

Zha, Y.X., Faeflen, S.J.W., Zhou, X.B., Tecimen H.B., Wright A.L. and Jiang X.J. (2022). Redox effect on carbon and nitrogen mineralization in the drawdown zone of the Three Gorges Reservoir. International Journal of Environmental Science and Technology. https://doi.org/10.1007/s13762-022-03950-1.

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