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Seasonal dynamics of soil microbial biomass in fragmented patches of subtropical humid forest of Jaintia hills in Meghalaya, Northeast India

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Abstract

Aim of the study: The aim of the study was to assess the seasonal dynamics of microbial biomass and its contribution to soil system along a fragment size gradient in subtropical humid forest of Meghalaya.

Area of study: The study was conducted in forest fragments located at Jarain and adjoining areas in Jaintia Hills of Meghalaya, northeast India.

Material and Methods: Forest fragments of sizes ranging from 3.8 to 105 ha were selected for the study and grouped into Small (< 5 ha), Medium (> 5 and < 15 ha), Large (>15 and < 50 ha) and Very Large (105 ha) classes. Three experimental plots each of 20 x 20 m were established at the forest edge and at 50 m distance assigned as 'interior' microsite in each of the fragments for sampling of soil. Soil samples (0-10 cm depth) from each of the experimental plots were collected in replicates on seasonal interval and microbial biomass was estimated by the fumigation extraction method.

Important findings: Microbial biomass -C, -N and -P varied significantly ($p< 0.05$) between the fragment sizes, microsites and seasons. The microbial biomass was higher in the interior as compared to the edge. It was also high during the winter season. Overall, soil microbial biomass -C, -N and -P ranged from 260 to 969; 25 to 95 and 8 to 67 μg g^{-1} respectively. The contribution of microbial biomass -C, -N and -P to soil organic carbon, total Kjeldahl nitrogen and phosphorus ranged from 1.48 to 1.81 %, 2.54 to 4.54 % and 3.41 to 5.22 % respectively. Fragmentation alters the microenvironmental conditions and soil properties that in turn affect the microbial biomass.

Highlights: This interaction of plant, soil and microbial community would gradually degrade in the fragments due to change in vegetation composition and structure, microclimatic conditions and soil physical and chemical properties. Our results suggests that microbial mediated ecosystem processes such as nutrient cycling are more susceptible to variation at the edge which may become unstable and unpredictable in forest fragments exposed to various human disturbances.

Additional keywords: fragment size, microbial biomass, microenvironment, subtropical forest.

Authors' contributions: Original idea and study design: KU. Data collection: NTP. Data analysis: NTP and KU. Manuscript preparation and revisions: NTP and KU.

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Introduction

Fragmentation of forests has been identified as a major cause of biodiversity loss. It leads to edge creation and alter the microclimatic conditions that may have deleterious effect on ecosystem structure and function (Chen *et al.*, 1999; Ibanez *et al.*, 2014). Forest edge experiences increased soil temperature, high evapotranspiration and reduced soil moisture content due to greater insolation (Camargo & Kapos, 1995). Edges are also exposed to high wind turbulence. Consequently, trees on the edge are prone to high mortality owing to physical damage as well as physiological stress (Laurance *et al.*, 1999; 2000). Thus forest fragmentation leads to a shift in ecological traits of dominant species and reduces the buffering capacity of microclimate at the edge (Zhu *et al.*, 2004). The elevated rates of tree mortality and recruitment in fragmented forests drive the biomass (Laurance *et al.*, 2014) and the litter quality that may alter carbon and

nutrient return to the soil (Laurance *et al.*, 1997; 1998). Studies have shown that the litterfall increases in the forest edge with high nutrient concentration (Sizer *et al.*, 2000) but often displays decrease decomposition rate (Moreno *et al.*, 2014; Ruitta *et al.*, 2012). Such changes may affect the soil nutrient balance in the edge (Bierregaard *et al.*, 1992). As a result synergistic impact of shift in dominant plant community and microclimatic conditions directly or indirectly influence the resource availability on the soil (Haddad *et al.*, 2015). Further, in fragmented forests, changes in microbial population and invertebrate activity may lead to reduced decomposition rates and may affect nutrient cycling (Yeong *et al.*, 2016).

Soil microbial biomass plays an important role in the conversion of organically bound plant nutrient into inorganic forms (Singh *et al.*, 1989). The role of microbial activities in regulating the nutrient dynamics is crucial in sustaining forest ecosystems. Soil microbial biomass is regulated by soil physical and chemical properties and microclimatic conditions (Chen *et al.*, 2005; Devi & Yadava, 2006). Fragmentation and habitat degradation may change plant-soil-microbe interaction, influence soil nutrient dynamics and control the above ground community of the fragments (Lazaro-Nogal *et al.*, 2012). Thus microclimatic conditions at the edge can further alter microbial dynamics and their role in biogeochemical cycles. As drier conditions will favour fungal-dominated soil microbial communities, leading to a deceleration of processes associated with the plant-soil-microbial system (Flores-Renteria *et al.*, 2015). However, there are very few studies related to the effect of fragmentation on ecosystem functions particularly nutrient dynamics and microbial activity. Soil microbial biomass and activity and the faunal group (especially the nematodes) are often used as important indicators to assess the ecosystem quality and health status after disturbances (Schloter *et al.*, 2003).

The subtropical broadleaved humid forests of Meghalaya in northeast India distributed between 1000 m and 1800 m are highly fragmented due to anthropogenic activities such as mining, shifting cultivation, construction of roads and urbanization (Pao & Upadhaya, 2017). These forests in the state are currently characterized by small remnant patches scattered on strolling grasslands and areas that are usually inaccessible. Fragmentation changes the vegetation composition, community structure and microclimatic conditions and thus could be one of the important factors affecting the soil nutrient status and the microbial biomass (C, N and P). Although there are a number of studies that have established that climatic factors, soil pH and temperature influence microbial biomass in different forest types (Maithani *et al.*, 1996; Singh & Kashyap, 2006; Singh *et al.*, 2010), but the effect of fragmentation is poorly understood. We hypothesize that along a fragment size gradient soil microbial biomass would vary and hence affect nutrient addition to the soil with low biomass and nutrient in the small as compared to larger fragments. Therefore, the specific objectives of the present study was to assess the seasonal dynamics of soil microbial biomass and its contribution to soil organic matter and nutrient along a fragment size gradient in subtropical forests of Jaintia hills in Meghalaya, northeast India.

Materials and methods

Study area

The study was conducted in Jarain (latitude 25°19' 20.45"N- 25°19'25.55"N and longitude 92°07' 42. 33"E- 92°09'23.09"E, altitudinal range 1000 – 1100 m) in Jaintia Hills of Meghalaya, northeast India. The forest in the study area occurs in the form of patches and was once part of the same continuous forests that got fragmented over time due to human disturbances such as road construction, shifting cultivation and mining (Pao & Upadhaya, 2017). For the present study a total of 10 fragments were selected. The size of the fragments ranged from 3.79 to 105 ha (Table 1). All the selected sites were within a 6 km radius of Jarain village and had similar vegetation and soil.

The forest fragments were classified into four size classes viz. Small (< 5 ha), Medium (> 5 and < 15 ha), Large (> 15 and < 50 ha) and Very Large (105 ha), so that they represent a size gradient and were abbreviated as S, M, L and VL respectively. A set of three forest fragments were maintained for each fragment class (Table 1). However, in the case of the Very Large (VL), three replicated plots were maintained from a single large fragment. This was due to lack of large continuous tract of forests in the study area.

The vegetation of the area falls under subtropical broadleaved humid forest type (Champion & Seth, 1968). The vegetation is dense with a canopy height where trees rarely exceeds 18 m. The canopy layer is dominated by species like *Castanopsis* spp., *Lithocarpus fenestratus* (Roxb.) Rehder, *Persea odoratissima* (Nees) Kosterm., *Quercus semiserrata* Roxb., *Sarcosperma griffithii* Hook.f. ex C.B.Clarke. The subcanopy layer is characterized by species such as *Litsea elongata* (Nees) Hook. f., *Rhus acuminata* DC., *Syzygium cumini* (L.) Skeels, *S. tetragonum* (Wight) Wall. ex Walp., *Helicia nilagirica* Bedd. and *Lithocarpus dealbatus*. (Hook.f. & Thomson ex Miq.) Rehder. The undercanopy layer is dominated

Table 1. Vegetation characteristics in the studied fragments.

Fragment classes	Site	Area (ha)	Woody species (≥ 5 cm dbh)			Shrubs		Herbs	
			Species richness	Density (ha^{-1})	Basal area (m^2 ha^{-1})	Species richness	Density (ha^{-1})	Species richness	Density (ha^{-1})
Small	S1	3.79	77	1675	43.53	45	9100	33	231500
	S2	4.13	60	1550	43.68	42	9980	46	194750
	S3	4.99	72	1628	50.43	48	11310	42	230000
Medium	M1	13.2	83	1658	42.10	43	7440	48	179500
	M2	6.23	79	1530	48.38	36	7640	39	221250
	M3	8.72	67	1858	41.18	36	11720	33	208750
Large	L1	28.7	75	1783	39.55	40	8110	43	171500
	L2	19.6	83	1253	52.55	44	9090	48	211250
	L3	21.02	72	1570	51.75	48	10310	51	306000
Very Large	VL1	105	83	1725	49.88	36	6880	44	251750
	VL2	105	69	1493	52.13	42	10580	46	354500
	VL3	105	76	1565	54.20	43	6540	39	214750

by large shrub or small trees such as *Camellia caduca* C.B.Clarke ex Brandis, *C. caudata* Wall, *Erythroxylon kunthianum* A.St.-Hil., *Eurya acuminata* DC., *Symplocos spicata* Roxb. (Pao *et al.*, 2016). The ground vegetation is dominated by ferns, mosses, and species belonging to Balsaminaceae, Orchidaceae, Rubiaceae and Asteraceae. The vegetation characteristics of the studied fragments are shown in Table 1.

The climate of the area is tropical monsoonal and the rainfall is influenced both by the south-west and north-east winds. Four seasons – autumn (September – November), winter (December – February), spring (March – May) and rainy (June – August) are distinguishable. The mean annual rainfall during the period (January 2013 – December 2015) was 5550 mm. The average maximum and minimum temperature was 22 °C and 14 °C respectively (Figure 1).

The Jaintia Hills is a continuation of the Meghalaya Plateau formed from the remnants of Pre-cambrian Indian peninsular shield. The rocks are mostly of Precambrian origin with gneissic composition such as granites, schist, amphibolits and calc-silicate. The topography of the study area is more or less flat with rolling mounds representing plateau (Central Groundwater Board, 2013). The soil texture in all the studied fragments was loamy sand. Soil bulk density ranged from 0.98 to 1.10 g cm^{-3} whereas, the water holding capacity ranged from 50 to 59 % (Table 2).

Experimental design

Micro-environmental variables

The micro-environmental variables in the selected fragments at the edge and interior microsites were studied for a period of two years (October 2013 to July 2015). Light intensity, relative humidity, air- and soil-temperature were measured during October, January, April and July. These months correspond to autumn, winter, spring and rainy seasons, respectively. The measurements were taken between 9 and 10 a.m. for three consecutive days in each of the four seasons of sampling. All the variables were measured randomly at three places in different microsites (edge and interior) in the selected fragments. Light intensity was measured by using Digital Luxmeter (TES 1332A), atmospheric temperature and relative humidity by Thermo-

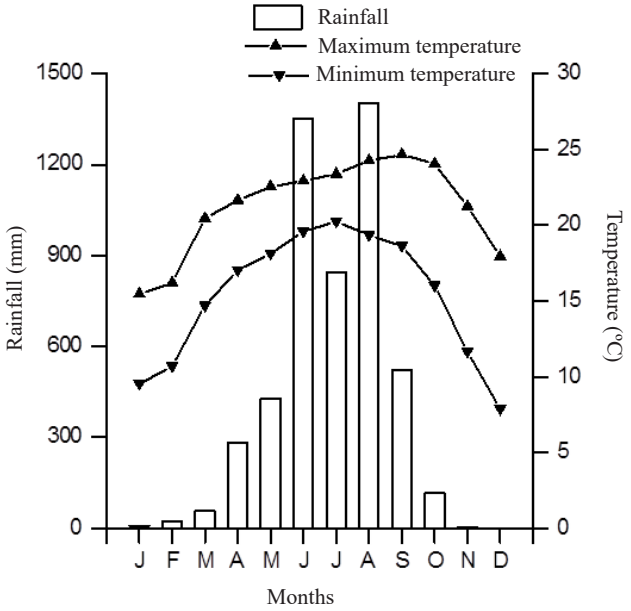

Figure 1. Mean monthly rainfall (mm) and maximum and minimum temperatures (ºC) in the study site (January 2013 – December 2015).

Table 2. Soil physical properties in the studied fragments.

Soil characteristics	Fragment classes			
	Small	Medium	Large	Very Large
Soil texture	Loamy sand	Loamy sand	Loamy sand	Loamy sand
Clay (%)	3.99 ± 0.11	7.57 ± 0.18	10.71 ± 0.53[a]	10.79 ± 0.46[a]
Silt (%)	12.73 ± 0.59[a]	11.76 ± 0.14[a]	11.89 ± 0.65[a]	11.93 ± 0.58[a]
Sand (%)	83.28 ± 0.50	80.66 ± 0.26	77.41 ± 0.84[a]	77.28 ± 0.92[a]
BD (g cm^{-3})	1.10 ± 0.03[a]	1.04 ± 0.02[ab]	0.98 ± 0.02[b]	1.01 ± 0.01[b]
WHC (%)	56.20 ± 1.13[a]	49.71 ± 2.21	55.37 ± 1.20[a]	58.85 ± 1.02[a]

Values are mean ± SE, n = 9; within a row, values followed by similar superscripts are not significantly different from each other (Tukey HSD test, $P < 0.05$); BD = bulk density, WHC = water holding capacity.

hygrometer TH-103 (Mex-therm). Soil temperature was measured by digital soil thermometer (Multi-Thermometer) by inserting the probe into the soil to a depth of 10 cm.

Soil sampling

Three experimental plots each of 20 x 20 m were established at the forest edge (measured as the distance from the last tree at the edge to 20 m into the forest) and at 50 m distance assigned as 'interior' microsite in each of the fragments for sampling of soil. The soils were sampled to a depth of 10 cm after removal of litter layer. Three soil samples from each of the experimental plots were collected using an iron soil corer (6.5 cm diameter and 20 cm height) on seasonal basis from each fragment. Thus a total of nine samples each were retrieved from edge and interior microsites separately on every sampling period for each fragment sites. These samples were bulked together microsite wise to get a composite soil sample for each fragment sites. The samples were further divided into sub samples for analysis. The first part was used for determination of soil moisture content (SMC), pH, microbial biomass, ammonium-N (NH_4^+–N) and nitrate-N (NO_3^- –N). The second part was air dried and grounded for determination of soil organic carbon (SOC), total Kjeldahl nitrogen (TKN) and extractable phosphorus (Ex. P). The data collected from both microsites and each fragment sites were pooled together and presented fragment class wise.

Laboratory analysis

SMC was determined gravimetrically by drying 10 g of fresh soil in a hot-air oven at 105 °C for 24 h and the result was expressed on oven-dry weight basis (Allen *et al.*, 1974). Soil pH was determined by a digital pH meter taking 1: 2.5 suspension of soil and distilled water. NH_4^+–N was determined by the indophenol blue method after extracting the fresh soil samples with 1 N KCl solution (Allen *et al.*, 1974). NO_3^-–N was determined by the phenol disulfonic acid method from fresh soil samples extracted with deionized water (Allen *et al.*, 1974). SOC was determined by colorimetric method following Anderson and Ingram (1993). TKN was determined by the semi-micro Kjeldahl digestion method by digesting air dried sample with concentrated H_2SO_4 using Kjeltabs as catalyst followed by distillation and titration (Allen *et al.*, 1974). Extractable P (Ex. P) was determined by Molybdenum blue method after extracting the air dried soil with 0.5 M $NaHCO_3$ (Allen *et al.*, 1974).

Soil microbial biomass -C, -N and -P was determined by the fumigation-extraction method. Three subsamples (10 g each) were fumigated by saturating with 10 mL of alcohol free liquid chloroform for lysing of cell while other three were unfumigated. The fumigated and unfumigated soils were extracted with 0.5 M K_2SO_4 and filtered through Whatman filter paper no. 42. These filtrates were used for the determination of microbial biomass -C and -N. The organic carbon content in the extracts was determined by digesting the extract in H_2SO_4 and 0.00667 M $K_2Cr_2O_7$. The digested sample was titrated with acidified ammonium ferrous sulphate solution using an indicator (O-phenolphthaline monohydrate and ferrous sulphate hexahydrate). The volume of titrant consumed was deduced for estimation of organic carbon extracted (Vance *et al.*, 1987).

Similarly, for microbial biomass nitrogen (MBN) the extracts were further digested with 4.4 mL of digestion mixture of selenium powder, lithium sulphate, hydrogen peroxide and H_2SO_4. The digested solution was extracted with distilled water in Whatman filter paper no.1. The filtrate was used to determine the ammonium released through distillation with 40 % NaOH. The distillate was collected in boric acid indicator till the permanent green colour develops. It was titrated against N/140 HCl till it turns into

pink colour. Microbial biomass phosphorus (MBP) was determined by chloroform fumigation-extraction method (Brookes *et al.*, 1982) and further extracted by ammonium molybdate blue method (Allen *et al.*, 1974). Microbial biomass -C, -N and -P were calculated as:

MBC (µg g^{-1} soil) = 2.64* Ec

Where, Ec = difference between the amount of organic carbon extracted from the fumigated and non-fumigated soils expressed in µg C per g of soil

2.64 = the relationship between biomass C as measured by incubation method and amount of C extracted by 0.5 M K_2SO_4 after chloroform treatment.

MBN (µg g^{-1} soil) = (N_f – N_o)* 1.46

N_f = biomass N of fumigated sample

N_o = biomass N of unfumigated sample

MBP (µg g^{-1} soil) = (b – a) / 0.4

Where, a = amount of phosphorus (µg g^{-1}) extracted from the unfumigated soil

b = amount of inorganic phosphorus (µg g^{-1}) extracted from the fumigated soil

0.40 = the fraction of biomass phosphorus mineralized and extracted in 0.5 M $NaHCO_3$ (Brookes *et al.*, 1985).

Statistical analysis

The data on microclimatic variables (light intensity, relative humidity, air- and soil- temperature) and soil moisture content, pH, SOC, TKN and Ex. P, NH_4^+ –N, NO_3^- –N and microbial biomass C, N and P were subjected to two-way analysis of variance (ANOVA) of repeated measures. The analysis considered three factors: two factors included fragment size and microsites (between subjects) and one time factor included season (within subject) with four levels (autumn, winter, spring and rainy) spread across two years. Assumptions of ANOVA were met through test for normality of variables (Kolmogorov-Smirnov test), and homogeneity of group variances (Levene's test). Pearson's correlation was computed to understand the influence of fragment size, microclimatic conditions and soil properties on microbial biomass. All statistical analysis were performed using the software SPSS, version 13.

Results

Micro-environmental variables and soil properties

Light intensity varied significantly (P< 0.05) across the seasons with higher values during spring and low in rainy season (Table 3 and 4). It was high in small patches and the edge as compared to larger patches and interior microsites (P< 0.05). The air- and soil-temperature showed a similar trend with higher values during spring and rainy and the lowest values were recorded during winter season. However, they did not vary significantly (P> 0.05) across the studied fragments but varied between microsites (P< 0.05). The air temperature ranged from 23 to 25 ºC while soil temperature ranged from 19 to 21ºC in the studied fragments. The soil moisture content showed a strong seasonality (P< 0.05) with higher values during rainy and lower during winter. It was higher in the larger patches (P< 0.05) and interior microsites as compared to small patches and edge microsites. It ranged from 19 to 29 % in the studied fragments. The soil in the studied fragments was acidic (pH 5.4 – 5.7) and showed a marked seasonality (Table 3 and 4). It was more acidic (4.53 – 4.88) during the rainy season.

The SOC showed a marked variation (P< 0.05) among the studied fragments, microsites and seasons (Table 3 and 4). It ranged from 144 to 613 g Kg^{-1} among the fragments. SOC content was higher in the interior microsites as compared to the edges in all the forest patches. TKN ranged from 7 to 48 g Kg^{-1}. Similarly, the values of Ex. P ranged from 6.54 to 8.36 µg g^{-1}. It varied significantly between the fragments and seasons (P< 0.05). NO_3^-–N was the dominant form of nitrogen in the study area. NH_4^+–N and NO_3^- –N concentration ranged from 9.73 to 11.18 µg g^{-1} and 10 to 13 µg g^{-1} respectively (Table 3). The values were significantly (P< 0.05) higher in the interior - as compared to the edge -microsites (Table 4).

Soil microbial biomass

The MBC concentration varied significantly (P< 0.05) between the fragment size, microsites and seasons (Table 5). The values of MBC in the fragments ranged from 260 to 969 µg g^{-1} (Figure 2a). The range of values were 260 – 748 µg g^{-1} in Small, 289 – 781 µg g^{-1} in Medium, 362 – 793 µg g^{-1} in Large and 351 – 969 µg g^{-1} in Very Large fragments. The values were significantly higher (P< 0.05) in the forest interiors as compared to the edges (Table 5). MBC showed a marked seasonality (P< 0.05) with highest values during the winter season that gradually declined through the spring to its minimum level in the rainy season in all the fragment classes (Figure 2a).

The MBN varied significantly (P< 0.05) between the fragments classes and ranged from 28 to 92 µg g^{-1} (Figure 2b). It was significantly higher (P< 0.05) in the forest interior as compared to the edge (Table 5). The mean values in the edge along the fragment size gradient (from Small to Very Large) were 43, 44, 46

and 50 µg g^{-1} respectively. Similarly, the mean in the interior of the fragments were 51 (Small), 55 (Medium and Large) and 58 µg g^{-1} (Very Large). It showed a marked seasonality with low values during rainy season and high during winter (Figure 2b) in all the fragment classes.

Similarly, the microbial biomass phosphorus (MBP) values in the studied fragments ranged from 10 to 51µg g^{-1}. It varied significantly ($P< 0.05$) between the fragments classes. The average MBP values for edge and interior was 26 and 29 in Small, 30 and 33 in Medium, 29 and 32 in Large and 35 µg g^{-1} in Very Large respectively. Although MBP increased significantly with the increase in fragment size class, there was no significant difference between the microsites ($P> 0.05$) (Table 5). It showed a marked seasonality ($P< 0.01$) with low values during rainy season and high during winter (Figure 2c).

Microbial C/N and C/P

The microbial C/N ratio varied in the studied fragments. The value was high (11.92) at the edge of Large fragment class and low (10.29) in the interior

Table 3. Seasonal fluctuations of microenvironmental variables and soil properties in the edge and interior of the studied fragments.

Fragments	Seasons	Microsites	Light int. (µ moles m^{-2} s^{-1})	Rel. hum. (%)	Air temp. (ºC)	Soil temp. (ºC)	SMC (%)
Small	A	E	60.78 ± 3.04	71.01 ± 0.72	23.80 ± 0.43	21.96 ± 0.44	21.71 ± 1.78
		I	44.78 ± 2.95	70.96 ± 0.95	22.05 ± 0.49	20.46 ± 0.47	29.35 ± 1.66
	W	E	69.75 ± 3.54	50.85 ± 1.65	18.39 ± 0.41	17.15 ± 0.54	15.60 ± 1.24
		I	50.30 ± 4.01	51.73 ± 1.71	18.00 ± 0.37	15.44 ± 0.41	15.77 ± 1.14
	S	E	97.93 ± 2.90	57.78 ± 2.50	26.65 ± 0.63	21.26 ± 0.34	17.55 ± 1.71
		I	59.25 ± 5.01	58.65 ± 2.60	23.21 ± 0.74	20.20 ± 0.53	22.74 ± 1.39
	R	E	57.60 ± 3.98	73.34 ± 1.18	25.08 ± 0.78	20.80 ± 0.37	33.66 ± 3.36
		I	38.27 ± 6.27	75.52 ± 1.43	22.33 ± 0.79	19.88 ± 0.46	35.96 ± 2.14
Medium	A	E	57.25 ± 3.51	72.35 ± 0.95	23.76 ± 0.36	22.84 ± 0.39	26.40 ± 1.51
		I	33.82 ± 3.70	73.29 ± 0.99	21.23 ± 0.45	19.76 ± 0.42	29.42 ± 2.07
	W	E	67.47 ± 2.23	56.64 ± 2.25	17.14 ± 0.54	16.89 ± 0.75	13.04 ± 1.15
		I	38.61 ± 3.52	60.47 ± 1.86	16.84 ± 0.46	14.70 ± 0.55	14.91 ± 1.50
	S	E	84.58 ± 2.73	60.01 ± 2.62	25.40 ± 0.50	22.00 ± 0.55	20.73 ± 2.20
		I	45.59 ± 4.42	61.70± 2.50	22.33 ± 0.75	20.63 ± 0.57	22.96 ± 2.00
	R	E	44.09 ± 4.46	75.16 ± 0.75	25.96 ± 0.69	21.87 ± 0.39	38.65 ± 1.97
		I	22.04 ± 4.29	77.31 ± 0.99	22.64 ± 0.82	19.97 ± 0.46	42.70 ± 2.31
Large	A	E	66.98 ± 3.24	73.09 ± 1.16	24.19 ± 0.27	21.92 ± 0.48	28.05 ± 1.54
		I	40.71 ± 3.64	73.38 ± 1.41	20.85 ± 0.54	20.57 ± 0.41	34.44 ± 2.17
	W	E	78.85 ± 3.52	53.95 ± 2.36	18.45 ± 0.47	17.15 ± 0.66	15.25 ± 0.91
		I	41.65 ± 3.53	58.60 ± 2.01	17.04 ± 0.49	13.88 ± 0.69	18.48 ± 2.07
	S	E	97.26 ± 3.48	57.74 ± 1.99	27.31 ± 0.63	21.26 ± 0.47	24.22 ± 2.43
		I	55.07 ± 3.85	63.32 ± 2.11	21.78 ± 0.70	20.20 ± 0.53	24.62 ± 3.69
	R	E	51.58 ± 5.54	75.72 ± 0.89	27.41 ± 1.00	20.27 ± 0.41	36.12 ± 1.3
		I	25.32 ± 4.00	78.02 ± 1.22	22.26 ± 0.87	19.12 ± 0.41	38.89 ± 1.55
Very Large	A	E	51.68 ± 2.78	74.82 ± 1.16	23.50 ± 0.45	22.28 ± 0.41	31.57 ± 2.21
		I	37.49 ± 3.39	76.65 ± 1.21	22.87 ± 0.34	21.20 ± 0.39	35.99 ± 2.07
	W	E	71.56 ± 4.76	59.71 ± 1.22	16.41 ± 0.36	16.37 ± 0.60	16.12 ± 1.39
		I	53.52 ± 4.15	62.68 ± 1.23	16.93 ± 0.42	14.53 ± 0.50	21.16 ± 1.25
	S	E	84.04 ± 5.14	59.13 ± 1.72	26.36 ± 0.59	21.56 ± 0.63	18.57 ± 1.5
		I	55.92 ± 4.34	60.37 ± 1.84	23.52 ± 0.67	21.83 ± 0.77	22.93 ± 1.40
	R	E	60.50 ± 7.16	79.48 ± 1.16	25.03 ± 1.20	19.95 ± 0.44	39.82 ± 1.32
		I	21.19 ± 4.56	79.29 ± 1.22	23.79 ± 0.78	20.46 ± 0.45	43.19 ± 1.84

Table 3. Continued.

Fragments	Seasons	Microsites	pH H_2O 1:2.5	NH_4^+- N (µg g^{-1})	NO_3^- -N (µg g^{-1})	SOC (g Kg^{-1})	TKN (g Kg^{-1})	ExP (µg g^{-1})
Small	A	E	5.49 ± 0.06	7.27 ± 0.74	9.07 ± 0.89	293.00 ± 16.72	15.50 ± 0.99	6.06 ± 0.37
		I	5.17 ± 0.07	7.74 ± 0.79	10.81 ± 0.88	340.00 ± 26.34	19.50 ± 1.43	7.99 ± 0.47
	W	E	5.83 ± 0.05	14.74 ± 0.48	18.19 ± 0.62	405.67 ± 23.21	26.33 ± 1.89	13.95 ± 0.57
		I	5.61 ± 0.05	14.97 ± 0.50	19.25 ± 0.54	463.00 ± 37.53	27.33 ± 1.56	15.69 ± 0.43
	S	E	5.89 ± 0.10	11.55 ± 1.10	12.72 ± 1.68	329.17 ± 32.75	20.50 ± 1.98	7.35 ± 0.43
		I	5.75 ± 0.12	12.42 ± 1.08	14.02 ± 1.60	348.33 ± 35.85	22.00 ± 1.75	7.03 ± 0.46
	R	E	4.88 ± 0.07	4.36 ± 0.31	5.08 ± 0.32	263.50 ± 23.11	15.83 ± 1.83	2.49 ± 0.79
		I	4.91 ± 0.10	5.28 ± 0.39	5.44 ± 0.36	294.83 ± 29.87	14.33 ± 1.58	2.39 ± 0.89
Medium	A	E	5.50 ± 0.05	7.79 ± 0.46	9.09 ± 0.80	294.17 ± 23.12	15.00 ± 0.77	7.26 ± 0.38
		I	5.28 ± 0.10	6.58 ± 0.62	9.60 ± 1.02	297.00 ± 16.07	14.83 ± 0.95	8.51 ± 0.22
	W	E	5.88 ± 0.07	13.47 ± 0.56	18.34 ± 0.58	441.00 ± 49.66	22.00 ± 1.24	15.23 ± 0.45
		I	5.84 ± 0.06	14.5 ± 0.65	19.53 ± 0.52	437.67 ± 43.42	23.83 ± 2.07	15.18 ± 0.64
	S	E	5.50 ± 0.11	11.74 ± 1.05	11.10 ± 1.89	342.83 ± 9.92	24.00 ± 4.82	8.26 ± 0.41
		I	5.34 ± 0.10	12.46 ± 1.06	12.91 ± 1.68	318.50 ± 6.15	16.50 ± 0.56	7.25 ± 0.44
	R	E	4.59 ± 0.05	4.19 ± 0.39	4.66 ± 0.33	241.50 ± 25.00	12.83 ± 0.6	2.69 ± 0.65
		I	4.73 ± 0.08	4.51 ± 0.34	5.50 ± 0.43	220.67 ± 23.52	12.17 ± 0.91	2.23 ± 0.76
Large	A	E	5.56 ± 0.06	6.31 ± 0.64	10.82 ± 0.8	345.17 ± 10.36	16.50 ± 1.96	4.44 ± 0.40
		I	5.41 ± 0.09	5.93 ± 0.70	10.72 ± 0.59	345.17 ± 14.48	20.50 ± 0.96	5.17 ± 0.53
	W	E	6.00 ± 0.07	14.14 ± 0.44	17.27 ± 0.50	437.67 ± 14.50	26.17 ± 2.82	12.41 ± 0.73
		I	5.95 ± 0.07	15.86 ± 0.48	17.92 ± 0.56	418.00 ± 28.31	26.17 ± 1.51	14.41 ± 0.65
	S	E	5.54 ± 0.12	11.92 ± 1.00	11.64 ± 1.53	383.83 ± 14.86	20.33 ± 1.54	7.40 ± 0.32
		I	5.33 ± 0.10	12.99 ± 1.12	14.35 ± 1.42	399.00 ± 13.12	22.50 ± 0.85	6.63 ± 0.39
	R	E	4.80 ± 0.08	3.67 ± 0.32	5.57 ± 0.23	260.00 ± 17.24	14.33 ± 1.02	1.92 ± 0.74
		I	4.69 ± 0.07	4.43 ± 0.37	6.70 ± 0.25	319.33 ± 17.89	16.17 ± 1.25	1.87 ± 0.69
Very Large	A	E	5.62 ± 0.06	6.83 ± 0.75	10.99 ± 0.81	343.33 ± 28.80	18.17 ± 1.19	5.67 ± 0.47
		I	5.28 ± 0.08	6.69 ± 0.75	11.78 ± 0.62	344.33 ± 27.74	21.67 ± 2.12	6.85 ± 0.34
	W	E	6.08 ± 0.08	14.23 ± 0.5	17.86 ± 0.92	426.33 ± 21.79	26.33 ± 3.33	10.4 ± 0.94
		I	5.99 ± 0.09	15.39 ± 0.63	19.53 ± 0.87	477.50 ± 32.33	27.67 ± 2.23	11.67 ± 1.12
	S	E	5.46 ± 0.06	11.59 ± 1.01	14.83 ± 1.70	375.83 ± 20.16	18.67 ± 1.80	8.51 ± 0.38
		I	5.06 ± 0.08	12.6 ± 1.05	17.42 ± 1.37	414.00 ± 19.07	19.67 ± 1.73	8.61 ± 0.54
	R	E	4.73 ± 0.05	4.07 ± 0.46	5.75 ± 0.18	293.83 ± 26.05	14.17 ± 1.11	1.92 ± 0.78
		I	4.53 ± 0.05	4.94 ± 0.44	6.87 ± 0.47	309.67 ± 20.76	16.33 ± 1.50	3.07 ± 1.05

Values are mean of two years ± SE (n = 18); A= autumn, W = winter, S = spring and R = rainy; E = Edge, I = Interior).

of Small fragment class. The ratios for the different fragment classes with their respective microsites viz., edge and interior were 11.05 and 10.29 in Small, 11.79 and 10.69 in Medium, 11.92 and 11.39 in Large and 11.55 and 11.04 in Very Large (Table 6).

Similarly, the microbial C/P ratio was high in the Larger fragment class in both the edge and interior (19) microsites. However, microbial C/P ratios did not show any consistent variation between the two microsites among the fragment classes except Very large (Table 6).

Contribution of microbial biomass to soil carbon, nitrogen and phosphorous

The soil microbial biomass -C, -N and -P as proportions to SOC, TKN and Ex. P in the studied fragments is shown in Table 6. The percentage contribution of MBC to SOC was 1.48, 1.62, 1.58 and 1.62 for the edge microsites of Small, Medium, Large and Very Large fragments respectively, while the corresponding values for the interior microsites were 1.54, 1.81, 1.70 and 1.66. Generally, the contribution of MBC to SOC was higher in the

Table 4. Two-way analysis of variance (ANOVA) showing the effects of fragment size class, microsites and seasons on microenvironmental variables and soil properties.

Source of variation	Degree of freedom	F value										
		Light int. (μ moles m^{-2} s^{-1})	Rel. hum. (%)	Air temp (ºC)	Soil temp (ºC)	SMC (%)	pH H_2O 1:2.5	NH_4^+- N (μg g^{-1})	NO_3^- -N (μg g^{-1})	SOC (μg g^{-1})	TKN (μg g^{-1})	Ex.P (μg g^{-1})
Fragment class	3	12.28*	18.48*	1.28^{ns}	2.05^{ns}	6.99*	3.52*	0.74^{ns}	12.19*	3.01*	2.21^{ns}	5.79*
Microsites	1	445.17*	14.65*	118.20*	71.55*	21.98*	31.0*	13.64*	18.94*	1.78^{ns}	1.05^{ns}	3.33^{ns}
Fragment class x microsites	3	2.69*	0.91^{ns}	7.39*	4.11*	0.19^{ns}	1.96^{ns}	1.76^{ns}	0.54^{ns}	0.72^{ns}	0.95^{ns}	0.57^{ns}
Season	3	113.26*	950.69*	321.16*	269.18*	312.18*	392.22*	1408.59*	1697.81*	71.56*	81.73*	436.27*
Season x fragment class	9	1.72^{ns}	2.39*	2.13*	1.54^{ns}	3.05*	5.33*	2.29*	8.59*	1.14^{ns}	1.02^{ns}	3.99*
Season x microsites	3	10.53*	2.11^{ns}	13.12*	3.64*	1.08^{ns}	4.84*	2.73*	2.45*	0.98^{ns}	2.59^{ns}	3.21*
Season x fragment class x microsites	9	1.35^{ns}	0.98^{ns}	0.36^{ns}	1.04^{ns}	0.86^{ns}	0.62^{ns}	1.41^{ns}	1.60^{ns}	0.86^{ns}	1.05^{ns}	0.51^{ns}

The F values marked with * are significant at P< 0.05, ns = not significant.

interiors than in the edges of most fragments under study.

Similarly, the percentage contribution of MBN to TKN was highest in the interior microsite of Very Large followed by Medium, Large and Small fragments (Table 6). The percentage contribution of MBP to Ex. P was high at the edge in the Very Large (5.22%) followed by the Large (4.45%), Medium (3.55%) and Small (3.41%) fragments. A similar trend was observed in the forest interior with the highest contribution by the Very Large (4.70%) and the lowest by the Small fragment class (3.48%) (Table 6).

Relationships between microclimatic variables, soil properties and microbial biomass

The soil microbial biomass -C, -N, and -P showed a weak correlation (P> 0.05) with the fragment size. It showed a strong relation with microclimatic conditions and soil properties (Table 7). Among the microclimatic variables, only light intensity was positively related (r = 0.54, 0.39 and 0.48 respectively), whereas relative humidity (r = -0.76, -0.77 and -0.69 respectively), soil-moisture (r = -0.77, -0.77 and -0.76 respectively) and - temperature (r = -0.65, -0.87 and -0.65 respectively) showed a negative correlation. Other soil parameters such as pH (r = 0.80, 0.76 and 0.74 respectively), SOC (r = 0.89, 0.85 and 0.83 respectively), TKN (r = 0.87, 0.84 and 0.84 respectively) and Ex. P (r = 0.85, 0.89 and 0.81 respectively) exerted strong influence on the microbial biomass -C, -N and -P as evident by a positive relation (Figure 3).

Discussion

Fragmentation of the forest resulted in considerable changes in the microclimatic variables, soil properties

Table 5. Two-way analysis of variance (ANOVA) showing the effects of fragment size class, microsites and seasons on soil microbial biomass -C, -N and -P.

Source of variation	Degree of freedom	F value		
		MBC	MBN	MBP
Fragment class	3	11.69*	34.41*	4.23*
Microsites	1	17.79*	280.30*	3.06^{ns}
Fragment class x microsites	3	0.09^{ns}	1.07^{ns}	0.16^{ns}
Season	3	946.08*	2615.91*	483.46*
Season x fragment class	9	4.59*	3.74*	5.66*
Season x microsites	3	0.47^{ns}	21.47*	0.44^{ns}
Season x fragment class x microsites	9	0.73^{ns}	2.10*	0.22^{ns}

The F values marked with * are significant at P < 0.05, ns = not significant.

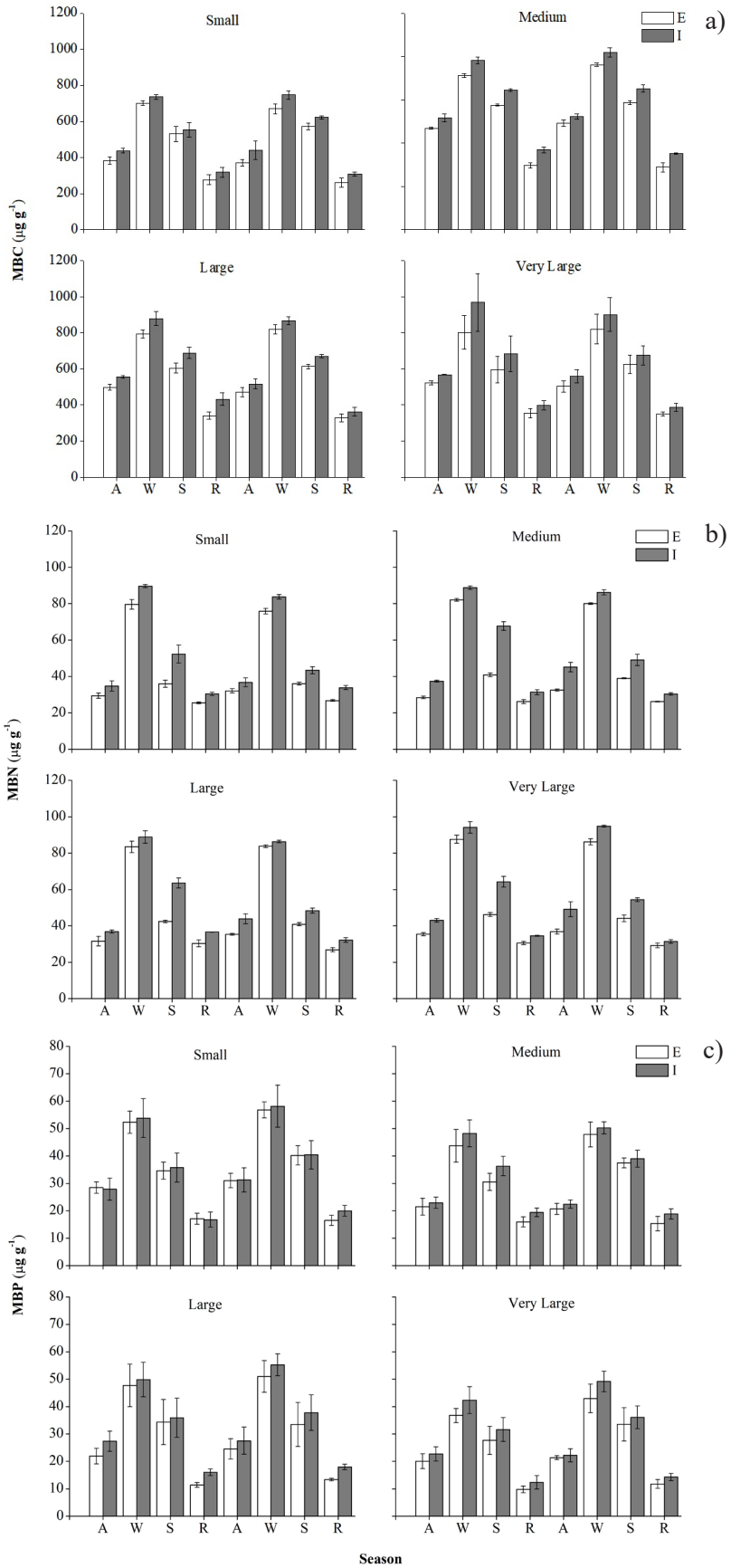

Figure 2. Seasonal variation of (a) soil microbial biomass carbon (MBC), (b) soil microbial biomass nitrogen (MBN) and (c) soil microbial biomass phosphorous (MBP) (µg g^{-1}) in different microsites along a fragment size gradient in Jaintia hills of Meghalaya, northeast India (A= autumn, W = winter, S = spring and R = rainy; E = edge, I = interior; ± SE, n = 9).

Table 6. Mean MBC, MBN and MBP (μg g^{-1}) and its proportion relative to SOC, TKN and Ex. P.

Parameters	Microsites	Fragment class			
		Small	Medium	Large	Very Large
MBC	Edge	470.65	523.00	558.03	571.92
	Interior	520.69	582.25	621.51	642.59
MBN	Edge	42.60	44.37	46.83	49.54
	Interior	50.60	54.48	54.58	58.22
MBP	Edge	25.48	28.83	29.71	33.45
	Interior	28.83	33.45	32.16	35.49
MBC:MBN	Edge	11.05	11.79	11.92	11.55
	Interior	10.29	10.69	11.39	11.04
MBC:MBP	Edge	18.47	17.6	19.18	16.53
	Interior	18.06	17.41	19.33	18.11
Percentage contribution of					
MBC to SOC	Edge	1.48	1.62	1.58	1.62
	Interior	1.54	1.81	1.70	1.66
MBN to TKN	Edge	2.27	2.42	2.44	2.57
	Interior	2.54	3.25	2.57	2.74
MBP to Ex.P	Edge	3.41	3.55	4.45	5.22
	Interior	3.48	4.03	4.58	4.70

and microbial biomass. The low values of nitrogen in the edge could be the inability of the plants to uptake nitrogen from the soil after disturbance and also due to leaching losses (Jose *et al.*, 1996; Ruitta *et al.*, 2012). Inorganic-N (NH_4^+–N and NO_3^-–N) concentrations were lower in the edge microsites and Small fragments. However, Ex. P showed no consistent trend along a fragment size gradient. This finding is similar to that observed from tropical deciduous forest of Mexico (Toledo-Aceves & Garcia-Oliva, 2008). Soil nutrient availability depends on abiotic and biotic factors such as mineralization, plant uptake, microbial uptake and leaching losses. Alteration of microclimatic conditions due to edge might have affected various nutrient return processes such as litter decomposition rate (Ruitta *et al.*, 2012) and microbial decomposition activities (Lazaro-Nogal *et al.*, 2012) thereby causing the variation in nutrient content among the microsites.

Habitat degradation due to human disturbances and fragmentation reduce canopy cover and initiates microclimatic variation in the remnant fragments (Brothers & Spingarn, 1992; Chen *et al.*, 1999). The higher microbial biomass -C, -N and -P in the larger fragments and interior microsites ($P< 0.05$) of the forest fragments can be attributed to an increase in light intensity and a decrease in air temperature, relative humidity, soil temperature and soil moisture content as well as soil organic carbon and nutrient (TKN and Ex. P) content. Similar results were found in tropical deciduous forest where microbial biomass increased from edge into the interior of forest fragments (Toledo-Aceves & Garcia-Oliva, 2008). The low soil microbial biomass at the edges is associated with low SOC,

Table 7. Correlation analysis showing Pearson's correlation coefficient (r).

Parameters	Area (ha^{-1})	Microclimate					Soil properties			
		LI (μ moles / m^2/s)	A T (˚C)	RH (%)	S T (˚C)	SMC (%)	pH H_2O 1:2.5	SOC (μg g^{-1})	TKN (μg g^{-1})	Ex.P (μg g^{-1})
MBC (μg g^{-1})	0.18^{ns}	0.54*	-0.71*	-0.76*	-0.65*	-0.77*	0.80*	0.89*	0.87*	0.85*
MBN (μg g^{-1})	0.11^{ns}	0.39*	-0.88*	-0.77*	-0.87*	-0.77*	0.76*	0.85*	0.84*	0.89*
MBP (μg g^{-1})	0.18^{ns}	0.48*	-0.70*	-0.69*	-0.65*	-0.76*	0.74*	0.83*	0.84*	0.81*

LI = light intensity, AT = air temperature, ST = soil temperature, SMC = soil moisture content, SOC = soil organic carbon, TKN = total Kjeldahl nitrogen and Ex.P = Extractable phosphorus (n = 48; values marked with * are significant at $P< 0.05$, ns = not significant).

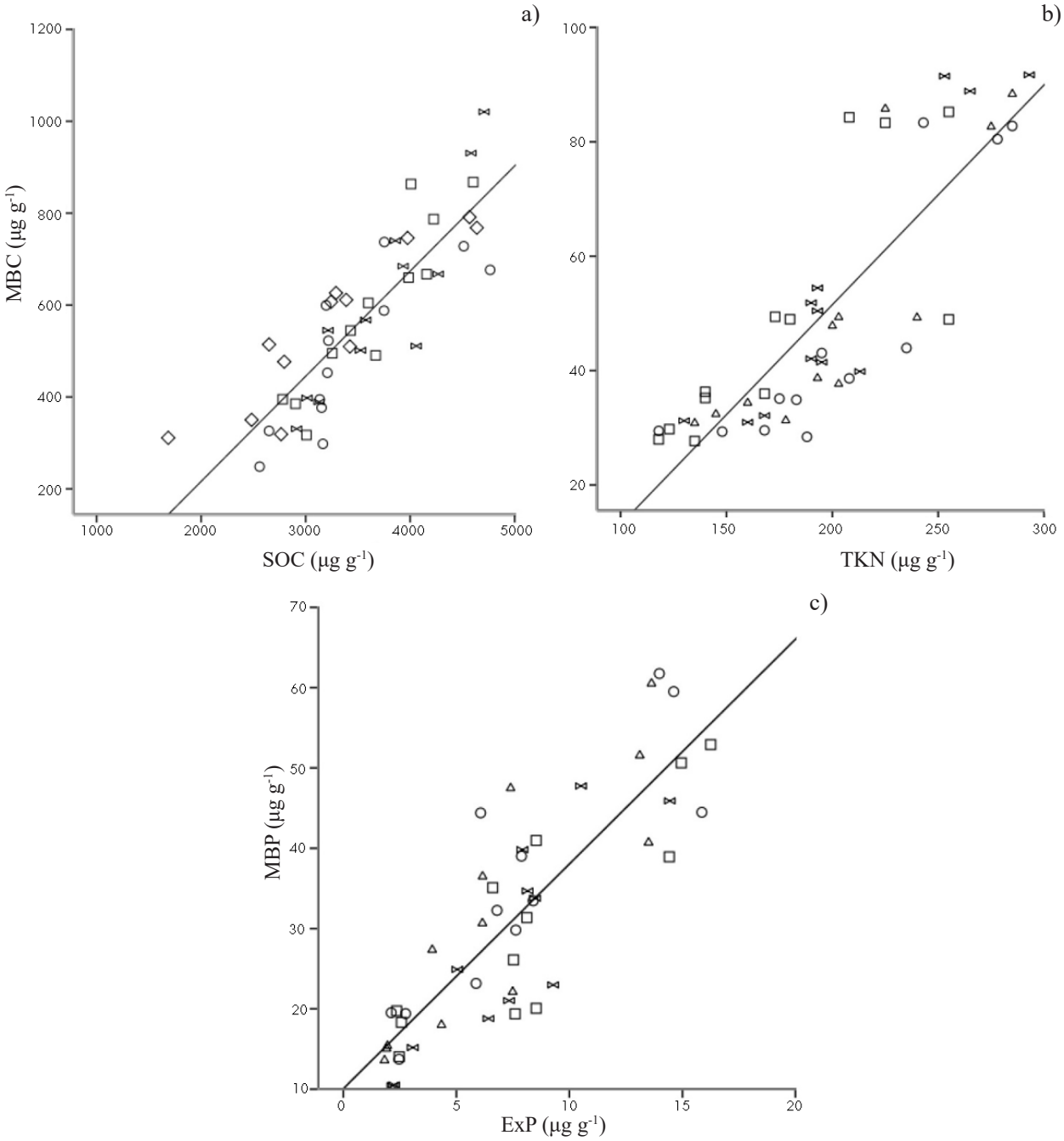

Figure 3. Correlation between MBC and SOC ($R^2 = 0.794$), MBN and TKN ($R^2 = 0.660$) and MBP and Ex. P ($R^2 = 0.726$) in the fragments (○ = Small, □ = Medium; Δ = Large; ⋈ = Very Large) in Jaintia hills of Meghalaya, northeast India (n = 48).

TKN and Ex. P as compared to the interior. Similar relationships between SOC, TKN and Ex. P with microbial biomass have been observed in temperate forests of Spain (Diaz-Raviña *et al.*, 1993) and subtropical forests of Meghalaya (Kamei, 2007). Small fragments were prone to human disturbances due to easy accessibility and dominated by edge environment (Pao & Upadhaya, 2017). This might have led to low microbial biomass in the smaller fragments.

The highest values of microbial biomass -C, -N and -P in the present study during winter season coincide with low air and soil temperatures (12.3 ºC and 11.5 ºC respectively). It also indicates the period of low microbial activity and greater nutrient immobilization in the soil microbial biomass. In contrast, lower values of microbial biomass observed during rainy or autumn seasons when temperature and soil moisture conditions were favourable for the growth of microbes indicated the period of rapid turnover

and cell lysis contributing to the mineralization of nutrients in soil (Singh *et al.*, 1989). This finding is similar to that observed in seasonally dry tropical forests and savanna of the Vindhyan region of India (Singh & Kashyap, 2006). Greater demand of nutrients by plants during rainy season when majority of them are at their peak vegetative growth, further limits the availability of nutrients to soil microbes, thereby reducing their immobilization in microbial biomass (Singh *et al.*, 1989). Seasonal variations observed in microbial biomass- C, -N and -P in the present study is in agreement with other studies from subtropical forests of northeast India (Upadhaya *et al.*, 2006; Kamei, 2007) and China (Wang *et al.*, 2016).

The concentration of microbial biomass C (260 – 969 μg g^{-1}) in the present study is well within the range (61 – 2000 μg g^{-1}) reported from temperate (Diaz-Raviña *et al.*, 1995) subtropical (Upadhaya *et al.*, 2006) and tropical (Barbhuiya *et al.*, 2008) forests. Similarly, the MBN obtained (28 – 92 μg g^{-1}) in the present study is well within the range (25 – 95 μg g^{-1}) reported from temperate (Diaz-Raviña *et al.*, 1995), humid subtropical (Arunachalam *et al.*, 1999; Kamei, 2007) and tropical (Barbhuiya *et al.*, 2004) forests. The MBP recorded (10 – 51 μg g^{-1}) in the present study is also within the range (8 – 67 μg g^{-1}) observed from temperate (Diaz-Raviña *et al.*, 1995) subtropical (Devi & Yadava, 2006) and tropical (Barbhuiya *et al.*, 2008) forests. The contribution of MBC to SOC in the forest fragments (1.5 – 1.8 %) was low but within the range (1.5 – 5.3 %) reported from various temperate (Theng *et al.*, 1989; Chen *et al.*, 2013), subtropical (Burton *et al.*, 2010; Chen *et al.*, 2013) and tropical forests (Theng *et al.*, 1989). Similarly, the percentage contribution of MBN to soil TKN (2.27 – 4.54 %) is comparable to the values (3.4 – 5.9 %) reported for temperate and subtropical forest soils (Das *et al.*, 1997; Chen *et al.*, 2013). The percentage contribution (3.48 – 4.76 %) of MBP observed in the edge and interior of the studied fragments to Ex. P is close to the values (3.09 – 4.31 %) reported from tropical rainforest of north east India (Barbhuiya *et al.*, 2008). The ratio of microbial biomass to the respective soil content reflects substrate availability and quality and the immobilization potential of the microbial community. This is further evident from a positive relation between microbial biomass -C, -N and -P and SOC, TKN and Ex. P.

Microbial organic content stoichiometry (MBC: MBN, MBC: MBP) were higher in the edge. In Small fragments, the higher MBC: MBP ratio in the edge could be attributed to immobilization of phosphate to cope up with reduced P availability. The mean C/N ratio (10 – 12) of soil microbial biomass in the studied forest fragments is closer to the range (6.5 – 10) reported from subtropical natural secondary forest (Chen *et al.*, 2013; Xing *et al.*, 2010), and subtropical forest (9.4) of Australia (Burton *et al.*, 2010). The values in the present study indicate that the soil microbial communities in the fragments were dominated by the fungal population (Brume & Khanna, 2009). The microbial biomass C/P ratios obtained in the present study (16 – 19) is close to that (18 – 26) reported from subtropical (Devi & Yadava, 2006) and tropical (Barbhuiya *et al.*, 2008) forest of the region.

Microclimatic factors and soil properties in the fragments played an important role in influencing microbial biomass (Table 7). The present study showed that microbial biomass -C, -N and -P was influenced by soil -moisture content ($r = -0.77, -0.77$, and -0.76 respectively) and -temperature ($r = -0.65, -0.87$, and $- 0.65$ respectively, $P< 0.01$). With the onset of monsoon, the soil gets saturated and during this period the temperature is also high. Such conditions favour the growth of microbial population. However, during this period there is a rapid turnover of microbes due to lysis, microvory and high demands of nutrients by the plants (Singh *et al.*, 2010) leading to low microbial biomass.

Our result suggests that soil microbial biomass increased along a fragment size gradient and was influenced by the prevailing microclimatic conditions and soil properties. Changes in soil microbial activity may alter the interaction of plant, soil and microbial community that would gradually degrade in the fragments due to edge effect. Such changes may become unstable and unpredictable in fragments that are exposed to human disturbances. Therefore, conservation of soil biological processes which is a key to nutrient cycling is essential for the stability of ecosystem functions in fragmented landscapes.

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References

Allen SE, Grimshaw HM, Parkinson JA, Quarmby C, 1974. Chemical Analysis of Ecological Materials. London: Blackwell Scientific Publication.

Anderson JM, Ingram JSI, 1993. Tropical Soil Biology and Fertility. A Handbook of Methods. U.K.: CAB International, Wallingford.

Arunachalam K, Arunachalam A, Melkania NP, 1999. Influence of soil properties on microbial populations, activity and biomass in humid subtropical mountainous ecosystems of India. Biol Fert Soils 30(3): 217-223. https://doi.org/10.1007/s003740050611

Barbhuiya AR, Arunachalam A, Pandey HN, Arunachalam K, Khan ML, Nath PC, 2004. Dynamics of soil microbial biomass C, N and P in disturbed and undisturbed stands of a tropical wet-evergreen forest. Europ J Soil Biol 40: 113-121. https://doi.org/10.1016/j.ejsobi.2005.02.003

Barbhuiya AR, Arunachalam A, Pandey HN, Khan ML, Arunachalam K, 2008. Effects of disturbance of fine roots and soil microbial biomass C, N and P in a tropical rainforest ecosystem of Northeast India. Curr Sci 94(5): 572-574.

Bierregaard Jr RO, Lovejoy TE, Kapos V, Santos AA dos, Hutchings RW, 1992. The biological dynamics of tropical rainforest fragments. BioScience 42: 859-866. https://doi.org/10.2307/1312085

Brookes PC, Powlson DS, Jenkinson DS, 1982. Measurement of microbial phosphorus in the soil microbial biomass. Soil Biol Biochem 14: 319-329. https://doi.org/10.1016/0038-0717(82)90001-3

Brookes PC, Landman A, Pruden G, Jenkinson DS, 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biol Biochem 17: 837-847. https://doi.org/10.1016/0038-0717(85)90144-0

Brothers TS, Spingarn A, 1992. Forest fragmentation and alien plant invasion of Central Indiana old-growth forests. Conserv Biol 6: 91-100. https://doi.org/10.1046/j.1523-1739.1992.610091.x

Brume R, Khanna PK, 2009. Functioning and Management of European Beech Ecosystems. Springer. https://doi.org/10.1007/b82392

Burton J, Chen C, Xu Z, Ghadiri H, 2010. Soil microbial biomass, activity and community composition in adjacent native and plantation forests of subtropical Australia. J Soil Sediments 10: 1267-1277. https://doi.org/10.1007/s11368-010-0238-y

Camargo JLC, Kapos V, 1995. Complex edge effects on soil moisture and microclimate in central Amazonian forest. J Trop Ecol 11:205–211. https://doi.org/10.1017/S026646740000866X

Central Ground Water Board, 2013. Ground Water Information Booklet Jaintia Hills District, Meghalaya. Ministry of Water Resources, Government of India. Technical Report Series 49/2011-2012.

Champion HG, Seth SK, 1968. A Revised Survey of Forest Types of India, New Delhi, Government of India Press.

Chen F, Peng X, Zhao P, Yuan J, Zhong C, Cheng Y, Cui C, Zhang S, 2013. Soil microbial biomass, basal respiration and enzyme activity of main forest types in the Qinling mountain. PLOS ONE 8(6): 1-12.

Chen J, Saunders SC, Crow TR, Naiman RJ, Brosofske KD, Mroz GD, Brookshire LB, Franklin JF, 1999. Microclimate in forest ecosystem and landscape ecology. BioScience 49(4): 288-297. https://doi.org/10.2307/1313612

Chen T, Chiu C, Tian G, 2005. Seasonal dynamics of soil microbial biomass in coastal sand dune forest. Paedobiologia 49: 645-653. https://doi.org/10.1016/j.pedobi.2005.06.005

Das AK, Boral L, Tripathi RS, Pandey HN, 1997. Nitrogen mineralization and microbial biomass-N in a subtropical humid forest of Meghalaya, India. Soil Biol Biochem 29(9/10): 1609-1612. https://doi.org/10.1016/S0038-0717(96)00298-2

Devi NB, Yadava PS, 2006. Seasonal dynamics in soil microbial biomass C, N and P in a mixed-oak forest ecosystem of Manipur, North-east India. Applied Soil Ecol 31: 220-227. https://doi.org/10.1016/j.apsoil.2005.05.005

Diaz-Raviña M, Acea MJ, Carballas T, 1993. Seasonal fluctuations in microbial populations and available nutrients in forests soil. Biol Fertil Soil 16: 205-210. https://doi.org/10.1007/BF00361409

Diaz-Raviña M, Acea MJ, Carballas T, 1995. Seasonal change in microbial biomass and nutrient flush in forests soils. Biol Fertil Soil 19: 220-226. https://doi.org/10.1007/BF00336163

Flores-Renteria D, Yuste JC, Rincon A, Brearley FQ, Garcia-Gil JC, Vallardes F, 2015. Habitat fragmentation can modulate drought effects on the plant-soil-microbial system in Mediterranean holm oak (Quercus ilex) forests. Microb Ecol 69(4): 798-812. https://doi.org/10.1007/s00248-015-0584-9

Haddad NM, Brudvig LA, Clobert J, Davies KF, Gonzalez A, Holt RD, Lovejoy TE, Sexton JO, Austin MP, Collins CD *et al.*, 2015. Habitat fragmentation and its lasting impact on earth's ecosystem. Science Advances 1(2):e1500052. https://doi.org/10.1126/sciadv.1500052

Ibanez I, Watz DSW, Pelteir D, Wolf SM, Barrie TC, 2014. Assessing the integrated effects of landscape fragmentation on plants and plant communities: the challenge of multiprocess-multiresponse dynamics. J Ecol 102: 882-895. https://doi.org/10.1111/1365-2745.12223

Jose S, Gillespie AR, George SJ, Kumar M, 1996. Vegetation responses along edge-to-interior gradients in a high altitude tropical forest in peninsular India. For Ecol Manag 87: 51-72.

Kamei J, 2007. Studies on interrelationship between tree diversity and N and P Dynamics in a humid Subtropical forest ecosystem of Meghalaya. PhD Thesis, Shillong, North-Eastern Hill University.

Laurance WF, Fearnside PM, Laurance SGW, Delamonica P, Lovejoy TE, Rankinde Merona JM, Chambers JQ, Gascon C, 1999. Relationship between soils and Amazon forest

biomass: a landscape-scale study. For Ecol Manag 118: 127-138.

Laurance WF, Andrade AS, Magrach A, Camago JLC, Campbell M, Fearnside PM, Edwards W, Valsko JJ, Lovejoy TES, Laurance SG, 2014. Apparent environmental synergism drives the dynamics of Amazonian forest fragments. Ecology 95: 3018-3026. https://doi.org/10.1890/14-0330.1

Laurance WF, Ferreeira LV, Rankin-de Merona JM, Laurance SG, 1998. Rainforest fragmentation and the dynamics of Amazonian tree communities. Ecology 79: 2032-2040. https://doi.org/10.1890/0012-9658(1998)079[2032:RFFATD]2.0.CO;2

Laurance WF, Laurance SGW, Ferreeira LV, Rankin-de Merona JM, Gascon C, Lovejoy TE, 1997. Biomass collapse in Amazonian forest fragments. Science 278: 1117-1118. https://doi.org/10.1126/science.278.5340.1117

Laurance WF, Delamonica P, Laurance SGW, Vasconcelos HL, Lovejoy TE, 2000. Rainforest fragmentation kills big trees. Nature 404: 836. https://doi.org/10.1038/35009032

Lázaro-Nogal A, Matesanz S, Gimeno TE, Escudero A, Valladares F, 2012. Fragmentation modulates the strong impact of habitat quality and plant cover on fertility and microbial activity of semiarid gypsum soils. Plant Soil 358: 213-223. https://doi.org/10.1007/s11104-012-1184-9

Maithani K, Tripathi RS, Arunachalam A, Pandey HN, 1996. Seasonal dynamics of microbial biomass C, N and P during regrowth of a disturbed subtropical humid forest in north-east India. Applied Soil Ecol 4(1): 31-37. https://doi.org/10.1016/0929-1393(96)00101-1

Moreno ML, Bernaschini ML, Prez-Harguindeguy N, Vallardes G, 2014. Area and edge effects on leaf-litter decomposition in a fragmented subtropical dry forest. Acta Oecologia 60: 26-29. https://doi.org/10.1016/j.actao.2014.07.002

Pao NT, Upadhaya K, 2017. Effect of fragmentation and anthropogenic disturbances on floristic composition and structure of subtropical broad leaved humid forest in Meghalaya, northeast India. Applied Ecol Environm Res 15(4): 385-407. https://doi.org/10.15666/aeer/1504_385407

Pao NT, Upadhaya K, Mir AH, 2016. Phenological behaviour of tree species in subtropical broadleaved humid forests of Jaintia Hills in Meghalaya, northeast India. Int Res J Biolog Sci 5(7): 10-15.

Ruitta T, Slade EM, Bebber DP, Taylor ME, Malhi Y, Riordan P, Macdonald DW, Morecroft MD, 2012. Experimental evidence for the interacting effects of forest edge, moisture and soil moisture on leaf decomposition. Soil Biol Biochem 49: 124-131. https://doi.org/10.1016/j.soilbio.2012.02.028

Schloter M, Dilly O, Munch JC, 2003. Indicators for evaluating soil quality. Agric, Ecosyst Environ 98: 255-262. https://doi.org/10.1016/S0167-8809(03)00085-9

Singh JS, Kashyap AK, 2006. Dynamics of viable nitrifier community, N-mineralization and nitrification in seasonally dry tropical forests and savanna. Microbial Res 161:169-179. https://doi.org/10.1016/j.micres.2005.07.009

Singh JS, Raghubanshi AS, Singh RS, 1989. Microbial biomass acts as a source of plant nutrients in dry tropical forest and savanna. Nature 338(6215): 499-500. https://doi.org/10.1038/338499a0

Singh JS, Singh DP, Kashyap AK, 2010. Microbial biomass C, N and P in dry tropical forest soils. Pedosphere 20(6): 780-788. https://doi.org/10.1016/S1002-0160(10)60068-9

Sizer NC, Tanner EVJ, Ferraz IDK, 2000. Edge effects on litterfall mass and nutrient concentration in forest fragments in central Amazonia. J Trop Ecol 16(8): 853-863. https://doi.org/10.1017/S0266467400001760

Theng BKG, Tata KR, Sollins P, 1989. Constituents of organic matter in temperate and tropical soils. In: Dynamics of Soil Organic Matter in Tropical Ecosystems eds. Coleman DC, Oades JM, Uehera G. pp. 5-32. Honolula, University of Hawaii Press.

Toledo-Aceves T, Garcia-Oliva F, 2008. Effect of forest pasture edge on C, N and P associated with Caesalpinia eriostachys a dominant tree species in a tropical deciduous in Mexico. Ecolog Restor 23: 271-280. https://doi.org/10.1007/s11284-007-0373-0

Upadhaya K, Pandey HN, Tripathi RS, 2006. Effect of anthropogenic disturbances on soil microbial biomass carbon in sacred groves of Jaintia hills in Meghalaya. Indian J Soil Conserv 34 (3): 221-225.

Vance ED, Brookes PC, Jenkinson DS, 1987. An extraction method for measuring soil microbial biomass. Soil Biol Biochem 19: 703-707. https://doi.org/10.1016/0038-0717(87)90052-6

Wang X, Wang X, Zhang W, Shao Y, Zou X, Liu T, Zhou L, Wan S, Rao X, Li Z et. al., 2016. Invariant community structure of soil bacteria in subtropical coniferous and broadleaved forests. Scientific Reports, 1-11. doi: 10.1038/ srep19071.

Xing S, Chen C, Zhou B, 2010. Soil soluble organic nitrogen and active microbial characteristics under adjacent coniferous and broadleaf plantation forests. J Soils Sediments 10:748-757. https://doi.org/10.1007/s11368-009-0159-9

Yeong KL, Reynolds G, Hill JK, 2016. Leaf litter decomposition in degraded and fragmented tropical rain forests of Borneo. Biotropica 48(4): 443-452. https://doi.org/10.1111/btp.12319

Zhu H, Xu ZF, Wang H, Li BG, 2004. Tropical rain forest fragmentation and its ecological and species diversity changes in southern Yunnan. Biodiv Conserv 13: 1355-1372. https://doi.org/10.1023/B:BIOC.0000019397.98407.c3