Comparison of soil N dynamics between dry dipterocarp forest and dry evergreen forest in Northeastern Thailand

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ABSTRACT We conducted a comparative study of nitrogen (N) dynamics in soil by examining a dry dipterocarp forest (DDF) and a dry evergreen forest (DEF), under similar climatic conditions, in northeastern Thailand. The soil N dynamics were described by measuring seasonal N mineralization and nitrification rates, soil microbial biomass, and the size of inorganic N pools and extractable organic N and C pools. We estimated the fluxes and production of inorganic N in soil using the ion exchange resin core and buried bag methods. Carbon and N accumulations were higher in the DEF than in DDF; DEF had likely been protected from fire for a longer time than DDF. We also found temporal and vertical differences in soil N dynamics between DDF and DEF. The greatest inorganic N flux in the soil occurred at the onset of the wet season in DDF, whereas inorganic N was produced throughout the wet season in DEF. N uptake occurred in the uppermost soil horizon in DDF, whereas N uptake in DEF occurred in the deeper soil horizon. The mean residence time of inorganic N was greater in DEF than in DDF. These results suggest that N cycles were faster in DDF than in DEF. During long-term incubation experiments, the dominant inorganic N form changed from NH_4^+ to NO_3^- , coinciding with declining extractable organic C (EOC) concentrations at both sites. Shortages of EOC occurred earlier in DDF than in DEF. This finding indicates that EOC may be a useful index of C availability for soil N dynamics.

Key words: dry tropical forest, N flux, soil N dynamics, C availability, extractable organic C

INTRODUCTION

Dry tropical forest constitutes a major type of terrestrial ecosystem, accounting for 42% of forest ecosystems in tropical and sub-tropical regions (Murphy and Lugo, 1986). In the tropics, as well as in temperate and boreal regions, nitrogen (N) availability is one of the limiting factors in dry forests and in forests on sandy soils (Vitousek, 1984; Vitousek and Sanford, 1986; Vitousek and Howarth, 1991).

The role of soil N dynamics in N cycling has received special attention because it directly relates to N availability for plants (Binkley and Hart, 1989). Previous studies in dry tropical forests have shown that soil N dynamics are highly seasonal, mainly because of fluctuations in moisture between the wet and dry seasons (Singh et al. 1989; Roy and Singh, 1994). For example, pools of inorganic N in soil, especially in surface mineral layers, are minimal in the mid to late wet season because of plant uptake, leaching, and surface runoff (Roy and Singh, 1994). These N pools gradually increase in size during the dry season because of reduced uptake by plants, increase rapidly with the first rain of the wet season, and rapidly decrease thereafter (Roy and Singh, 1994). Mineralization and nitrification rates of N in soil are low during the dry season, increase rapidly at the start of the wet season, and decrease again as the next dry season begins (Roy and Singh, 1994).

In Thailand, six major forest types are distributed from north to south: hill evergreen forest, dry evergreen forest, dry deciduous forest, mixed deciduous forest, tropical evergreen forest, and mangrove forest (Royal Forest Department, 1962). Among these forest types, dry evergreen forest and dry deciduous forest can occur under similar local climate and geomorphological conditions, but have different fire disturbance regimes

(Kanzaki et al. 1995; Sahunalu and Dhanmanond, 1995; Sakurai et al. 1998). Frequent fire is considered to be one of the factors changing dry evergreen forest to dry deciduous forest. Forest fire affects biogeochemical cycles through the loss of vegetation and forest floor organic matter. Also, the seasonality of soil N dynamics may be modified by different life forms of vegetation, disturbance regimes, or both. Thus, fire should result in different soil N dynamics between the two forest types. Today only small fragments of dry tropical forest remain (Murphy and Lugo, 1986), and the globalization of N deposition has affected the N status of forests (Matson et al. 1999). Understanding soil N dynamics is important for preserving and using dry tropical forest.

The primary objective of this study was to describe the soil N cycle in dry tropical forests. We evaluated variations in biogeochemical cycling, especially soil N dynamics, between the two types of dry tropical forest in Thailand. We assessed soil N dynamics, including plant N uptake, using a combination of two *in situ* methods: the buried bag method (Eno, 1960) and the ion exchange resin (IER) bag method (Binkley and Matson, 1983).

MATERIALS AND METHODS

Study sites

This study was conducted at the Sakaerat Environmental Research Station (SERS), located on the southeast edge of the Korat Plateau (14°31'N, 101°55'E) in northeastern Thailand. SERS encompasses 81 km² of forest reserve, containing both dry evergreen forest (DEF) and dry dipterocarp forest (DDF). We established an evergreen study site in SERS at an elevation of 520 m and a dipterocarp site, 80 km from SERS, at about 300 m elevation. Both sites were relatively flat. Sakurai et al. (1998) studied clay in this area and suggested that repeated slash-and-burn activity has converted evergreen forest to dipterocarp forest.

Both sites were underlain by sandstone formed in the Triassic to Cretaceous periods, classified as the Korat geological group (Moormann and Rojanasoonthorn, 1972). The soil is characterized by rock outcrops and dominated by laterite. The surface soil is mostly sandy loam and clay loam. The summer dry period lasts from March to mid-May and the cool dry season is from November to February. Annual precipitation is 1100–1300 mm (Fig. 1). The mean annual air temperature is 26

Fig. 1. Climatic conditions for dry dipterocarp forest (DDF) and dry evergreen forest (DEF). Bars are precipitation in DDF (black) and DEF (white). Lines with black dots indicate maxima and the broken line indicates the minimum temperatures in DEF.

°C, and monthly means in 1998 were 29°C for April and 18.5°C for December. The dominant tree species are *Hopea ferrea* and *Shorea henryana* in DEF (Kanzaki et al., 1995) and *Shorea obtusa* and *Xylia xylocarpa* in DDF (Wachrinrat, 2000).

Soils and precipitation sampling

In 1998, five replicated plots ($2 \times 2 \text{ m}^2$ each) were established to measure N flux at each forest site. The replications in this study are not true replications of forest stands, but rather pseudoreplications within a stand of each forest type. Because of variations among stands of the same forest type, further investigations are needed to reach a firm conclusion. In 1998 and 1999, soil was sampled during the early wet season (May), the mid wet season (September), and the late wet season (November) for chemical analysis and incubation. We obtained 100-cm³ soil cores from depths of 0–5 cm, 5–10 cm, and 10–30 cm for analysis of bulk density and fine soil content. Organic soil horizons occurred only in May, so we did not sample them. Precipitation was sampled weekly at an open site at SERS using a bottle with a funnel. Precipitation samples were refrigerated until analysis for NH_4^+ , NO_2^- , and NO_3^- using high-pressure ion chromatography (Shimadzu, SIL-10A, Kyoto, Japan).

Fresh soil samples were kept on ice, brought to the laboratory, and processed within 24 h. Each sample was sieved through 2-mm mesh, and moisture content was then determined by drying at 105°C for 48 h. Freshly sieved soils were extracted with 2M KCl (1:10 w/v).

Chemical properties of soil

Soil pH was measured with a glass electrode in fresh soil diluted with deionized water (1:2.5 w/v). A soil subsample from each subplot was oven-dried and ground using a TI-100 sample mill (CMT Ltd., Tokyo, Japan). Total C and N contents were determined with an NC analyzer (Sumigraph NC-900, Sumigraph Corp., Japan).

Exchangeable cations were removed from air-dried soil (5 g) by shaking for 1 h with 25 ml 1N NH_4COOH , centrifuging, and filtering. This procedure was repeated three times per sample. Concentrations of Ca^{2+} , Mg^{2+} , K^+ , and Na^+ were then determined.

Extractable inorganic and organic N and C

In this study, we defined inorganic N, namely NO_3^- and NH_4^+ , as the available N. The total of inorganic N (available N), organic N extractable with 2M KCl, and soil microbial biomass N (SMB-N) was defined as the potentially available N. Carbon extractable with 2M KCl (extractable

organic carbon, EOC) was used to estimate C availability for soil microbes. To elucidate the factors controlling N dynamics, the relationship between available N and EOC was investigated by long-term laboratory incubation. Fresh soil (5 g) was extracted by shaking for 1 h with 50 ml 2M KCl within 24 h of sampling. Samples were refrigerated until analysis. During transportation, samples were kept in a cooler. EOC concentration was determined by infrared spectrometry using high-temperature catalytic oxidation to CO_2 (680°C, Shimadzu, TOC-5000, Shimadzu Corp., Japan). Extractable organic N (EON) concentration was determined by colorimetry after reduction to NO_2 using O_3 (T-N unit of Shimadzu, TOC-5000, Shimadzu Corp., Japan). Ammonium was measured using the indophenol blue method, and NO_3^- and NO_2^- were determined colorimetrically after zinc reduction (Keeney and Nelson, 1982).

Soil microbial biomass (SMB)

SMB was used as an index of soil microbial activity and of potentially available N. SMB for C (SMB-C) and SMB-N were estimated using the chloroform fumigation/extraction method (Brookes et al., 1985). Freshly sieved soil was brought on ice to Japan and incubated for 10 days at 25°C and 60% water holding capacity. These samples were fumigated with CHCl_3 for 24 h. Fumigated and non-fumigated control soils were extracted with 0.5 M K_2SO_4 (1:10 w/v), and EOC and EON were determined (see next section). The chloroform-labile C and N levels were calculated as the difference in organic C and N pool sizes between pre- and post-fumigation soil samples. Values of SMB-C and SMB-N were calculated from the chloroform-labile C and N. Correction factors were applied to the SMB estimates ($K_c = 0.38$ and $K_N = 0.54$ for samples with $\text{pH} < 5$; Vance et al., 1987).

Net N mineralization and nitrification rates: laboratory incubations

Incubations were performed in the laboratory for 28 days at 25°C to estimate net N mineralization and nitrification rates. Fresh soil (10 g) and deionized water were added to a 30-ml glass vial to a water holding capacity of 60% and covered with parafilm with pinholes to allow air exchange. Deionized water was added weekly to maintain a constant water content during incubation. As no incubator was present at this site, incubation temperature ranged from 25 to 28°C for several days. After 28 days, the samples were extracted with 2M KCl in the same way as the fresh soil samples were extracted. Extracts were filtered and frozen until analysis. Concentrations of inorganic N in the

extracts were determined as described above.

Long-term incubations were also performed in the laboratory under the same conditions. Soil for long-term incubation was sampled in May 1999. Five replicates at each soil depth for each profile were prepared, for a total of 150 samples. During incubation, inorganic N and EOC concentrations were determined periodically. One of the five replicates for each depth was extracted.

***In situ* N mineralization and nitrification: buried bag method**

The buried bag method was used to estimate net *in situ* N mineralization (Eno, 1960). Fresh soil cores (100-cm³ each) were sampled at depths of 0–5 cm, 5–10 cm, 10–20 cm, and 20–30 cm in each site subplot. The soil core samples were carefully placed in polyethylene bags, which were then buried at the same depth from which they were sampled. The bags were incubated *in situ* from November 1998 to November 1999. They were exchanged in May and September 1999 and replaced during the dry season (November 1998 to May 1999), early in the wet season (May to September 1999), and late in the wet season (September to November 1999).

After incubation, the buried bags were sieved through 2-mm mesh and extracted with 2M KCl in the same way as the fresh soil samples and the laboratory incubations. Extracts were filtered with 1 µm-mesh filter paper (No. 6, Advantec Corp. Ltd.) and frozen until analysis. Inorganic N concentration of extracts was determined as described above. Net *in situ* mineralization, or inorganic N production, was calculated as the difference between pre- and post-incubation concentrations of NH₄⁺ and NO₃⁻. Net *in situ* nitrification was calculated as the difference between pre- and post-incubation concentrations of NO₃⁻. Inorganic N concentration was determined as described above.

Ion exchange resin bag method

We used the ion exchange resin (IER) method to measure NH₄⁺ and NO₃⁻ levels in soil solutions (Binkley and Matson, 1983; Binkley and Hart, 1989; Giblin et al. 1994). Binkley and Hart (1989) used a resin core filled with soil to estimate the available N entering the core from above. To measure N flux per unit area under the undisturbed condition, we modified the resin core as follows. We prepared each “IER bag” by first mixing 7.5 g of cation resin (IR-120, Organo Chemical Corp., Japan) with 7.5 g of anion resin (IRA-400, Organo Chemical Corp., Japan), and then pouring the mixture into a core 5 cm in diameter and 1 cm long. To prevent resin loss, we covered the top

of the IER bag with 1-mm nylon mesh and the bottom with 0.2-mm nylon mesh. The IER bag was inserted into the soil profile. This amount of ion resin was sufficient to retain N during the study period (Garcia-Montiel & Binkley, 1998). In May 1998, the IER bags were placed 5 cm, 10 cm, and 30 cm below the surface of the mineral soil in each site subplot. When soil was sampled, the soil profiles used for the IER bag were dug and the IER bags were sampled. Then new soil profiles were dug and new IER bags were inserted. The IER was then extracted by 2M KCl (1:10 w/v). Extraction was repeated twice per sample.

Estimation of N uptake

In this study, inorganic N was defined as available N. All concentrations were calculated on an area basis by multiplying by the oven-dry fine soil content per area of each subplot. Net inorganic N production rates were calculated using the *in situ* buried bag method. The amount of inorganic N leachate from the soil horizon was determined using the IER core method (e.g., Nadelhoffer et al. 1984). N input by bulk precipitation was used for N input. N uptake for vegetation was estimated using the following equation:

$$\text{Estimated N uptake} = N_{\text{Input (production + rainfall or leachate from upper horizon)}} + N_{\text{Pool size change (inorganic N pool at the previous sampling - inorganic N pool at current sampling)}} - N_{\text{Output (leachate to the lower soil horizon)}}$$

Data for available N fluxes were analyzed using two-way analysis of variance (ANOVA) with forest type and sampling date or depth as categorical variables (SPSS, 1996). In this study, no significant difference was found in leachate among depths, and most roots were distributed in the upper 30 cm. Therefore, we used the leachate value from a depth of 30 cm for all depths.

RESULTS

Differences in soil chemical characteristics between sites

Total soil C and N concentrations and contents were higher in DEF than in DDF (Table 1). Soil C and N pools (at 0–30 cm) were 2.00 kg m⁻² and 123 g m⁻² in DDF and 3.82 kg m⁻² and 282 g m⁻² in DEF, respectively. The C and N concentrations were highest in the surface soil horizon; both decreased with soil depth at both sites.

Although cation exchange capacity (CEC) was higher in DEF than DDF, DDF exhibited significantly higher soil pH and total exchangeable cation content ($P < 0.01$, Table 2). High concentrations of exchangeable Ca and Mg corresponded to high soil pH in DDF.

Table 1. Total C and N pools in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF) sites. Data are the means of five replicates per depth (± 1 SD).**(a). DDF**

Depth (cm)	C (%)	N (%)	C (kg m^{-2})	N (g m^{-2})	C/N
0–5	1.43 (0.31)	0.08 (0.01)	0.95 (0.41)	55.0 (5.2)	17.3
5–10	0.68 (0.26)	0.04 (0.01)	0.44 (0.15)	27.3 (8.0)	15.8
10–30	0.49 (0.40)	0.03 (0.02)	0.61 (0.89)	40.8 (23.0)	13.6
Total	–	–	2.00 (0.57)	123.1 (16.5)	16.3

(b). DEF

Depth (cm)	C (%)	N (%)	C (kg m^{-2})	N (g m^{-2})	C/N
0–5	2.54 (0.42)	0.18 (0.03)	1.32 (0.26)	93.7 (2.10)	14.3
5–10	1.85 (0.39)	0.14 (0.03)	0.84 (0.21)	62.3 (1.50)	13.5
10–30	1.46 (0.21)	0.11 (0.01)	1.65 (0.28)	126.1 (1.53)	13.1
Total	–	–	3.82 (0.63)	282.2 (4.56)	13.6

Table 2. Chemical and physical soil properties for 0–30 cm in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF). Ca^{2+} and Mg^{2+} contents were significantly greater in DDF than in DEF ($P < 0.01$). The sum of Ca^{2+} , Mg^{2+} , K^+ , and Na^+ was significantly greater in DEF than in DDF ($P < 0.01$). Data are the means of five replicates per depth (± 1 SD). Values denoted by asterisks are significantly different between sites at the same depth ($P < 0.01$).**(a). DDF**

Depth (cm)	Fine soil (g cm^{-3})	pH (H_2O)	Exchangeable cations (mmol kg^{-1})				CEC
			Ca^{2+}	Mg^{2+}	Na^+	K^+	
0–5	1.35 (0.08)	5.78 (0.10)	47.4* (17.0)	15.9* (7.6)	0.6 (0.1)	3.2 (1.0)	118* (32.9)
5–10	1.31 (0.08)	5.06 (0.62)	24.7* (8.5)	8.7* (4.3)	0.8 (0.2)	1.7 (0.6)	125* (47.5)
10–30	1.28 (0.09)	5.41 (0.43)	22.8* (21.9)	10.8* (2.9)	0.6 (0.1)	1.0 (0.5)	119* (42.8)

(b). DEF

Depth (cm)	Fine soil (g cm^{-3})	pH (H_2O)	Exchangeable cations (mmol kg^{-1})				CEC
			Ca^{2+}	Mg^{2+}	Na^+	K^+	
0–5	1.05 (0.21)	4.23 (0.24)	2.4* (0.1)	2.2* (1.1)	0.6 (0.2)	2.2 (0.7)	206* (23.7)
5–10	0.92 (0.20)	4.21 (0.19)	1.0* (0.4)	1.1* (0.4)	0.5 (0.2)	1.5 (0.6)	154* (46.6)
10–30	1.04 (0.30)	4.34 (0.20)	1.2* (0.5)	1.4* (0.8)	0.5 (0.2)	1.5 (0.8)	200* (15.8)

Soil characteristics related to N availability

SMB-N was greater than 60% of the potentially available soil N at both sites (Table 3). DEF had significantly more potentially available soil N than DDF, because concentrations of EON and SMB-N were higher in DEF than in DDF ($P < 0.01$). In DDF, potentially available N decreased significantly during the wet season because of a decrease in EON ($P < 0.01$, data not shown).

Inorganic N pool size did not change during the wet season. Inorganic N pools were larger in DEF (2.21 g

N m^{-2}) than in DDF (1.57 g N m^{-2} ; Table 3). Potentially available N concentrations in soil fluctuated seasonally except for NO_3^- and EON in DDF (data not shown). In DDF, NO_3^- concentrations were significantly negatively correlated with soil moisture content across all soil horizons (Table 4, $r < 0.66$, $P < 0.01$).

EOC concentration in DEF was significantly higher than in DDF (Table 5, $P < 0.01$). EOC concentration ranged from 1.5 to 20.9 g C m^{-2} horizon $^{-1}$, i.e., from 0.3 to 1.2 g C m^{-2} cm^{-1} , in DDF, whereas in DEF it ranged from 9.2 to 86.4 g C m^{-2} horizon $^{-1}$ or 1.7 to 4.2 g C m^{-2}

Table 3. Annual mean potentially available N content ($\text{g N m}^{-2} \text{ horizon}^{-1}$) in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF). Data are the means of five replicates and four sampling seasons per depth (± 1 SD). Potentially available N is the sum of inorganic N, extractable organic N (EON), and soil microbial biomass N (SMB-N). Values denoted by asterisks are significantly different between sites at the same depth ($P < 0.01$).

(a). DDF

Depth (cm)	$\text{NH}_4^+ \text{-N}$	$\text{NO}_3^- \text{-N}$	EON	SMB-N	Potentially available N
0–5	0.22 (0.14)	0.17 (0.19)	0.79* (0.49)	1.79* (0.88)	2.70 (0.97)
5–10	0.21 (0.15)	0.09 (0.08)	0.68* (0.42)	1.86* (1.59)	2.61 (1.81)
10–30	0.72 (0.42)	0.16 (0.14)	–	–	--

(b). DEF

Depth (cm)	$\text{NH}_4^+ \text{-N}$	$\text{NO}_3^- \text{-N}$	EON	SMB-N	Potentially available N
0–5	0.28 (0.20)	0.17 (0.19)	2.41* (1.12)	4.32* (1.82)	7.17 (2.45)
5–10	0.20 (0.14)	0.08 (0.09)	1.67* (0.68)	2.94* (0.96)	4.95 (1.15)
10–30	0.88 (0.49)	0.60 (1.23)	–	–	--

Table 4. Seasonal changes in soil moisture content for 0–30 cm in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF). The moisture content in September denoted by an asterisk is significantly higher than in other seasons at all depths in DDF ($P < 0.01$). Data are means of five replicates per depth (± 1 SD).

(a). DDF

Depth (cm)	Moisture (%)		
	May	September	November
0–5	14.4 (1.4)	18.5* (4.7)	13.0 (0.9)
5–10	12.8 (3.1)	14.2* (6.2)	11.0 (1.9)
10–30	13.6 (1.6)	18.5* (2.0)	11.7 (1.7)

(b). DEF

Depth (cm)	Moisture (%)		
	May	September	November
0–5	20.1 (1.1)	20.9 (2.2)	24.8 (9.3)
5–10	18.9 (1.2)	19.4 (1.1)	19.2 (2.0)
10–30	19.3 (0.8)	19.2 (0.6)	19.2 (1.5)

Table 5. Seasonal changes in extractable organic C (EOC) contents for 0–30 cm in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF). The values denoted by the same letter do not differ significantly at the same depth in each site. Data are means of five replicates per site (± 1 SD).**(a). DDF**

Depth (cm)	EOC ($\text{g C m}^{-2} \text{ horizon}^{-1}$)		
	May	September	November
0–5	5.94 ^a (0.65)	3.49 ^b (0.93)	1.49 ^c (0.15)
5–10	5.95 ^a (1.10)	3.56 ^b (0.58)	1.48 ^c (0.26)
10–30	20.9 ^a (3.51)	13.8 ^b (2.37)	5.37 ^c (1.47)

(b). DEF

Depth (cm)	EOC ($\text{g C m}^{-2} \text{ horizon}^{-1}$)		
	May	September	November
0–5	20.2 ^a (4.70)	19.3 ^a (4.86)	10.8 ^b (2.42)
5–10	19.4 ^a (3.26)	15.8 ^a (2.08)	9.17 ^b (1.38)
10–30	86.4 ^a (19.0)	85.4 ^a (22.8)	38.7 ^b (9.37)

cm^{-1} . SMB-C concentration was also significantly higher in DEF than in DDF ($P < 0.01$, data not shown). The EOC concentrations per depth did not differ significantly among soil horizons at either site. At both sites, EOC concentration significantly decreased during the course of the wet season (Table 5, $P < 0.01$). While this decrease occurred quickly in DDF, it occurred during the second half of the wet season in DEF.

Net mineralization and nitrification rates (determined in laboratory incubation) did not differ seasonally at either site (Table 6, $P > 0.01$) and were slightly greater in DEF than in DDF ($P > 0.06$). At both sites, the nitrification rate was higher than the mineralization rate.

Seasonal and vertical fluctuations in soil N dynamics

Figure 2 shows the temporal fluxes in N and the estimated N uptake in soil for the two sites. N input by bulk precipitation was 0.73, 3.37, and 1.27 $\text{kg N ha}^{-1} \text{ period}^{-1}$ from November to May, May to September, and September to November, respectively (data not shown). The trends in N dynamics at both sites were similar in some respects. Soil NH_4^+ -N pools ($0.6\text{--}2.1 \text{ g N m}^{-2}$ in DDF and $0.9\text{--}2.2 \text{ g N m}^{-2}$ in DEF) were always larger than NO_3^- -N pools ($> 0.9 \text{ g N m}^{-2}$ in DDF and $> 0.5 \text{ g N m}^{-2}$ in DEF, Fig. 2a, b). Buried bag results showed that NH_4^+ -N production was sometimes negative, because net nitrification rates were greater than net mineralization rates at both sites, thus consuming the NH_4^+ -N pool (Fig. 2c, d; Table 6). The high nitrification rates resulted in NO_3^- -N being the dominant form of N available for trees

at both sites (Fig. 2g, h).

There was also marked seasonality in soil N dynamics (Fig. 2). N leaching and estimated N uptake showed significant site effects ($P < 0.05$). Estimated N uptake by vegetation was greatest at the start of the wet season in DDF (Fig. 2g), mainly because of large changes in the inorganic N pool and high rates of net N production. While estimated N uptake decreased sharply during the wet season in DDF, both net N produced and estimated N uptake decreased throughout the wet season in DEF (Fig. 2d, h).

The vertical soil N dynamics along the soil profile differed between the sites (Fig. 3a–h). The N pool, inorganic N production, and estimated N uptake tended to be high in DDF in the surface 0–5 cm soil horizon (Fig. 3a, c, g). N fluxes in the surface 0–5 cm soil horizon were about 60% of annual production, and 64% of annual estimated N uptake occurred in the uppermost 30 cm. Later in the wet season in DDF, N leached into deeper soil and was not available for vegetation (Fig. 2e, g), while inorganic N was produced and available throughout the soil profile in DEF (Fig. 3). In particular, N fluxes in the 10–30 cm horizon reached about 60% of annual production and 78% of annual estimated N uptake (Fig. 3d, h) in DEF, in contrast to the N flux patterns in DDF.

Changes in C and N during long-term incubation

Figure 4 shows changes in EOC and inorganic N concentrations during long-term incubation. EOC concentrations were significantly higher in DEF than in DDF at all depths ($P < 0.05$; Fig. 4). During incubation,

Table 6. Seasonal changes in net N mineralization and nitrification rates for 0–30 cm in (a) dry dipterocarp forest (DDF) and (b) dry evergreen forest (DEF). Data are means of five replicates per depth (± 1 SD) and the units are $\text{g N m}^{-2} \text{ horizon}^{-1} \text{ day}^{-1}$.

(a). DDF

(a)–1. Mineralization rate

Depth (cm)	1998 Nov.	1999		
		May	Sep.	Nov.
0–5	–0.043 (0.105)	0.197 (0.118)	0.150 (0.085)	0.134 (0.082)
5–10	–0.068 (0.032)	0.056 (0.028)	0.087 (0.048)	0.259 (0.067)
10–30	–0.201 (0.114)	0.105 (0.145)	0.105 (0.123)	0.214 (0.121)

(a)–2. Nitrification rate

Depth (cm)	1998 Nov.	1999		
		May	Sep.	Nov.
0–5	0.046 (0.091)	0.251 (0.108)	0.161 (0.107)	0.139 (0.075)
5–10	–0.006 (0.041)	0.099 (0.010)	0.120 (0.043)	0.284 (0.048)
10–30	–0.009 (0.077)	0.211 (0.213)	0.408 (0.089)	0.278 (0.156)

(b). DEF

(b)–1. Mineralization rate

Depth (cm)	1998 Nov.	1999		
		May	Sep.	Nov.
0–5	0.046 (0.067)	0.105 (0.105)	0.281 (0.106)	0.362 (0.152)
5–10	0.016 (0.028)	0.017 (0.054)	0.151 (0.019)	0.079 (0.031)
10–30	0.042 (0.096)	0.277 (0.215)	0.643 (0.136)	0.132 (0.176)

(b)–2. Nitrification rate

Depth (cm)	1998 Nov.	1999		
		May	Sep.	Nov.
0–5	0.064 (0.063)	0.192 (0.126)	0.228 (0.098)	0.408 (0.153)
5–10	0.041 (0.040)	0.055 (0.024)	0.096 (0.036)	0.123 (0.030)
10–30	0.244 (0.098)	0.441 (0.225)	0.427 (0.207)	0.398 (0.179)

Fig. 2. Temporal variation in N pool size ($\text{g N m}^{-2} \text{ horizon}^{-1}$) and N flux ($\text{g N m}^{-2} \text{ horizon}^{-1} \text{ period}^{-1}$) for the 0–30 cm depth in dry dipterocarp forest (DDF; left) and dry evergreen forest (DEF; right). The black area indicates $\text{NH}_4^+\text{-N}$ and the bias area indicates $\text{NO}_3^-\text{-N}$. The residual effect was only shown in N production (two-way ANOVA, $P = 0.02$).

Fig. 3. Vertical distribution of inorganic N pools ($\text{g N m}^{-2} \text{ horizon}^{-1}$) and fluxes ($\text{g N m}^{-2} \text{ horizon}^{-1} \text{ sampling period}^{-1}$) for the 0–30 cm depth in dry dipterocarp forest (DDF; left) and dry evergreen forest (DEF; right). The black area indicates $\text{NH}_4^+\text{-N}$ and the bias area indicates $\text{NO}_3^-\text{-N}$. The residual effect was only shown in estimated N uptake (two-way ANOVA, $P = 0.03$). Different letters indicate significant differences among soil profiles at each site ($P < 0.05$, $n = 5$).

Fig. 4. Changes in extractable organic C (EOC; simple line; $\text{g C m}^{-2} \text{ horizon}^{-1}$) and inorganic N (line with black dots, ammonium; line with crosses, nitrate; $\text{g N m}^{-2} \text{ horizon}^{-1}$) for each horizon during long incubation in dry dipterocarp forest (DDF; left) and dry evergreen forest (DEF; right). The upper figures (a and d) indicate 0–5 cm horizon, the middle (b and e) show 5–10 cm horizon and the low show 10–30 cm horizon. Values of EOC with asterisks differ significantly at each depth (ANOVA, $P < 0.01$, $n = 5$). There was no significant difference in NH_4^+ and NO_3^- .

EOC concentration decreased significantly by 1 week in DDF and by 4 weeks in DEF ($P < 0.01$). At those times, the major form of inorganic N also changed from NH_4^+ to NO_3^- . These trends were observed at all soil depths (Fig. 4). After EOC concentration decreased, it remained relatively stable at both sites while NO_3^- concentration increased.

DISCUSSION

Influence of fire on C and mineral accumulation

Soil organic matter is extremely important for maintaining the fertility of highly weathered tropical soils (Zech et al. 1997). In this study, both sites had lower soil C concentrations than those found in other dry tropical forests (Brown and Lugo, 1990; Gonzalez and Zak, 1994). C dynamics are influenced by land-use changes and fire (Kauffman et al. 1993; Ellingson et al. 2000). The low C concentrations could be related to the fire history of these forests. Although C concentration was low relative to other forests, the soil C and N contents were not

especially low (Table 1; Lugo and Sanchez, 1986; Brown and Lugo, 1990). Fine soil content likely mediates low nutrient concentrations due to high adsorption and soil density. The high fine soil content in these highly weathered tropical soils may be important for nutrient accumulation.

The DDF site has been protected from forest fires for several decades, whereas the DEF site has been protected for a longer period. Soil C concentration in DEF was twice that in DDF (Table 1), probably because of the more recent fires at the former site. In DEF, but not in DDF, C concentration was significantly correlated with the sum of exchangeable cations ($\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+$, $P < 0.05$). Cations are considered to be absorbed by soil C.

Although CEC was high in DEF, Ca^{2+} and Mg^{2+} concentrations were significantly higher in DDF (Table 2). Ash from burned vegetation seems to accumulate in the surface soil in DDF (Sakurai et al. 1998), indicating that the influence of repeated, past slash-and-burn practices remains, even 20 years after the last practice.

Influence of fire on N dynamics

Inorganic N production in the surface soil horizon (0–5 cm) was similar between the sites: $3.0 \text{ g N m}^{-2} \text{ yr}^{-1}$ in DDF and $3.1 \text{ g N m}^{-2} \text{ yr}^{-1}$ in DEF (Fig. 3). Furthermore, the ratio of N leaching (8.9 in DDF and 11.9 in DEF) to N pool (123.1 in DDF and 282.2 in DEF) was greater in DDF than in DEF (0.07 and 0.04, respectively). Based on these results, N seems to cycle mainly in the surface soil horizon and to leach out easily in DDF, and to cycle faster in DDF than in DEF. The high Ca^{2+} and Mg^{2+} concentrations in DDF may support the active turnover of N through high soil pH (Table 2). Thus, forest fire seems to accelerate nutrient dynamics and to shift soil N cycling from dependence on the whole soil profile to surface-dependence.

Despite no clear difference between DDF and DEF in inorganic N production at the surface soil horizon, inorganic N production via the whole soil profile resulted in three times greater estimated N uptake in DEF than in DDF: $8.5 \text{ g N m}^{-2} \text{ yr}^{-1}$ in DEF and $3.1 \text{ g N m}^{-2} \text{ yr}^{-1}$ in DDF at 0–30 cm (Fig. 3). These values are comparable to N mineralization rates in Puerto Rico (Chestnut et al. 1999). Because N uptake is related to productivity (Reich et al. 1997), productivity may differ between DDF and DEF.

Factors controlling N dynamics

According to Hart et al. (1994), EOC is a useful index of available C and also partially controls N dynamics. Several studies have used EOC as an index of C availability for microbes (Ji-hyung and Matzner, 2001). Here, EOC differed between sites (Fig. 4, Table 5); the EOC pool was significantly smaller in DDF than in DEF ($P < 0.01$). Furthermore, during our long-term laboratory incubation, EOC significantly decreased after 1 week for DDF and after 2 weeks for DEF (Fig. 4, $P < 0.01$). This difference in EOC decrease may be related to the total C and EOC pool, i.e., the high total C and EOC in DEF. During the long-term incubation, the changes in inorganic N from NH_4^+ to NO_3^- coincided with the decrease in EOC at both sites. These data confirm that EOC drove N dynamics. During long-term incubation, NO_3^- became the dominant form of inorganic N. Nitrification is considered to be mainly an autotrophic process in dry tropical forest soil (Haynes, 1986), because heterotrophic immobilization is the predominant process when EOC is high. When EOC decreased, ammonification and immobilization may have been depressed, but autotrophic nitrification may have been accelerated. These findings suggest that EOC is more dynamic in DDF, which is consistent with the observation that N cycling is more dynamic in DDF than

in DEF. Our results show that EOC is one of the available sources of C for N dynamics. Available C would therefore be limited during long-term incubation.

On the other hand, the EOC pool significantly decreased during the wet season at both sites, while N mineralization and nitrification rates did not differ significantly during this season in the field (Tables 5 and 6, $P < 0.01$), inconsistent with the results of long-term incubation. This suggests that not only the quantity but also quality of EOC changed during long-term incubation. One possible explanation is that EOC originates partly from root exudates. During incubation, EOC from root exudates will be exhausted over time. Further research on C quality in dry tropical forest soil is needed.

Potentially available N did not differ significantly among sampling periods (Table 3, $P < 0.01$). In all horizons at both sites, the largest component of potentially available N was SMB-N. Singh et al. (1989) showed temporal variation in SMB-N between dry and wet seasons. Microbial immobilization plays a crucial role in the N-retention mechanism in organic soil pools (Tietema, 1998). In this study, the dominance of SMB-N suggests that N availability may be controlled by soil microbes. Specifically, N dynamics, especially ammonification and immobilization, appear to be controlled through available C, in the form of either SMB or EOC.

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