Dynamics of labile organic matter under shifting cultivation in different bio-climatic conditions in humid Asia

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Abstract

We investigated and compared the dynamics of readily mineralizable organic C and N (C_0 and N_0) of soils under shifting cultivation in East Kalimantan (EK), northern Thailand (NT), and Japan (JP). In EK, acidic and/or oligotrophic conditions of the soil as well as highly accumulated C_0 were considered to suppress nitrification and enhance immobilization of NH_4^+. Generally the potential for N supply through mineralization was low in the EK soils, and a long period of fallow followed by N release through intensive soil burning is necessary to sustain crop production. In NT, simultaneous increases in C_0, N_0, and bases in the surface soils were observed in a late stage of fallow, suggesting a kind of pump-up effect of nutritional elements by fallow vegetation. Maintenance of this particular forest-fallow system is probably dependent on this effect, and consequently shifting cultivation systems without sufficient fallow (i.e. less than five years) can be considered to be less sustainable. In JP, neither C_0 nor N_0 fluctuated appreciably during cropping and fallow phases, presumably because the northern temperate climate not only supplied lower amounts of forest litter during the fallow period, but also prevented soil organic matter from rapid decomposition. These characteristics allow continuous cultivation to be practiced for a period of several years. It was concluded that traditional systems of shifting cultivation in EK, NT, and JP are well adapted to their differing soil-ecological conditions.

Keywords: East Kalimantan, Japan, Northern Thailand, readily mineralizable soil organic matter, shifting cultivation

Introduction

Shifting cultivation is a rather extensive farming system that incorporates both cropping and fallow periods in its land rotation (Nye and Greenland 1960; Kunstadter and Chapman 1978). Recently population increase in the mountainous area of Southeast Asia has lead to an expansion of cropland, widespread forest degradation, and a shortening of the fallow period in traditional farming systems. This has resulted in an irreversible degradation of soil fertility. To alleviate forest degradation whilst maintaining or improving the living conditions of the hill people, it is essential to introduce improved and/or alternative land use systems which allow continuous cultivation.

It is widely believed that tropical soils are generally infertile and shifting cultivation is an adaptation to such poor soil conditions. But ecological conditions in the tropics are surprisingly diverse, and systems of shifting cultivation are consequently also quite variable. The main objective of this study is to compare shifting cultivation systems under different bio-climatic conditions with special reference to the dynamics of labile organic matter in soils. This fraction of organic matter is expected to be a good indicator for evaluating the overall sustainability of the fallow-cropping system, and may give an insight into how to achieve more efficient management of organic matter resources in forest-soil ecosystems.

Materials and Methods

This study was carried out in three areas under different bioclimatic conditions: East Kalimantan, Indonesia (EK), northern Thailand (NT), and Japan (JP).

In EK, two areas were selected for sample collection: one is the lower part of the R. Mahakam watershed with an elevation of less than 100 m, and the other is a mountainous area of the Apokayan border with Sarawak, Malaysia with an elevation of between 600 - 800 m. Both areas belong to Köppen's Af climate type and do not have a distinct dry season. Mean annual temperature is above 25 ºC and annual precipitation exceeds 2,000 mm. Parent materials are mainly tertiary sandstone and/or mudstone. According to the US soil classification system, most of the soils are Typic Paleudults or Typic Hapludults. After clearing and burning the forest cover farmers usually plant upland rice for one year only, and then leave the land for more than 20 years as fallow. On relatively fertile soils near the river however, cultivation of crops with a shorter fallow of around eight years is practised.

In NT, activities of shifting farmers were observed mainly in a mountainous area with an elevation of between 600 and 1,300 m. The climate type falls between Kö ppen's Aw and Cw classifications, with a distinct dry season. Mean annual temperature is in the range 20 to 25 ºC and annual precipitation is between 1,200 and 2,000 mm. Parent materials are mainly granite, shale, mudstone, and limestone. The soils are mostly classified as Typic Haplustults or Ustic Dystropepts. Although the traditional land use by the Karen people is one year-cropping and more than ten years of fallow, the fallow period has recently decreased to as little as three years as a result of increasing population pressure. Our survey was mainly carried out at a particular Karen village (DP village), at which the fallow period is still eight years. Upland rice is the main crop.

In JP, traditional shifting cultivation is difficult to find. Our study site, located in Ishikawa Prefecture, may be one of the last examples of shifting cultivation in JP. This area belongs to Köppen's Cf climate type, with an annual precipitation of 2,600 mm and a mean annual temperature of 12 ºC. Parent material is mudstone with some influence from volcanic ejecta. Soils are classified as Andic Dystrudepts. Traditionally farmers plant cereals for about five years, followed by a long period of fallow.

At the end of each dry season from 1997 to 2001, a total of 115 composite samples were collected from the surface 5 cm layer of soil in fields under different land use stages of shifting cultivation.

Incubation experiments

Fresh soil samples were passed through a 2 mm mesh sieve and their moisture contents adjusted to 60% of field moisture capacity. Mineralized C (74 samples) and N (115 samples) were determined in duplicate more than six times over a period of 133 days, using aerobic incubation with a constant temperature of 30 ºC. The C mineralization patterns were fitted to equations by the least squares method using SigmaPlot 5.0 (SPSS inc., 1999). As model functions, first order kinetic models with single (Fi model) or double (Fi+Fi model) sets of parameters were prepared:

$$C_m = C_0 \, (1\text{-exp} \, (-kt))$$

$$C_m = \alpha \, C_0 \, (1\text{-exp} \, (-k_1 t)) + (1-\alpha) \, C_0 \, (1\text{-exp} \, (-k_2 t))$$

where C_m is the amount of mineralized C at time t, C_0 is the pool of readily mineralizable C, and k, k_1, and k_2 are rate constants. N mineralization patterns were fitted to the Fi model or a logistic model (Lo model) as given below:

$$N_m = N_{init} + N_0 \, (1\text{-exp} \, (-kt))$$

$$N_m = N_0 \, / \, (1 + (N_0 \, / \, N_{init} - 1) \, \text{exp} \, (-kt))$$

where N_m is the amount of mineral N at time t, N_{init} is the initial amount of mineral N, N_0 is the pool of readily mineralizable N, and k is the rate constant. The most suitable model in each case was selected by comparing r^2 values.

General physicochemical properties of the soils

Soils were air-dried and passed through a 2 mm mesh sieve prior to chemical analysis consisting of: pH (in water and 1 M KCl solution), total C and N, contents of exchangeable cations (Na, K, Mg, Ca, NH_4, Al, and H), available phosphate (Bray-II method), and particle size distribution. Moisture content of these soils was also measured. The data obtained here was statistically analyzed using analysis of variance (ANOVA), principal component analysis, and linear regression programs in SYSTAT 8.0 (SPSS Inc., 1998).

Results and Discussion

General physicochemical properties

Table 1 shows the general physicochemical properties of the soils studied. The soils from EK were generally more acidic than those from NT, with higher Al, lower bases, and lower pH values. The soils from JP were somewhat intermediate between those of EK and NT in terms of exchangeable cation composition, since they had higher amounts of bases than EK or NT but at the same time had high Al. The soils from low-elevation area of EK had relatively coarse texture, presumably because of progressive clay translocation in the soil profiles due to a relatively stable topography.

Readily mineralizable C (C_0) and N (N_0)

The C mineralization pattern of the soils from EK and JP was mostly fitted by the Fi model (Figure 1a), whereas that from NT was better simulated by the Fi+Fi model (Figure 1b). As regards N mineralization, it was remarkable that NH_4^+ often accumulated during the incubation experiment (Figure 1d). Such an NH_4^+ accumulation was commonly observed for the soils in EK (Figure 2b), indicating a quite low nitrification activity in these soils. Accumulation of NH_4^+ may lead to enhanced immobilization, and this may be why *No* is quite low relative to *Co*, compared to the other soils (Figure 2a). The potential for N supply through mineralization was generally lower in the soils from EK than those from NT or JP, except for the riverside soils (see later). Both the quantity of *Co* and *No* and their proportion to total C or N content increased in the order JP, NT, EK (Table 1), suggesting a higher turnover rate of soil organic matter in tropics than in the temperate zone.

Table 1 General physicochemical properties of the soils.

Area	n	pH(H_2O)	pH(KCl)	Exch. K (cmolc/kg)	Exch. Mg (cmolc/kg)	Exch. Ca (cmolc/kg)	Exch. NH_4 (cmolc/kg)	Exch. Al (cmolc/kg)	Sum of exch. Bases (cmolc/kg)	Base saturation (%)
EK, low elevation	36	4.7 a	3.9 a	0.45 a	1.22 a	1.80 a	0.41 b	3.13 b	3.90 a	43.5 a
EK, high elevation	34	4.9 a	3.9 a	0.51 a	1.66 a	2.38 a	0.72 c	4.35 b	5.28 a	52.5 ab
NT	40	5.8 b	5.1 b	0.98 b	2.95 b	6.45 b	0.20 a	0.64 a	10.46 b	90.0 b
JP	5	4.8 a	4.3 a	1.00 ab	2.60 ab	9.10 b	0.04 a	3.19 ab	12.89 b	76.0 b

Area	Total C (g/kg)	Total N (g/kg)	*Co* (% as TC) (g/kg)	*No* (% as TN) (g/kg)	CN ratio	Available phosphate (mg/kg)	Sand (%)	Silt (%)	Clay (%)
EK, low elevation	30.5 a	2.2 a	7.02(22) a(ab)	0.15(7) a(b)	14.2 a	39.4 a	56.9 b	20.7 a	22.4 a
EK, high elevation	63.4 c	4.4 c	15.05(26) b(b)	0.28(6) b(b)	14.3 a	57.8 a	36.8 a	26.2 ab	37.0 c
NT	48.1 b	3.3 b	4.45 (9) a(a)	0.20(6) a(b)	14.3 a	105.5 ab	44.0 a	28.5 b	29.5 b
JP	68.3 bc	5.2 c	1.87 (3) a(a)	0.09(2) a(a)	13.1 a	321.9 b	53.3 ab	23.6 ab	23.1 ab

* The values with the same letters are not significantly different ($p<0.05$).

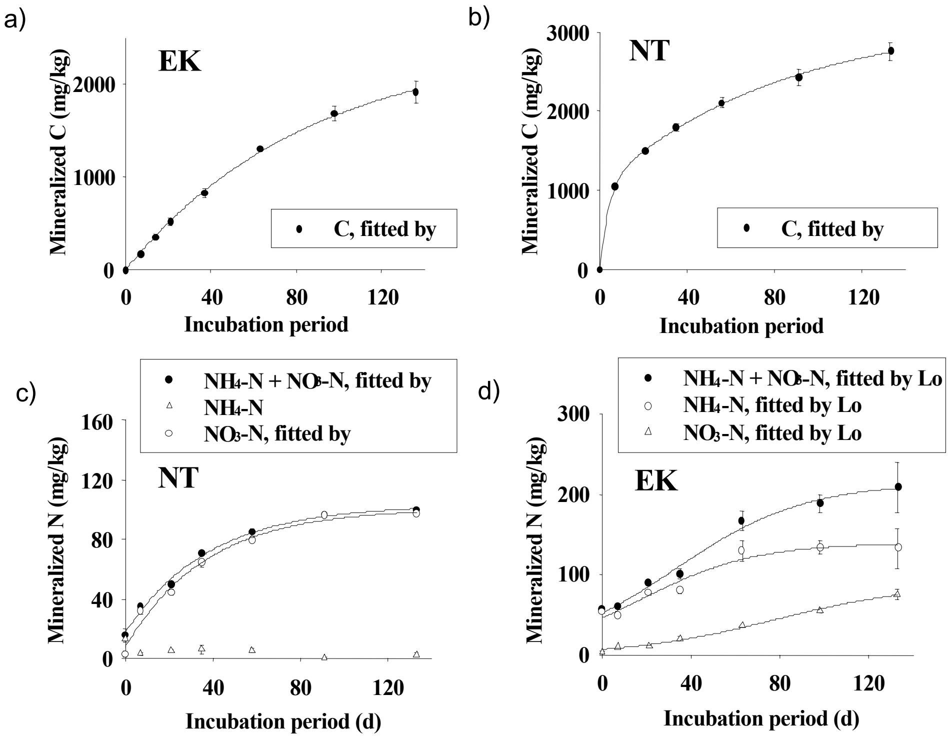

Figure 1 Mineralization patterns of C and N during the incubation experiments.

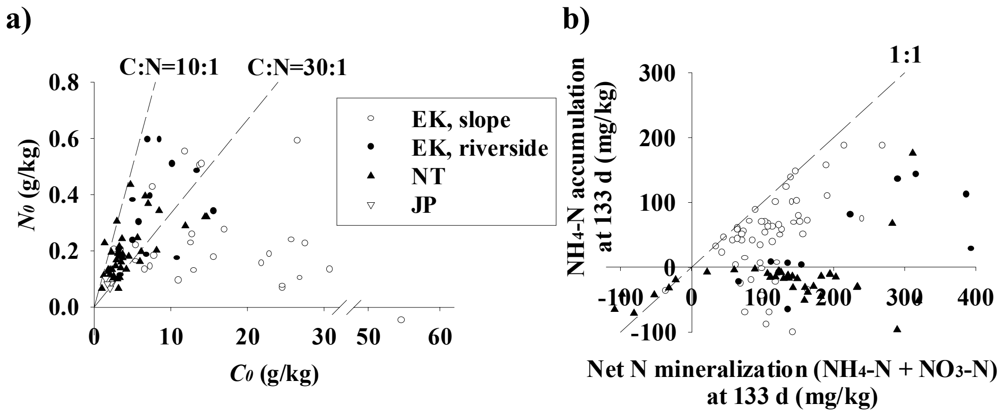

Figure 2 Scattergrams between C_0 and N_0, and N_0 and net nitrification.

Factors controlling the amounts of C_0 and N_0

To analyze the effect of physicochemical properties on the amounts of C_0 and N_0, principal component analysis followed by stepwise multiple linear regression was conducted for the soils from EK and NT. Variables employed included pH(H_2O), pH (KCl), exchangeable K, Mg, Ca, and Al, available phosphate, total C and N, CN ratio, and contents of sand, silt and clay fractions. Tables 2 and 3 show the factor patterns for the first four principal components determined for the EK and NT soils, which accounted for 86 and 82% of their total variances, respectively. The factor patterns in both soils were rather similar, with factors relating to the quantity of organic matter, soil acidity, and NC ratio commonly determined.

Table 2 Factor pattern for the first four principal components in EK samples (n=70).

Variable	PC1	PC2	PC3	PC4
pH(H_2O)	0.13	-0.89	0.05	0.16
pH(KCl)	0.13	-0.93	0.01	0.18
Exch. K	0.09	-0.18	0.84	0.07
Exch. Mg	0.16	-0.83	0.16	0.19
Exch. Ca	0.20	-0.91	-0.01	0.12
Exch. Al	0.50	0.80	-0.12	0.10
Avail. P	0.29	0.04	0.82	0.02
Total C	0.93	-0.03	0.18	-0.26
Total N	0.94	-0.11	0.18	-0.11
CN ratio	0.01	0.25	-0.02	-0.87
Sand	-0.84	0.18	-0.18	-0.44
Silt	0.58	-0.25	0.26	0.54
Clay	0.91	-0.09	0.09	0.28
Eigenvalue	4.05	4.02	1.58	1.52
Proportion	0.311	0.310	0.122	0.117
	organic matter and texture (OM)	acidity	P and K	NC ratio

Table 3 Factor pattern for the first four principal components in NT samples (n=40).

Variable	PC1	PC2	PC3	PC4
$pH(H_2O)$	-0.77	-0.42	0.37	0.20
pH(KCl)	-0.86	-0.31	0.31	0.19
Exch. K	-0.57	0.21	-0.23	0.45
Exch. Mg	-0.79	0.34	-0.17	-0.01
Exch. Ca	-0.92	0.01	0.10	0.10
Exch. Al	0.74	0.39	0.07	0.13
Avail. P	-0.32	0.06	0.67	0.20
Total C	0.05	0.97	-0.08	-0.17
Total N	0.05	0.98	-0.08	0.03
CN ratio	0.06	0.15	0.07	-0.91
Sand	0.16	-0.22	0.87	-0.23
Silt	-0.56	-0.08	-0.65	0.22
Clay	0.43	0.43	-0.58	0.11
Eigenvalue	4.28	2.74	2.33	1.32
Proportion	0.329	0.211	0.179	0.102
	acidity	organic matter (OM)	texture and P	NC ratio

In the next step, stepwise multiple regression analysis was conducted to examine the contribution of each factor (determined above) to C_0, N_0, NH_4^+ accumulation by the 133rd day ($NH_{4\,(133d)}$), and net nitrification by the 133rd day ($NO_{3\,(133d)}$) for EK and NT soils. The following equations were obtained for the EK soils:

$$C_0 = 9310 + 4290 \times (\text{OM factor}) + 2540 \times (\text{acidity factor}) - 1530 \times (\text{P and K factor}) \quad r^2 = 0.48,\ n = 38 \qquad \text{(Eq. 1)}$$

$$N_0 = 210.2 + 82.2 \times (\text{OM factor}) - 29.7 \times (\text{acidity factor}) + 24.1 \times (\text{P and K factor}) \quad r^2 = 0.35,\ n = 70 \qquad \text{(Eq. 2)}$$

$$NH_{4\,(133d)} = 41.9 + 26.8 \times (\text{OM factor}) + 45.3 \times (\text{acidity factor}) - 9.46 \times (\text{P and K factor}) - 13.2 \times (\text{NC ratio factor}) \quad r^2 = 0.72,\ n = 69 \qquad \text{(Eq. 3)}$$

$$NO_3\,(133d) = 97.5 + 20.1 \times (\text{OM factor}) - 63.8 \times (\text{acidity factor}) + 28.3 \times (\text{P and Kfactor}) \quad r^2 = 0.51,\ n = 70 \qquad \text{(Eq. 4)}$$

If we introduce standardized C_0 (C_0-std) into the regression to take account of the effect of mineralizable C on N mineralization, Eq. 2 and 4 can be improved as follows:

$$N_0 = 199.7 + 102 \times (\text{OM factor}) + 62.8 \times (\text{P and K factor}) - 38.3 \times (\text{NC ratio factor})\ 85.1 \times (\text{C0-std}) \quad r^2 = 0.51,\ n = 36 \qquad \text{(Eq. 5)}$$

$$NO_3\,(133d) = 104.0 + 31.4 \times (\text{OM factor}) - 68.5 \times (\text{acidity factor}) + 55.0 \times (\text{P and K factor}) - 33.4 \times (\text{C0-std}) \quad r^2 = 0.66,\ n = 38 \qquad \text{(Eq. 6)}$$

For NT soils, the following equations were obtained:

$C_0 = 4420 + 544 \times \text{(acidity factor)} + 2550 \times \text{(OM factor)}$ $r^2 = 0.53$, $n = 40$ (Eq. 7)

$N_0 = 196.9 + 64.0 \times \text{(OM factor)}$ $r^2 = 0.48$, $n = 39$ (Eq. 8)

Since NH_4^+ accumulation was scarcely observed for the NT soils, $NH_{4\,(133d)}$ could not be explained by the regression analysis. $NO_{3\,(133d)}$ showed a similar trend to N_0.

These equations indicate that:

(1) Since the OM factor positively contributes to C_0, N_0, $NH_{4\,(133d)}$, $NO_{3\,(133d)}$, the quantity of readily mineralizable organic matter reflects overall organic matter accumulation in the soils.

(2) Eq. 2, 3 and 4 indicate that, in EK, the factors relating to the acidic and/or oligotrophic nature of the soils, such as high acidity and P depletion, suppress nitrification and hence accelerate NH_4^+ accumulation, resulting in a reduction in net N mineralization.

(3) C_0 contributes negatively to nitrification and net N mineralization, implying that accumulation of readily mineralizable C accelerates microbial activity and N immobilization during the incubation experiment (Eq. 5 and 6).

Thus more acidic and/or oligotrophic conditions of soils in EK suppress nitrification. This in turn retards further loss of bases and slows soil acidification. Furthermore, the accumulation of C_0 under highly productive rainforest in EK may enhance the immobilization of NH_4^+ through the activity of soil microbes. Hence the ecology of EK is not so beneficial for shifting farmers in terms of N supply for agricultural production. It is thus indispensable to keep a long period of fallow, so that N can be released through the intensive soil burning effect that only occurs when a large amount of plant biomass is burnt (Tanaka *et al*., 2001).

Dynamics of C_0, N_0, and related soil properties in the shifting cultivation systems of EK, NT, and JP

There was no clear fluctuation of C_0, N_0, and related properties of the soils in EK in response to shifting cultivation. Rather these properties seemed to be affected chiefly by topography. The soils near the river showed higher net nitrification/net N mineralization and N_0/C_0 ratios than the other EK soils (Figure 2). This reflects the chemical properties of the soils, as indicated by the fact that the acidity factor (determined earlier) was lower and the P and K factor higher in the soils from the riverside (Figure 3a). The riverside soils were exceptionally fertile in terms of soil acidity, P and K status, and N supply potential, promising a better agricultural response at this location.

Figures 3b and 3c show the dynamics of the acidity and OM factors through different land use stages of shifting cultivation, mainly in the DP village of NT. The OM factor was relatively low through the fallow period and slightly increased in the last stage of fallow (> 7 years). The fluctuation of the acidity factor showed that the soils in the middle stage of fallow (3 to 5 years) were more acidic than those just after cropping and/or in the late stage of fallow. Since similar but more prolonged acidification was reported for subsoils under fallow in the area (Tanaka *et al*., 1997), soil acidification may commonly occur as a result of cation uptake by fallow vegetation.

Figures 4a and 4b show the fluctuation of C_0 and N_0 in the shifting cultivation system of NT. The values of C_0 and N_0 were low through the cropping year and the initial stage of fallow (0 to 4 years), and then increased along with the estabelishment of secondary forest and an increasing supply of forest litter (5 to 8 years). Since the acidity factor showed a decreasing trend at the same time (Figure 3b), this litter may be supplying bases (obtained by tree roots from further down the soil profile) to the surface soil.

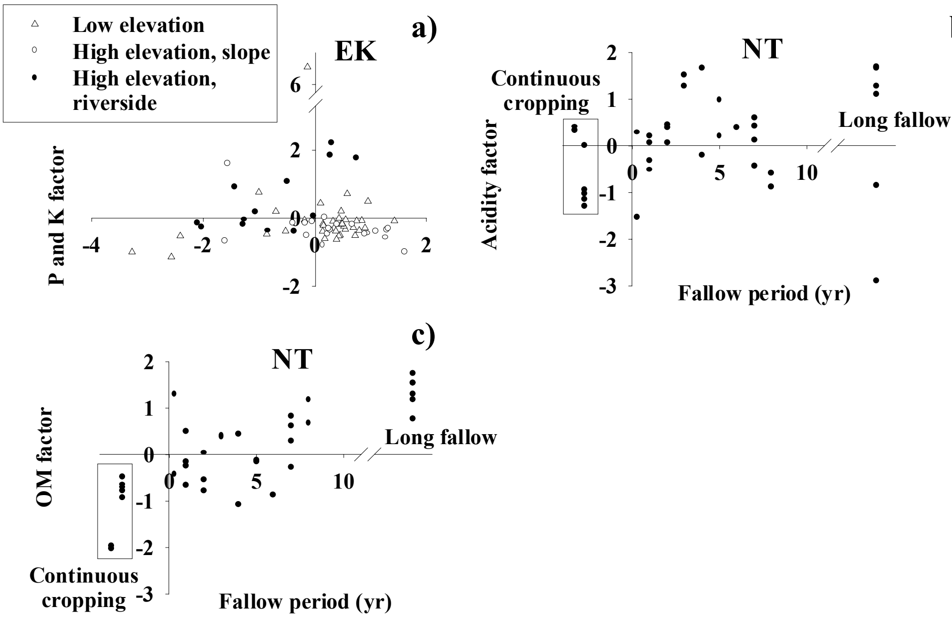

Figure 3 Distribution of factor scores in relation to topography or land use stages.

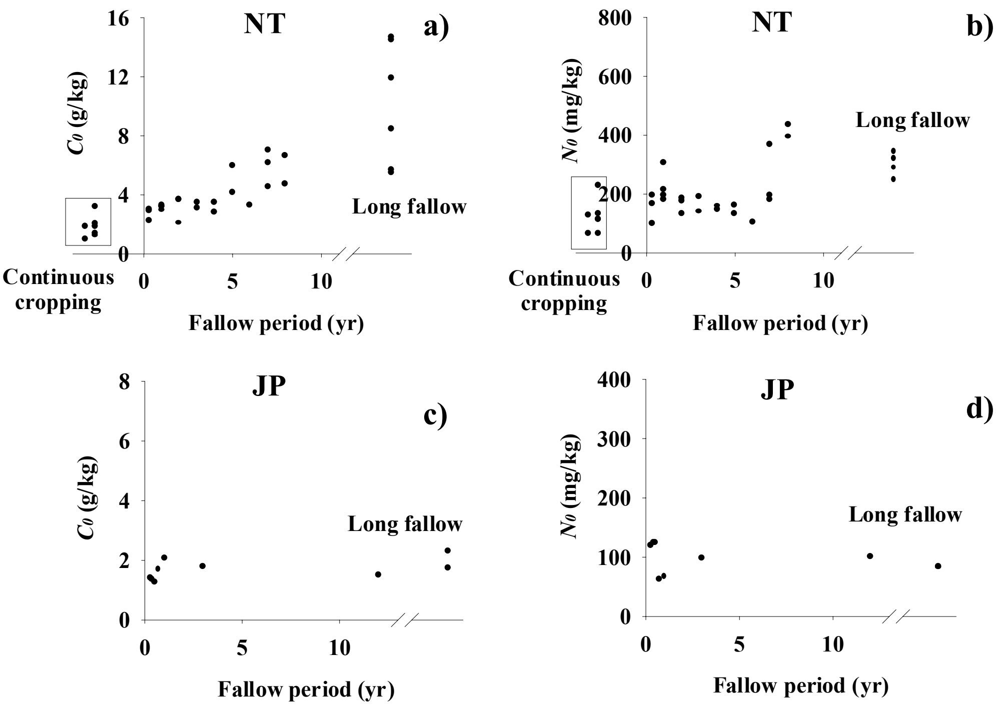

Figure 4 Dynamics of *Co* and *No* throughout different stages of shifting cultivation in NT and JP.

This simultaneous increase in *Co* and bases in the surface soil through forest litter deposition in a late stage of fallow has a kind of pump-up effect on nutritional elements, and can be considered essential to the maintenance of this forest-fallow system. Agricultural production can thus be maintained with a relatively short fallow period of around ten years. Conversely, fallow periods of less than five years can be considered to be less sustainable. As shown in Figures. 3c, 4a, and 4b, *Co*, *No*, and the OM factor clearly decrease under continuous cropping, suggesting that increasing land use pressure will eventually consume a large part of organic matter-associated soil fertility.

Figures 4c and 4d show the fluctuation of *Co* and *No* in the shifting cultivation system in JP. Unlike EK or NT, neither *Co* nor *No* fluctuate appreciably during the cropping and fallow phases, presumably because the northern temperate climate produces lower amounts of forest litter during the fallow period. Such a mild climate also prevents soil organic matter from actively decomposing, allowing continuous cultivation for several years.

Traditional shifting cultivation in EK, NT, and JP can be seen to be well adapted to their respective soil-ecological conditions. Socioeconomic conditions are, however, drastically changing, making it difficult to sustain these systems. Even so, these systems provide an insight into basic soil processes-an understanding of which is essential to the better management of organic matter in all agroecosystems.

Conclusion

The dynamics of readily decomposable organic matter was investigated for soils under shifting cultivation in EK, NT, and JP. In EK, acidic and/or oligotrophic conditions of the soil as well as highly accumulated *Co* were considered to suppress nitrification and enhance immobilization of NH_4^+. In NT, simultaneous increases of *Co*, *No*, and bases observed in surface soil in a later stage of fallow suggest a nutrient pump-up effect by fallow vegetation. This effect is considered to be essential for the maintenance of the forest-fallow systems in NT. In contrast, *Co* and *No* did not fluctuate appreciably during cropping and fallow phases in JP. A mild climate seems to decrease both the production and decomposition of organic matter.

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