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ORIGINAL PAPER

Decline of soil nitrogen mineralization and nitrification during forest conversion of evergreen broad-leaved forest to plantations in the subtropical area of Eastern China

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Abstract We examined soil nitrogen (N) mineralization and nitrification rates, and soil and forest floor properties in one native forest: evergreen broad-leaved forest (EBLF), one secondary shrubs (SS), and three adjacent plantation forests: Chinese fir plantation (CFP), bamboo plantation (BP) and waxberry groves (WG) in Tiantong National Forest Park, Eastern China. All forests showed seasonal dynamics of N mineralization and nitrification rates. Soil N mineralization rate was highest in EBLF (1.6 ± 0.3 mg-N kg^{-1} yr^{-1}) and lowest in CFP (0.4 ± 0.1 mg-N kg^{-1} yr^{-1}). Soil nitrification rate was also highest in EBLF (0.6 ± 0.1 mg-N kg^{-1} yr^{-1}), but lowest in SS (0.02 ± 0.01 mg-N kg^{-1} yr^{-1}). During forest conversion of EBLF to SS, CFP, BP and WG, soil N mineralization rate (10.7%, 73%, 40.3% and 69.8%, respectively), soil nitrification rate (94.9%, 32.2%, 33.9% and 39%, respectively), and soil N concentration (50%, 65.4%, 78.9% and 51.9%, respectively) declined significantly. Annual soil N mineralization was positively correlated with total C and N concentrations of surface soil and total N concentration of forest floor, and negatively correlated with soil bulk density, soil pH and C:N ratio of forest floor across the five forests. Annual soil nitrification was positively correlated with total C concentration of surface soil and N concentration of forest floor, and negatively correlated with soil bulk density and forest floor mass. In contrast, annual soil nitrification was not correlated to pH value, total N concentration, C:N ratio of surface soil and total C concentration and C:N ratio of forest floor.

Keywords Evergreen broad-leaved forest · Forest conversion · Forest floor · Nitrogen mineralization · Nitrogen nitrification · Soil properties

Introduction

Historical forest management has lasting effects on many ecosystem functions such as soil nitrogen (N) mineralization and nitrification (Neill et al. 1999; Templer et al. 2005). Studies on soil N mineralization and nitrification dynamics under forest conversion from native forests to plantations can provide substantial insight into the impacts of forest management

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histories on soil fertility and ecosystem function (Verchot et al. 2001). In order to understand the impacts of historical forest conversion on ecosystem properties, space-for-time substitution is still used as an evaluation method. Generally, the adjacent native forests are chosen to represent a reference condition, and neighboring plantation forests are recognized as the experimental units.

Previous studies have provided mixed results on the effects of forest conversion on soil N mineralization and nitrification. For instance, intact tropical forests have higher rates of soil N mineralization and nitrification than neighboring disturbed sites (Piccolo et al. 1994; Reiners et al. 1994; Neill et al. 1995, 1997, 1999; Verchot et al. 1999). In contrast, some other studies found that, following the slash-and-burn conversion of forest to annual crops or pastures, soil N mineralization and nitrification may increase in pastures (Matson et al. 1987; Montagnini and Buschbacher 1989; Corre et al. 2006). Goodale and Aber (2001) reported no change in soil N mineralization and nitrification under similar conversion patterns in northern hardwood forests.

Soil N mineralization and nitrification rates are determined by many factors, such as availability of organic N, the activity of microbes and demand for organic C and N (Nicolardot et al. 2001; Chapin et al. 2002). Since the forest floor is the major component for soil organic matter accumulation to sustain soil N transformations, the quality and quantity of forest litter would indirectly control soil N mineralization and nitrification (Ferrari 1999; Compton and Boone 2000; Uri et al. 2003). The influence of plant species, particularly the difference between broadleaves and conifers, on N mineralization rates has been demonstrated in many field and laboratory trials (Gower and Son 1992; Prescott and Preston 1994; Prescott 1996; Thomas and Prescott 2000; Latty et al. 2004). However, results of these studies were not consistent and appeared to be highly species dependent.

While soil N cycling following the conversion of native forests to various types of vegetation has been extensively documented in temperate and tropical ecosystems (Matson et al. 1987; Montagnini and Buschbacher 1989; Verchot et al. 1999; Compton and Boone 2000; Goodale and Aber 2001; Verchot et al. 2001; Uri et al. 2003; Latty et al. 2004; Corre et al. 2006), the impacts of forest conversion from native forests to plantations and secondary forests on soil N processes are poorly understood for evergreen broad-leaved forests (EBLF, hereafter) in Eastern China. Evergreen broad-leaved forests, covering a large area of China, are the typical vegetation type in the subtropical area. Despite their formerly widespread geographical distribution, these EBLFs are now undergoing rapid conversion to secondary shrubs and plantations (Song and Chen 2007).

To understand the impacts of forest conversion on soil N transformation in EBLF, we quantified soil N mineralization and nitrification rates in five forest types with different management histories in Tiantong National Forest Park, Zhejiang province, Eastern China. Our objectives were: (1) to compare soil N mineralization and nitrification rates among the five vegetation types with different forest management histories; (2) to examine the effect of seasonality on soil N mineralization and nitrification rates; and (3) to relate N cycling to soil and forest floor properties.

Methods

Study area and site description

This study was carried out in Tiantong National Forest Park (29°48′ N, 121°47′ E, 200 m a.s.l.), Zhejiang province, China. The climate of this region is subtropical monsoon with a hot and humid summer and a dry and cold winter. The annual mean temperature is 16.2°C; the warmest month is July with a mean temperature of 28.1°C, and the coldest is January with a mean temperature of 4.2°C. Average annual precipitation is 1374.7 mm concentrated from May to August. The substrate parent materials are mesozoic sediments and acidic intrusive rocks, including quartzite and granite. The soil texture is mainly medium-heavy loam, and soil pH ranges from 4.4 to 5.1. The mature forests around a Buddhist temple in the centre of the park are considered as climax monsoon EBLF because this area has been protected from clear cutting (Yan et al. 2006). Outside the central park area, shrubs, plantations and orchards (e.g. tea, tangerine and waxberry groves) are widespread, which results in a diverse mosaic of forest types.

The EBLF is the dominant forest types in the central area of the park. The canopy of this forest is dominated by evergreen broad-leaved trees such as *Castanopsis fargesii* Franch and *C. carlesii* (Hemsl.)

Hayata and *Schima superba* Gardn. et Champ. The tree layer is 12–25 m high and coverage is 70–85%. The shrub layer is <2.5 m and coverage is 65–80%. The herb layer is <1 m, coverage is 10–30%, and the dominant species are normally ferns.

The majority of the non-EBLF forest in the park is secondary shrubs, which are derived from natural regeneration after cessation of the practice of repeated cutting for firewood. With the supply of natural gas for cooking and heating, the extent of forest clearance has been significantly reduced in recent decades. This forest is occupied by coniferous species such as *Pinus massoniana* Lamb and resprouting evergreen broadleaf species such as *S. superba*. The canopy height is nearly 5–10 m, coverage is 30–70%. Waxberry groves often border the secondary shrubs. The dominant tree is *Myrica rubra* (Lour.) Sieb. et Zucc. The tree layer is 5–10 m high and coverage is 50–60%. This plantation mainly came from the clear cutting of shrubs in 1996 by local farmers for picking waxberry fruit.

Plantations such as Chinese fir and bamboo are located on the margins of EBLF and secondary shrubs. Because these plantations are monocultures, the forest structure is often homogeneous and the canopy is dominated by a single species. In the Chinese fir plantations, the dominant tree species is *Cunninghamia lanceolata* (Lamb.) Hook. and the tree layer is 10–15 m high. Because forest management practices such as mowing were performed only once every 3 years, the herb layer had grown to 1 m high when this study was conducted. According to the record in the local forestry bureau, the *C. lanceolata* forest was established on abandoned tea groves in 1976, which had originated from the conversion of EBLF following clearing and slash-burning in 1964.

The dominant tree in the bamboo plantations is *Phyllostachys pubescens* Mazel ex H. de Lehaie and the tree layer is 12–15 m high. Bamboo plantation mainly resulted from the invasion of this species from the adjacent artificial bamboo forest that was introduced by a local farmer for picking bamboo shoots and logging timber. In 1960, the area that is currently our experimental bamboo forest was EBLF started to be invaded by *P. pubescens*; and bamboo forest became dominant since 1978 (personal communication with local forest managers). Since then the bamboo forest has received the heaviest human disturbances including dead wood harvesting, picking bamboo shoots and fertilization every year (53 kg-N ha^{-1}, personal communication with local farmers).

Experimental design

We selected five vegetation types: evergreen broad-leaved forests (EBLF), secondary shrubs (SS, hereafter), Chinese fir plantations (CFP, hereafter), bamboo plantations (BP, hereafter) and waxberry groves (WG, hereafter), to examine the effects of forest conversion on soil N transformation. The five forest types used for this study were located on the same position of the slope, had the same original vegetation in the history, and the soils were developed from the same quartzitic parent material (Song and Chen 2007). We randomly selected four 20 × 20 m plots for each forest type and those plots were separated by at least 50 m buffer zones from the edge.

Soil in situ N mineralization and nitrification rates were examined five times a year, with seasons defined according to plant phenology: summer, full leaf (June, July, August and September); fall, abscission layer formation and leaf fall (October and November); winter, dormant season (December, January and February); and spring, bud break (March, April and May). Soil properties (total Carbon (C), total N, C:N ratio, and pH values) and forest floor properties (litter mass, total C and total N concentrations and C:N ratio) were also quantified.

Determination of soil properties

Five soil samples were taken with a metallic tube (20 cm height and 7.5 cm in diameter) from randomly chosen spots in each plot. The litter layer was removed before soil was taken. Soil samples (5 forests × 4 plots × 5 spots) were air-dried for 30 days, and passed through a 0.5 mm sieve. Subsamples of ~5 g were analyzed for total N concentration using the flow-injection autoanalyser (Skalar, Netherlands). Another sub-sample in each of the 100 soil samples was ground to pass a 2 mm sieve for total carbon concentration using the oil bath-K_2CrO_7 titration method (Nelson and Sommers 1975). Soil pH was determined by Metterler-143 Toledo pH meter (1:2, H_2O). Approximately 20–25 soil cores per forest type were used to estimate soil bulk density (0–20 cm soil layer).

Determination of forest floor properties

Forest floor included the fine materials, such as leaf litter and small branches (<2.5 cm in diameter). The forest floor profile was divided into litter (L), fermentation (F) and humified (H) layers. The L layer consisted of fresh or slightly decomposed litter from trees and understory; the F layer consisted of partly decomposed litter, the origin of which was mainly identifiable; and the H layer consisted of decomposed organic matter, the origin of which could not be identified.

To account for the seasonal variations in forest floor properties, five samples were randomly collected in each of the plots every 3 months during 1 year period (four times: April, June, September and December). Forest floor organic matter was collected using a 0.4 × 0.4 m frame. In the field, L, F, and H layers were separated, and returned to the laboratory in the plastic bags. All samples were oven dried at 70°C to constant weight, weighed and stored in a refrigerator (~4°C) to reduce decomposition until the fourth sampling was completed. Then all the samples from different seasons were combined to give one composite sample for each layer. In total, there were 300 samples (5 forests × 4 plots × 5 spots × 3 layers). Subsamples of approximately 50 g were ground, and passed through a 6.0-mm sieve, and then digested to analyze total N concentration (Kjeldahl) using the flow-injection autoanalyser. Total carbon concentration was determined using oil bath-K_2CrO_7 titration method (Nelson and Sommers 1975).

Determination of soil N mineralization and nitrification

Soil N mineralization and nitrification rates were measured from in situ incubations using the PVC method (Binkley and Hart 1989). At the start of each incubation period, soil cores (positioned in pairs) were taken with the PVC tubes (20 cm height and 7.5 cm in diameter) from five randomly chosen spots in each plot. The lower end of PVC pipes was sharpened to permit insertion with a minimum of compaction. The litter layer was removed before soil was taken. One of each pipe pair (initial sample) was removed and returned to the laboratory in an icebox to determine initial soil ammonium (NH_4^+-N) and nitrate (NO_3^--N) concentrations. The second pipe of each pair (incubated sample) was wrapped with low-density polyethene on the top and with gauze under the bottom, and then left in its original position from which it was taken. At the end of the each incubation period the incubated samples were removed and the amount of mineral N accumulated was determined.

All collected soil cores were kept cool until returned to the laboratory (in Tiantong National Station of Forest Ecosystems, Ningbo), stored in a refrigerator at 4°C until analyzed, usually within 36 h. In the laboratory, following removal of roots and stones, each soil core was well mixed by hand to form a homogenous sample and then passed through a ~6 mm sieve. One sub-sample (20 g) was placed in a 105°C oven for >12 h to obtain oven-dry weight. The inorganic-N concentrations were expressed on a dry-weight basis. Subsamples of ~5 g were extracted in 20 ml of 2 M KCl for 1 h and filtered through Whatman 42 filter paper. NH_4^+-N and NO_3^--N were then analyzed with a Skalar flow-injection autoanalyser (Netherlands) using alkaline phenol and cadmium reduction techniques, respectively.

Net N mineralization of a sample for the five incubation period was obtained by subtracting the initial (NH_4^+ and NO_3^-)-N concentration of the initial sample from that of the incubated sample. Soil net nitrification of a sample was obtained by subtracting the NO_3^- concentration of the initial sample from that of the incubated sample. Net N mineralization rate and soil net nitrification rate were expressed as the net mineralization (or nitrification) per gram soil per day. Annual rates of soil N mineralization and nitrification were calculated by summing the values for all five incubation periods.

Statistical analyses

To determine the effects of forest types on soil and forest floor properties, one-way analysis of variance (ANOVA) was used. Forest type was included as a fixed effect. If there was a significant effect of forest type, least-squares mean separation with Tukey's correction was used to test for differences among forests.

Mixed model with repeated measures was used to determine whether there were significant "forest type" effects on each response (N-mineralization and N-nitrification) over the five sample dates. To avoid the autocorrelation by measuring the response based on the time, unstructured covariance was selected based on best fit principle (the smallest BIC value) (Littell et al. 1996). Least square means were used to test for the difference for each forest type and time effects. Differences were compared with Tukey's adjustment. All statistical tests were considered significant at the $P < 0.05$ level. Pearson correlation was used to relate soil N mineralization and nitrification rates with soil and forest floor properties.

Results

Soil and forest floor properties

Soil properties

There were significant effects of forest type on soil bulk density, pH, total C, total N, C:N ratio, NH_4^+-N and NO_3^--N concentrations (Table 1). Soil bulk density was significantly greater in CFP, BP and WG than that in SS and EBLF. Soil pH was highest in BP, lowest in EBLF, and intermediate in WG, CFP and SS. In contrast, EBLF had higher C concentrations than SS, CFP, BP and WG (5.56%, 2.9%, 2.02%, 2.42% and 2.06%, respectively). Similarly, BP and CFP had the lowest soil N concentration (0.18% and 0.11%, respectively) while EBLF had the highest (0.52%). Soil C:N ratio was highest in BP, lowest in WG and intermediate in EBLF, SS and CFP (Table 1).

Forest floor properties

Forest floor properties varied across different forests (Table 2). The total mass was highest in SS, lowest in BP and WG, and intermediate in EBLF and CFP. Generally, the mass in each layer was highest in the litter layer (L), intermediate in the fermentation (F) layer and lowest in the humified (H) layer.

Total C concentration in L and F layers exhibited significant differences among different forests while it did not differ in H layer. When the three layers were averaged, total C concentration was significantly greater in EBLF, CFP and WG than that in BP and SS (Table 2).

EBLF and BP had the higher total N concentration in each forest floor layer, while CFP had the lowest, and SS and WG were intermediate between them (Table 2). C:N ratios in all L, F and H layers were lower in EBLF and BP than CFP (Table 2).

Annual soil N mineralization and nitrification rates

Annual N mineralization rate on the area basis in five forests varied substantially, which was highest in EBLF and SS, lowest in CFP and intermediate in BP and WG (Table 3). In contrast, annual soil nitrification in five forests ranged from 5.6 to 78.6 kg ha^{-1} yr^{-1}. Among five forests, the annual nitrification rate was lowest in SS and highest in EBLF. There were no significant differences of annual nitrification rate among EBLF, CFP, BP and WG (Table 3).

Effects of forest type and seasonality on soil N mineralization and nitrification

Soil N mineralization and nitrification rates showed remarkable seasonal dynamics. Among EBLF, CFP, BP and WG, soil N mineralization and nitrification rates were highest in summer and lowest in winter. By

Table 1 Soil properties of five forest types in Tiantong National Forest Park, Eastern China

Soil properties	Evergreen broad-leaved forest (EBLF)	Secondary shrubs (SS)	Chinese fir plantation (CFP)	Bamboo plantations (BP)	Waxberry groves (WG)	Forest type effect (F)
Bulk density (g cm^{-3})	1.1 (0.1)a	1.3 (0.04)b	1.4 (0.1)c	1.3 (0.03)bc	1.4 (0.1)c	60.3***
pH value (2:1 H_2O)	3.8 (0.1)a	4.2 (0.1)b	4.5 (0.1)bd	5.2 (0.2)c	4.7 (0.3)d	33.5***
Total C (%)	5.6 (0.7)a	2.9 (0.4)b	2.0 (0.1)c	2.4 (0.3)bc	2.1 (0.2)bc	56.5***
Total N (%)	0.5 (0.04)a	0.3 (0.03)b	0.2 (0.02)c	0.1 (0.02)d	0.3 (0.04)b	320.8***
C:N ratio	10.8 (1.3)ac	11.1 (1.3)a	11.2 (1.4)a	22.1 (1.3)b	8.3 (1.0)c	70.6***
NH_4^+ (mg-N kg^{-1})	14.2 (1.3)a	16.5 (0.8)b	22.1 (2.9)c	24.1 (2.4)bc	19.5 (1.9)d	86.0***
NO_3^- (mg-N kg^{-1})	1.1 (0.4)ab	0.4 (0.2)a	1.6 (0.2)bc	0.5 (0.1)a	2.0 (0.6)c	19.1***

Note: *** $P < 0.001$. Effect of forest types is presented as P-values of one-way ANOVAs. Different letters in each row indicate significant differences (adjusted $P < 0.05$). Data are means ± SE ($n = 4$)

Table 2 Properties of litter (L), fermentation (F) and humified (H) layer of forest floor in five forest types in Tiantong National Forest Park, Eastern China

Forest floor properties	Evergreen broad-leaved forest (EBLF)	Secondary shrubs (SS)	Chinese fir plantations (CFP)	Bamboo plantations (BP)	Waxberry groves (WG)	Forest type effect (F)
Mass (kg m^{-2})						
L	0.6 (0.1)ac	0.8 (0.2)a	0.4 (0.1)b	0.2 (0.04)b	0.4 (0.1)cb	18.9***
F	0.4 (0.1)a	0.8 (0.1)b	0.5 (0.1)a	0.3 (0.1)a	0.3 (0.2)a	13.4***
H	0.4 (0.1)ab	0.5 (0.1)a	0.4 (0.1)ab	0.2 (0.1)bc	0.2 (0.04)c	14.1***
Total	1.3 (0.1)a	2.1 (0.4)b	1.2 (0.2)ac	0.8 (0.1)c	0.8 (0.2)c	23.5***
Total C (%)						
L	15.3 (0.4)ab	14.3 (1.9)ac	16.7 (0.7)b	13.4 (0.8)a	16.1 (0.3)bc	7.2**
F	14.1 (0.9)ab	13.7 (1.5)ab	14.5 (1.3)a	12.1 (0.5)b	14.2 (0.2)ab	3.4*
H	12 (0.9)a	10.1 (1.7)a	10.3 (1.5)a	10.4 (0.4)a	11.5 (1.6)a	1.6
Average	13.8 (0.4)a	12.7 (1.4)ab	13.8 (0.6)a	12 (0.3)b	13.9 (0.7)a	5.0**
Total N (%)						
L	1.2 (0.1)a	0.9 (0.06)b	0.5 (0.05)c	1.2 (0.03)a	0.8 (0.1)b	43.3***
F	1.8 (0.3)a	1.0 (0.02)b	0.7 (0.1)c	1.5 (0.2)a	1.1 (0.1)b	28.5***
H	2.1 (0.5)a	1.1 (0.02)bc	0.8 (0.2)b	1.7 (0.2)ad	1.5 (0.3)cd	15.3***
Average	1.7 (0.3)a	1.0 (0.04)b	0.7 (0.1)c	1.45 (0.1)a	1.1 (0.1)b	32.6***
C:N ratio						
L	13.0 (1.0)ab	15.8 (1.1)ad	31.3 (3.1)c	11.3 (0.7)b	19.5 (3.0)d	60.8***
F	8.1 (1.6)a	13.5 (1.7)a	23.0 (4.7)b	8.5 (1.1)a	13.3 (1.5)a	23.2***
H	5.8 (1.1)a	9.1 (1.8)a	12.8 (2.2)v	6.1 (0.5)a	8.2 (2.1)a	11.2***
Average	9.0 (1.2)a	12.8 (1.6)b	22.4 (3.3)c	8.6 (0.8)a	13.6 (2.2)b	44.2***

Note: * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. Effect of forest types is presented as *P*-values of one-way ANOVAs. Different letters in each row indicate significant differences (adjusted $P < 0.05$). Data are means ± SE ($n = 4$)

Table 3 Annual soil N mineralization and nitrification rates on the area basis in five forest types in Tiantong National Forest Park, Eastern China

	Evergreen broad-leaved forest (EBLF)	Secondary shrubs (SS)	Chinese fir plantation (CFP)	Bamboo plantations (BP)	Waxberry groves (WG)	Forest type effect (F)
Mineralized N pool (kg-N ha^{-1} yr^{-1})	217.7a (12.3)	205.7a (12.2)	94.2b (2.9)	176.4ac (26.2)	109.3bc (15.3)	12.8***
Nitrified N pool (kg-N ha^{-1} yr^{-1})	78. 6a (5.5)	5.6b (1.1)	73.5a (1.1)	64.4a (4.1)	61.0a (6.3)	48.6***

Note: *** $P < 0.001$. Effect of forest types is presented as *P*-values of one-way ANOVAs. Letters on the same column signify Tukey's honestly significant differences between forest types ($P < 0.05$). Data are means ± SE ($n = 4$)

contrast, the soil N mineralization rate in SS was highest in the early-summer and lowest in the middle summer (Fig. 1). Furthermore, in the seasonal rhythm of spring to winter, soil N mineralization rate in EBLF showed a parabola trend peaking in the early summer, but it fluctuated significantly in three plantations and SS (Fig. 1a). The rate of soil nitrification was constantly low in SS, but there was a consistent seasonal pattern of it in EBLF, CFP, BP and WG (Fig. 1b).

Forest type, seasonality and the interaction between forest type and seasonality affected annual soil N mineralization and nitrification rates significantly (Table 4). Across five seasons, annul soil N mineralization rate was highest in EBLF and SS, intermediate in BP and lowest in CFP and WG. Annual soil nitrification rate

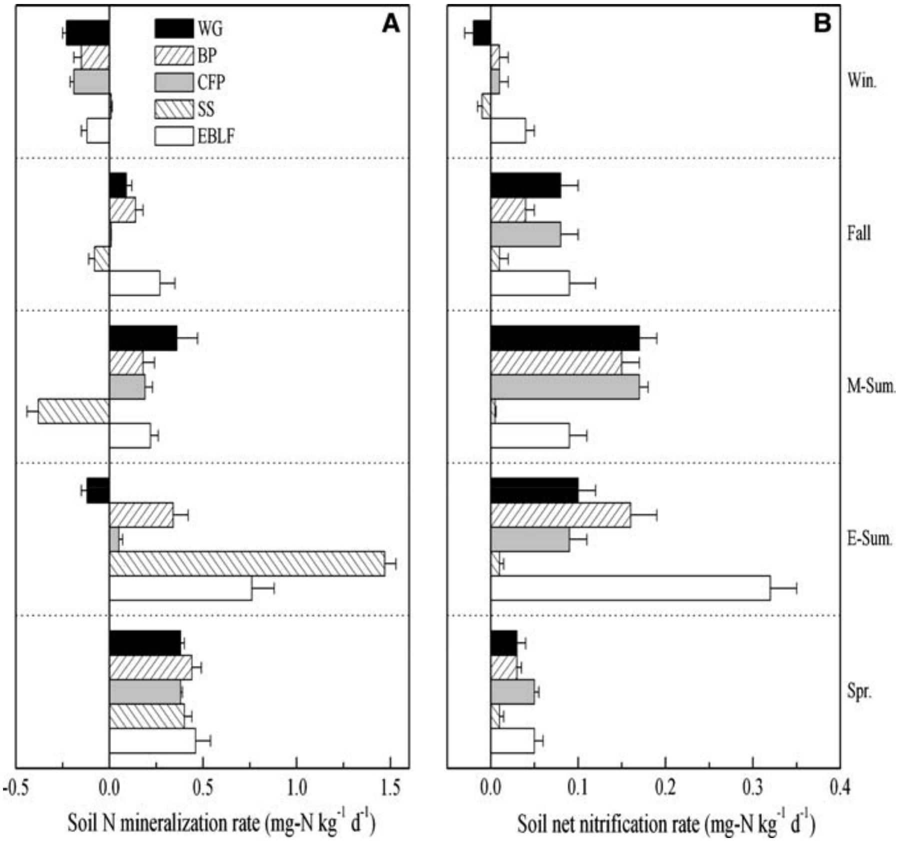

Fig. 1 Seasonal dynamics of soil N mineralization and nitrification rates in five forest types in Tiantong National Forest Park, Eastern China. EBLF: Evergreen broad-leaved forest; SS: Second shrubs; CFP: Chinese fir plantations; BP: Bamboo plantations; WG: Waxberry groves; Win: Winter; M-Sum: Middle summer; E-Sum: Early summer; Spr: Spring

Table 4 Results of mixed model with repeated measures for "forest type" effects on N mineralization rate and nitrification rate over the five sample dates (different seasons)

Factor	df	Soil net nitrification rate		Soil net N mineralization rate	
		F	*P*	*F*	*P*
Forest type	4	38.5	<0.0001	26.2	<0.0001
Seasonality	4	287.6	<0.0001	1021.5	<0.0001
Forest type*Seasonality	16	28.2	<0.0001	134.1	<0.0001

The *F*-values and *P*-values are presented

was highest in EBLF, followed by CFP, BP and WG, and lowest in SS (Fig. 2b). During forest conversion of EBLF to SS, CFP, BP and WG, soil N mineralization rate (10.7%, 73%, 40.3% and 69.8%, respectively) and soil nitrification rate (94.9%, 32.2%, 33.9% and 39%, respectively) decreased.

In different seasons, the soil nitrification rate was highest in summer, intermediate in spring and fall, and lowest in winter (Fig. 3a). The soil N mineralization rate was highest in spring and early summer and decreased afterwards (Fig. 3b).

Correlation of soil N mineralization and nitrification rates with soil and forest floor properties

The annual soil N mineralization rate was positively correlated with soil C and N concentrations, negatively correlated with soil bulk density and pH value and not correlated with C:N ratio (Table 5). Annual soil nitrification rate was positively correlated with soil C concentration and negatively correlated with soil bulk density. It showed no correlations with soil pH, soil N concentration and C:N ratio (Table 5).

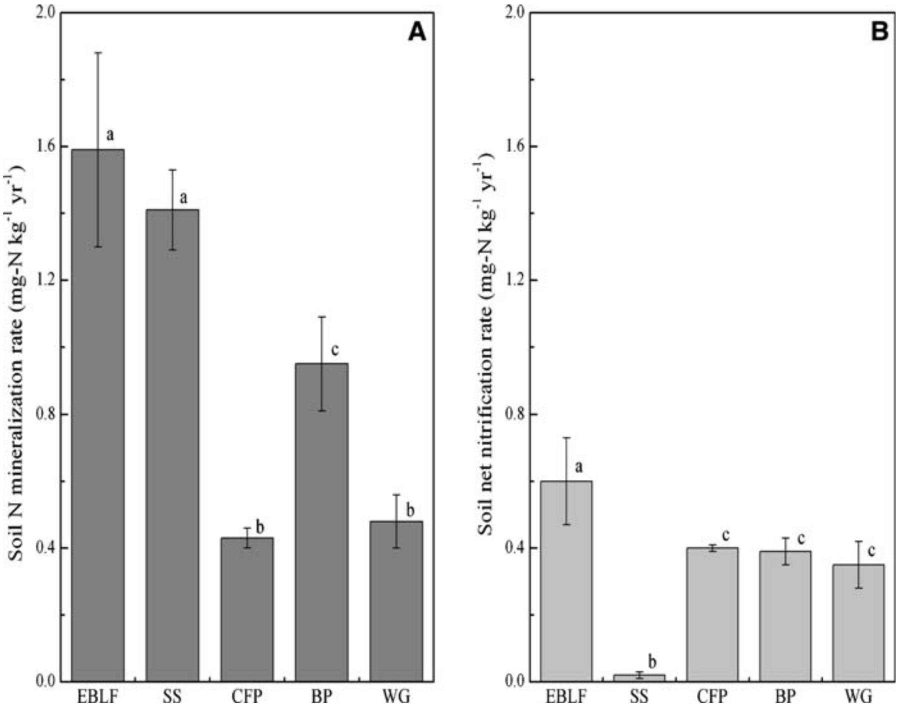

Fig. 2 Annual soil N mineralization and nitrification rates of five forest types in Tiantong National Forest Park, Eastern China. Means and SE are presented. Different letters indicate significant differences at Tukey's adjusted $P < 0.05$. See Fig. 1 for forest abbreviations

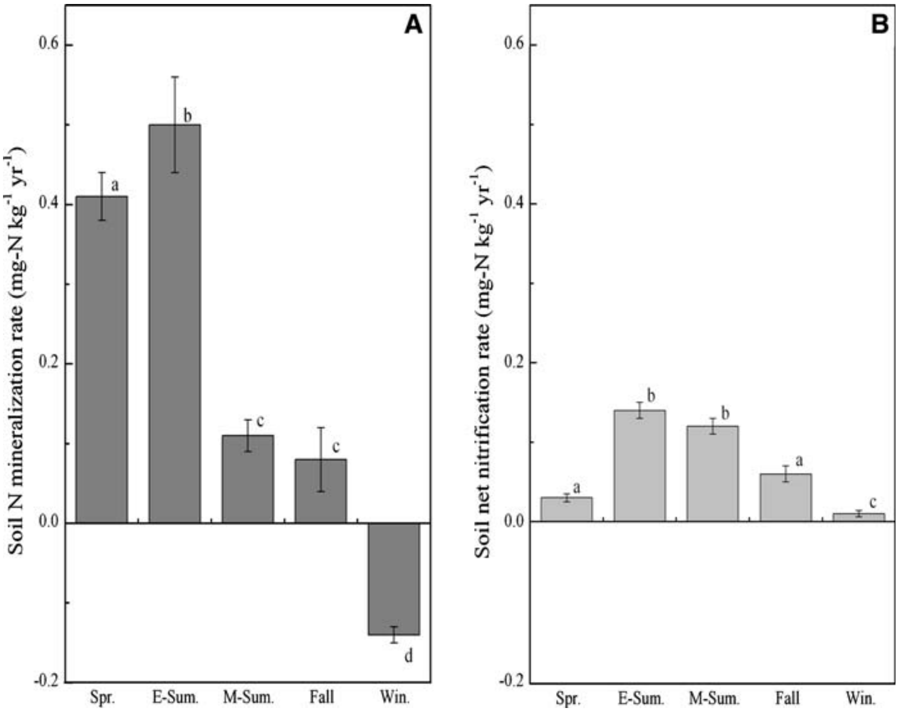

Fig. 3 Differences of soil N mineralization and nitrification rates in different seasons in Tiantong National Forest Park, Eastern China. Soil N mineralization and nitrification rates were calculated by averaging the value for five forests. Means and SE are presented. Different letters indicate significant differences at Tukey's adjusted $P < 0.05$. See Fig. 1 for time intervals abbreviations

The total mass of forest floor was positively correlated with annual soil N mineralization rate and negatively correlated with soil nitrification rate. Averaged C concentration in forest floor did not correlate with annual soil N mineralization and nitrification rates. If total C concentration and mass were combined, total C

Table 5 Pearson correlation coefficients for the relation between soil N mineralization and nitrification rates and soil properties in the top 20 cm soil, Tiantong National Forest Park, Eastern China

	Bulk density	pH value (2:1 H_2O)	Total C	Total N	C:N ratio
Annual soil N mineralization rate	**−0.8*****	**−0.55***	**0.74*****	**0.59****	0.11
Annual soil nitrification rate	**−0.46***	−0.16	**0.48***	0.42	0.07

Note: All the significant correlations indicated in bold. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. $n = 20$

Table 6 Pearson correlation coefficients for the relation between soil N mineralization and nitrification rates and forest floor properties in Tiantong National Forest Park, Eastern China

Forest floor properties	Annual soil N mineralization rate				Annual soil nitrification rate			
	L	F	H	Total/average	L	F	H	Total/average
Mass	**0.62****	0.25	**0.58****	**0.52***	−0.35	**−0.65****	−0.34	**−0.51***
Total C	−0.4	−0.12	0.08	−0.21	0.29	0.08	0.41	0.35
Total C mass	**0.54***	0.23	**0.62****	**0.48***	−0.28	**−0.62****	−0.15	−0.42
Total N	**0.63****	**0.6****	**0.53***	**0.6****	0.26	**0.49***	**0.57****	**0.5***
C:N ratio	**−0.64****	**−0.56****	**−0.53***	**−0.61****	−0.01	−0.19	−0.28	−0.13

Note: All the significant correlations indicated in bold. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$. $n = 20$. L: litter layer; F: fermentation layer; H: humified layer

mass was positively correlated by soil N mineralization rate and was not correlated with soil nitrification rate. Both soil N mineralization and nitrification positively correlated with average N concentration of forest floor. The average C:N ratio of the forest floor showed a negative correlation with soil N mineralization and no correlation with soil nitrification rate (Table 6). For the different layers, there were no consistent relationships between soil N mineralization and nitrification rates and forest floor properties (Table 6).

Discussion

Interactive effects of forest type and seasonality on soil N mineralization and nitrification

The five forests in this study are considered to have similar community structure and soil conditions in the history (Song and Chen 2007). As such, differences in present soil N mineralization and nitrification rates are assumed to be the result of the forest conversion and site management practices (Yan et al. 2007). Differences between the EBLF and the SS soils may reflect the impacts of the repeated cutting and the shifts in plant species composition (Song and Chen 2007; Yan et al. 2007), the ensuing difference in the quality of organic matter input, and changes in microclimate (Song and Chen 2007; Yan et al. 2008). The larger differences of soil N mineralization and nitrification among native forests (i.e. EBLF), secondary shrubs and plantations (i.e. CFP, BP and WG) may reflect the different extents of historical biomass N removing (Yan et al. 2007) and subsequent changes of ecosystem structure and function such as soil erosion (Dai et al. 2007; Song and Chen 2007; Yan et al. 2007), as well as the effect of closed and open canopy on soil temperature (Song and Chen 2007). Although the species composition and forest management history varied considerably, soil nitrification rates did not differ among three plantations, which may reflect the same degraded condition of these artificial ecosystems due to the intensive disturbances (i.e. slash- and-burn) that received during the establishment of plantations (Yan et al. 2007). The different soil N mineralization between BP and other two plantations (i.e. CFP and WG) may reflect the different forest management practices in BP (Yan et al. 2007). The N fertilization that BP receives every year (53 kg-N ha^{-1}), may be responsible for improving soil N mineralization rate.

Soil N transformations involve biological processes that are temperature and moisture dependent (Dalias et al. 2002; Knoepp and Swank 2002). In our study, the forests showed remarkable seasonal dynamics for soil N mineralization and nitrification rates. The rapid increase of soil N transformation rates in summer (i.e. higher temperatures and moistures), and the rapid decrease in winter (i.e. lower temperatures and moistures) can be explained by the altered temperature and water availability among different seasons, which directly control soil microbial activity (Nicolardot et al. 1994; Stark and Firestone 1996; Nicolardot et al. 2001). Consequently, the results in this study suggest that forest types and seasonality could interactively affect soil N mineralization and nitrification rates when forest conversion developed in this region.

Effects of soil and forest floor properties on soil N mineralization and nitrification

Soil N cycling in forest ecosystems is influenced by soil properties and the quality of organic matter input (Prescott 1996; Hart et al. 1997; Finzi et al. 1998; Compton and Boone 2002; Grenon et al. 2004). These factors are likely to change during forest conversion (or land-use change) (Mladenoff 1987; Lovett and Rueth 1999; Verchot et al. 2001). Our results showed that surface soil and forest floor properties varied considerably during the forest conversion of EBLF to SS, CFP, BP and WG. Generally, soil bulk density, soil pH and soil and forest floor C:N ratios increased, whereas soil total N, soil total C, and forest floor mass and total N decreased (Tables 1, 2). We suggest that soil and forest floor properties play important roles in regulating soil N transformation during forest conversion.

Soil bulk density was negatively correlated with both soil N mineralization and nitrification, suggesting that soil N transformation rate was reduced with the increase of soil compaction during the forest conversion of native EBLF to plantations. The strongly negative relationship between soil pH and soil N mineralization suggests that pH may be responsible for the decrease in soil N mineralization in the plantations. Lower soil organic C and N in the plantations and the secondary shrubs, together with the positive correlation between soil total C (and N) and soil N mineralization and nitrification indicated that the decline of soil C and N was the main factor to decrease the rate of soil N transformation in these forests.

Differences in soil N mineralization and nitrification following forest conversion can be attributed to the altered soil properties and soil microbial community (Verchot et al. 2001; Ross et al. 2004; Ste-Marie and Houle 2006). In the present study, secondary shrubs exhibited a particularly low soil nitrification rate when comparing with the other three plantations (Table 3; Figs. 1, 2), which may result from the specific soil nitrification process in SS. Because soil nitrification is directly controlled by the availability of soil ammonium, soil ammonification and the fate of soil ammonium are the most important factors in determining soil nitrification rate. In secondary shrubs, soil N mineralization rate was highest, but soil ammonium concentration and soil nitrification rate were lowest, suggesting that soil ammonium was a critical factor in reducing soil nitrification. The most convincing explanation of this was due to the intensive N competition between plant uptake and immobilization by soil microbes. This can be demonstrated by exploring the patterns of soil N mineralization rate and soil ammonium concentration in SS. When the soil core was incubated in situ and the effects of plant uptake were eliminated, the higher soil net N mineralization indicated the abundant remains of ammonium following immobilization by soil microbes. This result indicates that the decrease in soil nitrification may mainly result from the lower availability of ammonium due to the exhaustion of ammonium by the rapidly-growing plants, which are often the initial colonists in secondary shrubs. Therefore, the shifts in plant species composition during forest conversion are crucial in affecting soil N mineralization and nitrification.

Changes of forest composition during forest conversion can affect soil N transformation through changes in litter quality and quantity (Finzi et al. 1998; Ferrari 1999; Ollinger et al. 2002). For instance, some studies have documented significantly higher soil N mineralization rates in broad-leaved-dominated forests compared to coniferous-dominated forests (Gower and Son 1992; Prescott and Preston 1994; Prescott 1996; Thomas and Prescott 2000). In our study, when native EBLF was transformed to secondary shrubs and plantations, the proportion of evergreen broad-leaved species was significantly replaced by canopy species with coniferous and (or) monoculture of single species. Due to the differences of nitrogen use strategies and litter decomposition of these species (Yan et al. 2006; Huang et al. 2007), the amount of N returned to soil was different. For example, the conservative nitrogen use strategies and the higher C:N ratio in litter of *C. lanceolata*, *P. pubescens*, *M. rubra* and *P. massoniana* (Yan et al. 2006, 2007, unpublished data) contribute to the accumulation of the forest floor and poor soil N in forests dominated by these species (i.e. CFP, BP, WG plantations and SS). As a result, the lower N litter would significantly reduce soil N mineralization and nitrification (Binkley and Valentine 1991; Rhoades and Coleman 1999; Grunzweig et al. 2003; Burns and Murdoch 2005). Furthermore, correlation analysis demonstrated that soil N mineralization and nitrification positively correlated with total N and negatively correlated with C:N ratio of the forest floor (Table 6). This result suggested that there was higher N concentration in the forest floor and more rapid N mineralization and nitrification in soils, indicating that decreasing total N in the forest floor leads to the lower soil N mineralization and nitrification during forest conversion from native EBLF to plantations and secondary shrubs. These results are consistent with previous studies (Piccolo et al. 1994; Reiners et al. 1994; Neill et al. 1997, 1999; Verchot et al. 1999; Goodale and Aber 2001).

Overall, the factors that reduced soil N mineralization and nitrification in secondary shrubs and plantations could be summarized as: (1) large biomass N removal in the past (Song and Chen 2007; Yan et al. 2007); (2) the considerable shifts of canopy species and the subsequently changes of litter quality in forest floor (Yan et al. 2008); (3) the altered soil physical characteristics such as soil compaction and habitat aridity, and chemical properties (i.e. N and C stocks), as well as biological characteristics (i.e. microbial structure) (Dai et al. 2007; Yan et al. 2007; Song and Chen 2007); and (4) the enhanced N loss through leaching (Song and Chen 2007).

Conclusion

During forest conversion from evergreen broad-leaved forest to secondary shrubs and plantations, soil N mineralization rate was highest in the native evergreen broad-leaved forest and lowest in the Chinese fir plantations; soil nitrification rate was also highest in the native forest, but lowest in secondary shrubs. We concluded that there was a significant decline in soil N mineralization and nitrification under forest conversion, and evergreen broad-leaved forests play important roles in sustaining soil N storage and cycling in the subtropical area of Eastern China. However, these forests have been dramatically transformed to the secondary shrubs and plantations in China. Due to their importance in both the N biogeochemical cycling and the sustainable development of the subtropical regions of China, the conservation of remnant forests and the restoration of secondary shrubs to evergreen broad-leaved forest are urgently required.

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