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論　文（Original article）

Variation in nitrogen status indices among forest types within the Yahagi River watershed, central Japan

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Abstract

We report N status indices for surface mineral soils and related physicochemical soil properties in three major forest types of differing geomorphology (natural forests, conifer plantations, and secondary forests) within the Yahagi watershed, central Japan. N status indices include in situ N status indices (total and inorganic [NH_4^+-N and NO_3^--N] N concentrations) and potential N transformation indices measured using aerobic laboratory incubations at 30ºC for 4 weeks (net N mineralization, ammonification, and nitrification). The N status and soil property datasets are included with the baseline dataset for future use in studies of spatial and temporal variation in the nitrogen cycle. Average N status indices were highest in natural forests, intermediate in conifer plantations, and lowest in secondary forests. Net nitrification potential differed clearly among forest types. Within natural forests, net nitrification potential was higher in moderately moist brown forest soil than in dry brown forest soil. Similarly, net nitrification potential was higher in soil samples from *Fagus crenata* stands than from *Quercus crispula* stands. The two soil types differed in C:N ratio and pH, whereas those from stands of the two dominant tree species differed in soil moisture conditions. Conifer plantations had relatively high variation in the depth of the A layer and in the maximum water-holding capacity. The large variation in the depth of the A layer creates difficulty in quantitatively evaluating the N cycle based on area. Secondary forests appeared to be consistently associated with dry soil and varied greatly in C:N ratio.

Key words : Forest mineral soil, laboratory incubation method, nitrification, nitrogen cycle, nitrogen mineralization, physicochemical soil property, regional scale.

1.INTRODUCTION

Increases in nitrogen (N) emission and deposition have occurred in industrialized regions of the Northern Hemisphere over the past century (Galloway *et al*., 1994). Increased N deposition affects belowground N cycling (Barnard *et al*., 2005) and affects forest ecosystems primarily through N saturation, resulting in the release of significant amounts of N into groundwater (Vitousek *et al*., 1997; Aber *et al*., 1998; Fenn *et al*., 1998). The onset of N saturation, marked by high nitrate concentrations in stream waters, suggest that Japan is experiencing high rates of N deposition (>10 kg ha^{-1} $year^{-1}$; Mitchell *et al*., 1997; Ohrui & Mitchell, 1997; Acid deposition and oxidant research center, 1999).

The Yahagi River runs through three prefectures in central Japan: Nagano, Gifu, and Aichi (Fig. 1a). The watershed covers 1830 km^2, 74% of which is forested area. The forested area can be generally divided into three forest types: natural forests at the headwaters; conifer plantations in the middle reaches; and secondary forests in the lower reaches. There is a major industrial area in Japan in the western portion of the watershed. The prevailing westerly winds carry anthropogenic N from the western source area into the eastern forested area. Therefore, nitrogen saturation of the Yahagi watershed forest ecosystem might occur due to N deposition originating from the industrial area , located in the western portion of the watershed as well as suggested in the Kanto plain region (Ohrui & Mitchell, 1997). It is predicted that N deposition originating from continental Asia will increase in this area in the future (Galloway *et al*., 1998; Bouwman & Vuuren, 1999).

The relationships between soil processes and nitrogen availability have been well documented (Gundersen *et al*., 1998). Increased N deposition is proposed to change these processes in several ways. First, it would cause a change in the lignin:N ratio in leaves, followed by a change in the C:N ratio in the forest floor, which might affect N mineralization and nitrification. These changes would then result in increased N export (McNulty *et al*., 1991; McNulty *et al*., 1996). Increased N mineralization and nitrification are the most important outward signs indicating the possible excess of N leaching into groundwater.

Net N mineralization and net nitrification measured using aerobic soil incubations in the laboratory have been widely

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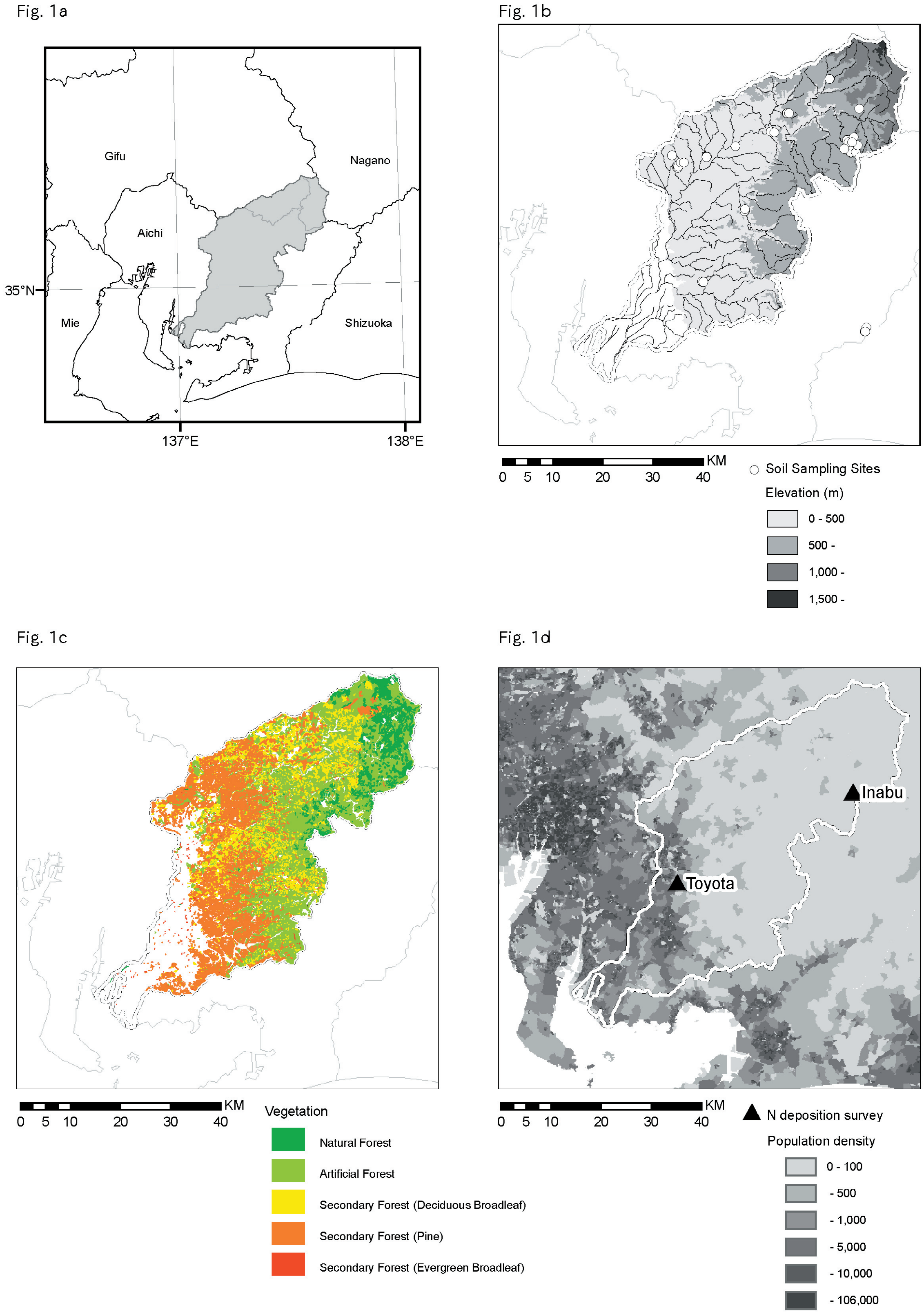

Fig. 1. The Yahagi River watershed and study sites. (a) Regional location of the watershed. Grey shading indicates the Yahagi watershed. (b) Soil sampling points and digital elevation model. Double white lines and black lines indicate the Yahagi watershed and streams of the Yahagi River, respectively. (c) Forested areas and the distribution of forest types. Colored areas and white area in the watershed indicate forested areas and non-forested area, respectively. Natural forests occur at the headwaters, conifer plantations in the middle reaches, and secondary forests in the lower reaches. (d) Population density (persons km^{-2}) in 2000 in and around the Yahagi watershed. Double white lines indicate the Yahagi watershed. Triangles indicate locations of N deposition survey points.

used as an index of N status; these correlate significantly and positively with ecological properties such as net primary productivity in forest ecosystems (Zak *et al*., 1994; Fernandez *et al*., 2000; Ross *et al*., 2004). The main advantage of the laboratory incubation method is that it is possible to make spatial comparisons of soil N availability under comparable environmental conditions (Vitousek *et al*., 1982). Numerous studies using laboratory incubation methods have been conducted in Japan in order to provide a relative index of N status in forest soils. However, incubation conditions such as temperature, soil moisture, and the duration of incubation varied among the studies (Hirai *et al*., 2006). Therefore, Hirai *et al*., (2006) proposed that N mineralization rates should be measured under Japanese standard conditions, i.e., at 30°C for 4 weeks.

It is in this context that we investigated in situ N status indices and potential N transformation indices measured using aerobic laboratory incubations in surface mineral soils from the Yahagi watershed. Our main objective was to compare N status indices and related physicochemical properties among three forest types differing in geomorphology: natural forests, conifer plantations, and secondary forests.

2. METHODS

2.1. Study sites

The Yahagi River runs through three prefectures in central Japan: Nagano, Gifu, and Aichi (Fig. 1a). The main channel is 117 km long. The elevation of the watershed is between 0 and 1908 m (Fig. 1b). The watershed covers 1830 km^2, which is a typical size for watersheds of class A rivers in Japan (Ministry of land, infrastructure and transport government of Japan). Forested area covers 74% of the Yahagi watershed (1354 km^2; Fig. 1c). The annual mean precipitation in the Yahagi watershed is 1654 mm, with two peaks in precipitation: in July (the rainy season) and in September (the typhoon season). Precipitation and temperature gradually change along the river with changes in elevation. The annual mean precipitation is approximately 2000 mm at the upper reaches, 1600 mm in the middle reaches, and 1400 mm in the lower reaches. The annual mean temperature is 11°C in the upper reaches and 15°C in the lower reaches.

Table 1. Regional distribution of three major forest types in the Yahagi watershed.

Forest Type / Subtype	Elevation (m, a.s.l) average	SD	max.	min.	Area (km^2)
Natural Forest	1052	194	1909	1	97
Conifer Plantation	629	290	1861	9	686
Secondary Forest					
Broadleaved Deciduous	430	242	1496	8	204
Conifer Evergreen (Pine)	277	192	1324	3	355
Broadleaved Evergreen	162	151	717	0	8

The Yahagi watershed has topography that is typical of watersheds in central Japan: the upper reaches are forested, the middle reaches contain agricultural land, and the lower reaches contain urban and industrial areas (Fig. 1d). Vegetation changes along the river (J-IBIS; Fig. 1c, Table 1). At the headwaters are natural forests mainly dominated by *Fagus crenata* (Japanese beech) and *Quercus crispula* (Japanese oak). Natural forests comprise 7% of the forested area. In the middle reaches are plantations of *Cryptomeria japonica* (Japanese cedar) and *Chamaecyparis obtusa* (hinoki cypress), as well as occasional *Pinus densiflora* (Japanese red pine) planted on the upper valley side and Larix kaempferi (Japanese larch) planted at high elevations. These conifer plantations comprise 51% of the forested area. In the lower reaches are young secondary forests (<40 years old), which comprise 42% of the forested area. The secondary forests are dominated by deciduous broadleaved trees such as *Quercus serrata* (konara oak; 15%), and by evergreen conifer trees such as *Pinus densiflora* or *Pinus thunbergii* (Japanese black pine), which were planted to prevent soil erosion (26%), or evergreen broadleaved trees such as *Quercus glauca* (arakashi oak; 1%). The soil type also changes along the river (Ministry of Land, Infrastructure and Transport, Government of Japan, Kokudo suuchi jyoho; http://nlftp.mlit.go.jp/ksj/). At the headwaters, moderately moist brown forest soil (B_D), as defined by the Forest Soil Division (1976), comprises 26% of the forested area. In the middle reaches, mainly dry brown forest soil (B_B) comprises 35% of the forested area. Both soil types appear in both areas along a single elevation gradient. In the lower reaches, dry yellowish brown forest soil (yB_A) and reddish brown forest soil (rB_B) comprise 20% and 6%, respectively, of the forested area. Granite is found throughout the forested areas of the Yahagi watershed, except in the southwest section, which is covered by metamorphic rock. In the lower reaches, some alluvial plains are covered by sedimentary rock. More detailed information about the Yahagi watershed and readily available GIS data are reported elsewhere (Ito *et al*., 2004).

Severe social and environmental effects of excess N leaching resulting from N saturation in the Yahagi watershed are possible due to the decreased quality of drinking water provided to the 1.4 million people living in the Yahagi and neighboring watersheds and the eutrophication of Mikawa bay, into which the Yahagi River flows. The Yahagi watershed borders large cities with high population densities (Nagoya and Toyota) and one of the major industrial areas in Japan (Chubu industrial area to the west). High nitrate concentrations (>0.6 mg NO_3^--N L^{-1}) are not commonly found in streams of the Yahagi watershed (Takenaka, Nagoya University, personal communication) or in many other Japanese watersheds (Kato *et al*., 1999; Shibata *et al*., 2001). However, the Yahagi watershed forests receive a considerable amount of atmospheric N deposition. Secondary forests near urban areas (Fig. 1d, Toyota) receive 16.0 kg N ha^{-1} in 10 months (January to October), whereas artificial forests in the upper reaches (Fig. 1d, Inabu) receive about 4.6 kg N ha^{-1} in 8 months (April to November; Takenaka, Nagoya University, personal communication). These values may exceed the 10 kg N ha^{-1} $year^{-1}$ that is considered the deposition threshold, beyond which N leaching occurs, in Europe (Dise & Wright, 1995).

2.2. Soil sampling

We sampled forest surface soil at 56 locations, designed to encompass all occurring combinations of soil type and dominant tree species in each forest type (Table 2). Surface mineral soil samples (0–5 cm in depth) were collected at 50 sites in the center of the forests, and six samples in which the parent material was metamorphic rock were collected in the center of the forests in a neighboring watershed (Table 3, Location). Sampling sites ranged from 132 to 1192 m in elevation, covering 55% of the vertical range of the watershed (Fig. 1b). Samples were taken between 2 and 6 August 2004 to exclude seasonal variation in the quality and/or quantity of soil organic matter or in the diversity and/or biomass of soil microorganisms. The sampling season was in mid-summer, when there was generally little rain, although heavy rains fell occasionally (Table 3, Rain conditions). After the removal of leaf litter (the A_0 horizon), mineral soil was collected from between 0 and 5 cm in depth and kept cool during transport to the laboratory. Three 100-mL soil cores were collected at each site and mixed thoroughly in a PVC bag by hand. The mixed soil samples were used for laboratory incubations and measurements of physicochemical soil properties, except for bulk density, bulk density of fine soil, and depth of the A layer. An additional 100-mL soil core was collected in each site to determine bulk density and bulk density of fine soil.

Table 2. Soil sampling matrix relating soil types and dominant tree species.

Forest Type	Soil type	Pd	Qg	Qs	Cj	Co	Lk	Fc	Qc	Total
		Dominant tree species[a]								
Natural Forest	B_B								2	2
	B_D							3	2	5
	Total							3	4	7
Conifer Plantation	B_B	2			2	4	2			10
	B_D				8	4	3			15
	rB_B					1				1
	yB_A				1	1				2
	Total	2			11	10	5			28
Secondary Forest	B_B	1		3						4
	B_D			1						1
	rB_B			1						1
	yB_A	5	1	9						15
	Total	6	1	14						21

[a]Pd, *Pinus densiflora*; Qg, *Quercus glauca*; Qs, *Quercus serrata*; Cj, *Cryptomeria japonica*; Co, *Chamaecyparis obtusa*; Lk, *Larix kaempferi*; Fc, *Fagus crenata*; Qc, *Quercus crispula*.

2.3. Geomorphological properties

We measured several geomorphological properties at each soil sampling point as a baseline dataset: elevation, slope, aspect, geomorphic unit on a subdetailed scale (hereafter, geomorphic unit), parent material, soil type, dominant tree species (hereafter, dominant species), and vegetation type (Table 3). Elevation was measured using a GPS (GPS V, Garmin Ltd.) and confirmed using topographical maps. Slope and aspect were measured at each site using a hand-held clinometer and a compass, respectively. We assigned geomorphic unit and soil type according to the classifications of Tamura & Yoshinaga (1995) and Forest Soil Division (1976), respectively.

2.4. Physicochemical soil properties

We obtained several key physicochemical soil properties related to N cycling: total C, C:N ratio, soil pH, bulk density of fine soil, depth of the A layer, three gravimetric indices of water condition, and rock mass (Appendix I). Total C was determined using an NC analyzer (Sumigraph NC-22F, Sumika Chemical Analysis Service, Ltd.). Total N was also determined using an NC analyzer to calculate C:N ratio. C:N ratio was calculated as total C divided by total N. Soil pH was determined by creating a slurry (soil mixed with 1 M KCl at a ratio of 1:2.5) and measuring its pH using a glass electrode. To determine bulk density of fine soil, a subsample of 100-mL was dried in an oven at 105°C. The subsample was then divided into fine soil, coarse gravel, and roots, and weighed. Bulk density of fine soil is defined as the weight of fine soil per unit volume, including the pore space, but excluding the root and rock space (Mg m^{-3}). Bulk density of fine soil has traditionally been used in forest soil studies in Japan. To obtain the root and rock space, we converted the dry weight of roots and rocks into volume assuming that the specific gravities of roots and rocks were 1.56 and 2.70, respectively, and that the water content of fresh roots was 63% (Kawata & Kojima, 1979). Rock mass defined as gravimetric rock abundance by soil volume (Mg m^{-3}) was also calculated.

To measure the water condition of the soil samples, separate 10-g soil samples were saturated with distilled water and then dried at 105°C, after weighing at each step. We calculated two gravimetric indices of water condition: water content mass ratio (WCMR), calculated as the weight of water in a sample divided by the weight of the fresh soil sample (kg water kg fresh $soil^{-1}$); and maximum water-holding capacity (MWHC), calculated as the weight of the water in a water-saturated sample divided by the weight of the fresh soil sample (kg water kg fresh $soil^{-1}$). We then calculated a third index of

Table 3. Location, previous precipitation, and geomorphological properties of sampling sites.

Site No.	Sampling Date (2004)	Location[a]		Rain condition[b]		Geomorphologic properties							
		N. Lat.	E. Long.	Duration of no precip.	Previous precip.	Elev.	Slope	Aspect	Geomorphic units[c]	Parent material[d]	Soil type[e]	Dominant species[f]	Vegetation type[g]
1	8/2	34.963	137.253	0	45	232	7	NE	Cr	Gr	yB_A	Qs	S
2	8/2	34.963	137.253	0	45	225	25	N	Lvs	Gr	yB_A	Qs	S
3	8/2	34.963	137.253	0	45	214	22	N	Vh	Gr	yB_A	Qs	S
4	8/2	34.964	137.253	0	45	199	6	N	Vf	Gr	yB_A	Qs	S
5	8/2	34.963	137.255	0	45	242	5	W	Cr	Gr	yB_A	Pd	S
6	8/2	35.091	137.345	0	10	518	30	N	Lvs	Gr	B_B	Co	C
7	8/2	35.090	137.344	0	10	522	21	SW	Cr	Gr	B_B	Pd	S
8	8/2	35.091	137.345	0	10	529	4	W	Vh	Gr	BD	Cj	C
9	8/3	35.188	137.260	1	10	160	33	E	Cr	Gr	yB_A	Qs	S
10	8/3	35.188	137.260	1	10	140	36	E	Lvs	Gr	yB_A	Qs	S
11	8/3	35.187	137.259	1	10	143	3	S	Vf	Gr	yB_A	Pd	S
12	8/3	35.167	137.195	1	10	139	4	E	Uvs	Se	yB_A	Pd	S
13	8/3	35.167	137.197	1	10	132	2	SW	Cr	Se	yB_A	Pd	S
14	8/3	35.167	137.197	1	10	134	15	SW	Lvs	Se	yB_A	Pd	S
15	8/3	35.170	137.198	1	10	143	6	S	Uvs	Se	yB_A	Qg	S
16	8/3	35.177	137.203	1	10	172	13	NE	Vh	Se	yB_A	Qs	S
17	8/3	35.177	137.203	1	10	166	22	NE	Lvs	Se	yB_A	Qs	S
18	8/3	35.176	137.203	1	10	189	12	N	Cr	Se	yB_A	Qs	S
19	8/3	35.189	137.184	1	10	222	38	NE	Lvs	Gr	yB_A	Co	C
20	8/3	35.189	137.184	1	10	202	0	S	Vf	Gr	yB_A	Cj	C
21	8/4	35.207	137.322	2	16	281	43	SW	Lvs	Gr	B_B	Cj	C
22	8/4	35.234	137.400	2	16	525	15	E	Lvs	Gr	B_B	Cj	C
23	8/4	35.234	137.400	2	16	525	36	NE	Lvs	Gr	B_B	Co	C
24	8/4	35.234	137.399	2	16	523	23	W	Lvs	Gr	B_B	Pd	S
25	8/4	35.233	137.399	2	16	475	42	S	Lvs	Gr	B_B	Qs	S
26	8/4	35.267	137.434	2	16	623	26	E	Cr	Gr	B_B	Qs	S
27	8/4	35.267	137.434	2	16	611	40	E	Cr	Gr	B_B	Qs	S
28	8/4	35.267	137.434	2	16	576	35	E	Lvs	Gr	B_B	Co	C
29	8/4	35.267	137.435	2	16	641	33	E	Lvs	Gr	B_D	Cj	C
30	8/4	35.331	137.528	2	16	642	46	SE	Lvs	Gr	B_D	Cj	C
31	8/4	35.331	137.527	2	16	625	30	SE	Lvs	Gr	B_B	Co	C
32	8/4	35.277	137.586	2	16	752	38	NE	Lvs	Gr	B_D	Cj	C
33	8/5	35.198	137.575	3	7	1149	17	S	Vh	Gr	B_D	Fc	N
34	8/5	35.198	137.575	3	7	1192	21	SE	Lvs	Gr	B_D	Fc	N
35	8/5	35.198	137.575	3	7	1143	8	SE	Cr	Gr	B_D	Fc	N
36	8/5	35.199	137.576	3	7	1173	20	NW	Cr	Gr	B_D	Co	C
37	8/5	35.199	137.576	3	7	1137	28	NW	Lvs	Gr	B_D	Co	C
38	8/5	35.199	137.575	3	7	1158	15	W	Vh	Gr	B_D	Cj	C
39	8/5	35.210	137.574	3	7	1078	23	S	Vh	Gr	B_D	Co	C
40	8/5	35.211	137.574	3	7	1094	20	SE	Lvs	Gr	B_B	Pd	S
41	8/5	35.211	137.575	3	7	1104	20	S	Vh	Gr	B_D	Lk	C
42	8/5	35.211	137.575	3	7	1103	13	SE	Cr	Gr	B_B	Lk	C
43	8/5	35.220	137.566	3	7	1042	12	E	Cr	Gr	B_B	Qc	N
44	8/5	35.220	137.566	3	7	1021	26	S	Lvs	Gr	B_B	Qc	N
45	8/5	35.220	137.567	3	7	1027	24	S	Vh	Gr	B_D	Qc	N
46	8/5	35.216	137.570	3	7	1036	14	NE	Cr	Gr	B_B	Lk	C
47	8/5	35.216	137.570	3	7	1041	36	NE	Lvs	Gr	B_D	Lk	C
48	8/5	35.216	137.570	3	7	1050	16	N	Vh	Gr	B_D	Lk	C
49	8/5	35.216	137.571	3	7	1024	18	NE	Vf	Gr	B_D	Qc	N
50	8/6	35.205	137.568	4	4	958	18	NW	Vf	Gr	B_D	Cj	C
51	8/6	34.876	137.610	0	81	398	4	NE	Cr	Me	rB_B	Co	C
52	8/6	34.876	137.610	0	81	401	20	NE	Lvs	Me	B_D	Co	C
53	8/6	34.876	137.609	0	81	400	30	NE	Cr	Me	B_D	Cj	C
54	8/6	34.876	137.609	0	81	420	21	NW	Lvs	Me	B_D	Cj	C
55	8/6	34.883	137.613	0	81	289	17	E	Cr	Me	rB_B	Qs	S
56	8/6	34.883	137.613	0	81	290	13	NE	Uvs	Me	B_D	Qs	S

[a]WGS84. [b]Data were obtained for the nearest observation point from Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html). Duration of no precip. indicates days from the latest precipitation. Previous precip. indicates precipitation for the 10 days before soil sampling (mm). [c]Geomorphic units in subdetailed scale, Tamura and Yoshinaga (1995): Cr, Crest; Uvs, Upper valley side; Vh, Valley head; Lvs, Lower valley side; Vf, Valley floor. [d]Gr, Granite; Me, Metamorphic rock; Se, Sedimentary rock. [e]Forest Soil Division (1976): B_B, dry brown forest soil; B_D, moderately moist brown forest soil; yB_A, dry yellowish brown forest soil (loose granular structure type); rB_B, dry reddish brown forest soil (granular and nutty structure type). [f]Cj, *Cryptomeria japonica*; Co, *Chamaecyparis obtusa*; Fc, *Fagus crenata*; Lk, *Larix kaempferi*; Pd, *Pinus densiflora*; Qc, *Quercus crispula*; Qg, *Quercus glauca*; Qs, *Quercus serrata*. [g]C, Conifer plantation; N, Natural forest; S, Secondary forest.

Units: Duration of no precip., days; Previous precip., mm; Elev., m (a.s.l.); Slope, degrees.

Table 4. N status indices along the forest-type gradient.

	Natural Forest				Conifer Plantation				Secondary Forest				Levene test for equal variance
	Mean	SD	Range	CV	Mean	SD	Range	CV	Mean	SD	Range	CV	
in situ N status indices													
Total N	8.0 ^{a}	2.7	4.9 - 12.0	33.6	7.0 ^{a}	2.8	3.1 - 13.4	40.0	3.9 ^{b}	1.4	1.9 - 6.3	35.1	$p < 0.01$
Initial inorganic N concentration	25.2	15.5	9.9 - 54.9	61.5	23.3	9.3	8.1 - 39.7	39.8	20.5	17.5	10.6 - 90.4	85.3	*n.s.*
Initial NH_4^+-N	17.0 ^{a}	5.3	9.9 - 23.4	31.1	13.2 ^{ab}	6.1	5.5 - 31.1	46.2	10.3 ^{b}	3.4	6.1 - 17.5	32.6	*n.s.*
Initial NO_3^--N	8.1	11.1	0.0 - 31.5	136.3	10.2	6.9	0.2 - 24.2	67.7	10.2	16.2	0.4 - 77.2	159.1	*n.s.*
potential N transformation indices													
Net N mineralization	195.6 ^{a}	99.9	102.2 - 380.7	51.1	131.4 ^{b}	67.5	34.6 - 249.3	51.4	69.8 ^{c}	26.6	22.1 - 112.9	38.1	$p < 0.001$
Net ammonification	71.3	41.4	4.3 - 135.5	58.1	49.2	41.3	-1.5 - 138.1	84.0	41.8	26.2	-1.3 - 90.4	62.6	$p < 0.05$
Net nitrification	124.3 ^{a}	85.0	25.2 - 245.2	68.4	82.3 ^{a}	61.7	8.5 - 206.0	75.0	28.0 ^{b}	23.6	5.6 - 87.7	84.2	$p < 0.0001$

Means, ±SD, and ranges for each forest type are given. Potential N transformation indices are calculated based on three laboratory incubations. In each line, means data not share a common superscript letter are statistically different at P = 0.05 based on the Tukey HSD test for indices with no significant difference in SD among forest types by Levene test for equal variance, and based on the rank sums in Kruskal–Wallis non-parametric test for indices with significant difference in SD among forest types. In the Levene test column, *n.s* indicates no significant difference in variance among forest types.

Units: Total N, mg N g $soil^{-1}$; Initial concentrations of inorganic N, NH_4^+-N and NO_3^--N, mg N kg $soil^{-1}$; Net N mineralization, net ammonification and net nitrification, mg N kg $soil^{-1}$ 28day^{-1}.

Table 5. Physicochemical soil properties along the forest-type gradient.

	Natural Forest			Conifer Plantation			Secondary Forest			Levene test for equal variance
	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range	
Total C	129.8 ^{a}	52.1	61.8 - 197.7	122.9 ^{a}	47.7	41.8 - 217.2	75.3 ^{b}	36.1	32.9 - 158.8	*n.s.*
C:N ratio	16.0	2.9	12.7 - 20.9	17.6	2.3	13.5 - 23.5	19.2	5.0	12.9 - 30.6	$p < 0.01$
pH	3.56	0.25	3.19 - 3.89	3.66	0.47	2.96 - 5.17	3.49	0.51	2.59 - 4.53	*n.s.*
Bulk density of fine soil	0.38 ^{a}	0.09	0.27 - 0.53	0.45 ^{ab}	0.15	0.19 - 0.73	0.56 ^{b}	0.18	0.30 - 1.00	*n.s.*
Depth of A layer	12.0 ^{ab}	6.4	6 - 25	15.4 ^{a}	11.5	5 - 50	6.0 ^{b}	2.5	5 - 15	$p < 0.001$
WCMR	1.17 ^{a}	0.44	0.61 - 1.95	0.77 ^{b}	0.43	0.17 - 1.53	0.25 ^{c}	0.17	0.03 - 0.64	$p < 0.01$
MWHC	1.98 ^{a}	0.57	1.21 - 2.93	1.53 ^{a}	0.65	0.49 - 2.72	0.76 ^{b}	0.34	0.30 - 1.68	$p < 0.01$
WSR	0.58 ^{a}	0.07	0.50 - 0.67	0.47 ^{a}	0.10	0.26 - 0.66	0.30 ^{b}	0.12	0.10 - 0.56	*n.s.*

Units: Total C, mg C g $soil^{-1}$; C:N ratio, dimensionless; Bulk density of fine soil, Mg m^{-3}; Depth of A layer, cm; WCMR and MWHC, kg water kg dry $soil^{-1}$; WSR, dimensionless.

soil moisture status, i.e., the water saturation ratio (WSR), defined as WCMR/MWHC (no dimensions).

2.5. *In situ* N status indices and potential N transformation indices

We measured five N status indices in soils from each of the 56 sampling sites. We measured three *in situ* N status indices (total N, and initial NH_4^+-N and NO_3^--N concentrations) and two potential N transformation indices measured through laboratory incubations (net ammonification potential and net nitrification potential). Additionally, two derived indices were calculated: initial inorganic N concentration, given as the sum of initial NH_4^+-N and NO_3^--N concentrations; and net N mineralization potential, given as the sum of net ammonification and nitrification potential.

Total N (mg N g $soil^{-1}$) was determined using an NC analyzer, following the same procedure as used for measuring total C. Potential N transformation indices were determined using net nitrogen transformation rates during aerobic laboratory incubations. Coarse gravel, roots, and litter were removed from each soil sample by hand. About 5 g of each fresh soil sample was incubated in a glass beaker at 30° C for 4 weeks. The water content of the incubated soil was kept at about 60% of the maximum water capacity. Initial concentrations of inorganic N in the soil (NH_4^+ and NO_3^-) were determined before incubation. Soil samples were extracted with 50 mL of 2 M KCl. Ammonium and nitrate concentrations in the KCl extract were measured using a TN analyzer (TN-30/NN, Mitsubishi Chemical Co., Ltd.). Inorganic N content was also determined after incubation. Net N mineralization potential was calculated as the difference in inorganic N content before and after incubation. Net ammonification potential and net nitrification potential (mg N kg $soil^{-1}$ 28 $days^{-1}$) were calculated as the difference in NH_4-N and NO_3-N content before and after incubation, respectively (see Appendix II).

2.6. Statistical analyses

We used one-way ANOVA to test for differences among the three forest types in the N status indices and physicochemical soil properties. Tukey HSD tests were used to distinguish differences among forest types at $P < 0.05$. For all analyses, we used a Levene test for equal variances. For analyses of datasets that did not meet the criterion of equal variances, we used Kruskal-Wallis and Steel-Dwass non-parametric tests.

Pearson correlation analysis was used to examine relationships among physicochemical soil properties as necessary. Statistical analyses were performed using JMP 5.0.1a (SAS Institute Inc., 2003).

3. RESULTS AND DISCUSSION

3.1. Differences in N status indices among forest types

Because our soil sampling design aimed to cover all occurring combinations of soil type and dominant tree species in each forest type, the mean N status indices for each forest type obtained may be biased toward minor stands with particular combinations of soil type and dominant tree species. Therefore, comparing mean index values among forest types may not accurately reflect a quantitative understanding of the relationship between the index and forest type. However, we were able to examine general trends in the differences among forest types.

There were significant differences in total N, initial NH_4^+-N concentration, net mineralization potential, and net nitrification potential among forest types (Table 4). With the exception of initial NO_3^--N concentration, average N status indices were highest in natural forests, intermediate in conifer plantations, and lowest in secondary forests. Net nitrification potential showed a clear difference among forest types, with nitrification potential in natural forests 4.4 times that in secondary forests, and in conifer plantations 2.9 times that in secondary forests. Owing to this clear difference in net nitrification potential among forest types, there were significant differences in net mineralization potential for all pairs of forest types since there was no significant difference among forest types in net ammonification potential.

3.2. Differences in physicochemical soil properties among forest types

There were significant differences among forest types in total C, bulk density of fine soil, depth of the A layer, and the three gravimetric indices of water condition (Table 5). The trend in total C was similar to that observed in total N, with values highest in natural forests, intermediate in conifer plantations, and lowest in secondary forests (Tables 4, 5). There was no significant difference in the C:N ratio among forest types. However, relatively a high C:N ratio (>22) was occasionally observed in secondary forests, as discussed below. Relatively low pHs were observed in parts of secondary forests, although there was no difference among forest types. Soil samples with high C:N ratios were mostly coincident with those of low pH because pH was negatively correlated with C:N ratio ($r = -0.67$, $p < 0.0001$). This finding agrees with a previous study placing pH and C:N ratio in the same principal component, which primarily related to the regulation of nitrification (Hirobe *et al*., 1998).

There was a considerable variation in rock mass among soil samples (Appendix I). Due to the variation in rock mass, N status on an areal basis, added to N status on a soil mass basis, should be considered when evaluating N cycle quantitatively. Secondary forests had significantly higher bulk density of fine soil than did natural forests, and substantially higher bulk density of fine soil than did conifer plantations. Such a high bulk density of fine soil might affect the activity of soil microbes (White, 1997).

Significant differences among forest types were found in both WCMR and MWHC (Table 5). Soil moisture conditions were highest in natural forests, intermediate in conifer plantations, and lowest in secondary forests. The values of WCMR and MWHC in natural forests rarely overlapped those in secondary forests. These results indicate that there are distinct differences in soil moisture conditions between the two forest types, both *in situ* and under laboratory incubation. Such differences probably cause some differences in N status indices. Previous precipitation may cause considerable variation in the initial water conditions of soil samples, prior to laboratory incubation, through the effect of soil moisture on the activity and biomass of soil microbes (Kutsuna *et al*., 1988). There was considerable variation in previous precipitation across the sampling dates; precipitation in the 10 days prior to soil sampling ranged from 4 to 81 mm (Table 3). Nevertheless, there was no evident effect of previous precipitation on soil moisture conditions in this study.

3.3. Variation in N status indices and related soil properties within a single forest type

There were significant differences in the group sample variances of total N and all three potential N transformation indices (Table 4). Although natural forests showed the lowest coefficient of variation (CV) of net nitrification potential among forest types, there were clear divisions in net nitrification potential among soil types and dominant tree species. In natural forests, high net nitrification potential was found for B_D samples (88−245 mg N kg soil^{-1} 28 days^{-1}), which did not overlap with the lower values found for B_B samples (25−30 mg N kg soil^{-1} 28 days^{-1}; Table 3, Appendix II). Similarly, net nitrification potential differed between the two dominant tree species. High values were found for soil samples from beneath *Fagus crenata* (169−245 mg N kg soil^{-1} 28 days^{-1}), and they did not overlap with the lower values found for samples from beneath *Quercus crispula* (25−108 mg N kg soil^{-1} 28 days^{-1}). Furthermore, clear divisions in the C:N ratio and pH were seen between the two soil types (Table 3, Appendix I). The C:N ratio ranged from 18.7 to 20.9 in B_B samples and from 12.7 to 16.1 in B_D samples; pH ranged from 3.2 to 3.3 in B_B samples and from 3.5 to 3.9 in B_D samples. Similarly, a clear division in soil properties between samples from beneath the two dominant tree species was found in the soil moisture measures, particularly WSR. Hirobe *et al*. (1998) found that nitrification is primarily explained by the C:N ratio and pH, and residual variation in nitrification rates is explained by soil moisture conditions. It is interesting to note that we found that the first principal component (i.e., C:N ratio and pH) was directly associated with soil type, whereas the second principal component (i.e., soil moisture) was directly associated with the dominant tree species. Further studies are required to clarify the mechanisms underlying these two associations, i.e., soil type and C:N ratio and pH, and dominant tree species and soil moisture.

In conifer plantations, high net nitrification potential was found for samples of B_D soil (61−206 mg N kg soil^{-1} 28 days^{-1}; Table 3, Appendix II), and these values slightly overlapped with the lower values found for other soil types (B_B, yB_A, and rB_B, 14−66 mg N kg soil^{-1} 28 days^{-1}). A similar trend occurred in the C:N ratio (Table 3, Appendix I); that in B_D soil (mean ± SD, 16.4 ± 1.2) was significantly lower than that in the other soil types (19.1 ± 2.5; $p < 0.05$). Furthermore, the C:N ratio showed the highest single-correlation coefficient with net nitrification potential ($r = -0.65$, $p < 0.001$). In this way, the division in net nitrification potential among soil types seems to be explained by C:N ratio as well as the case in natural forests mentioned the above. On the other hand, conifer plantations showed a relatively high SD for MWHC, indicating that soil moisture conditions varied during laboratory incubations. Thus, soil moisture conditions also possibly contribute to variation in net nitrification potential within the conifer plantations added to the C:N ratio.

Mean net ammonification potential was lower in *Cryptomeria japonica* soil samples (13 mg N kg soil^{-1} 28 days^{-1}) than in soil samples from the other dominant tree species (*Larix kaempferi*, 94 mg N kg soil^{-1} 28 days^{-1}; *Pinus densiflora*, 65 mg N kg soil^{-1} 28 days^{-1}; *Chamaecyparis obtusa*, 62 mg N kg soil^{-1} 28 days^{-1}). A similar trend was not found for either net nitrification potential or soil properties. These results suggest that nitrification activity is promoted in soils from *Cryptomeria japonica* stands. The mechanisms resulting in accelerated nitrification activity in *Cryptomeria japonica* stands require further study.

Conifer plantations showed a relatively high CV for total N, indicating that the availability of organic N varied within the forest type (Table 4). Added to that, conifer plantations showed the largest variation in the depth of the A layer (Table 5). A very deep A layer (>25 cm) was occasionally observed in conifer forests (Appendix I). Such large variation in the depth of the A layer makes it difficult to quantitatively measure the N cycle on a per area basis, indicating the need for future study in this area.

Secondary forests showed the highest CV for net nitrification potential. Secondary forests showed the lowest variation in soil moisture conditions and depth of A layer among the forest types, which indicates that secondary forests are associated consistently with dry soil conditions and thin A layer, respectively. On the other hand, secondary forests showed a relatively large variation in the C:N ratio rather than the other forest types (Table 5). It suggests that the highest CV of net nitrification potential found in secondary forests due to the large variation in the C:N ratio. This insight is consistent with that the largest variation in the C:N ratio was found in secondary forests due to the particularly high C:N ratios (>22) of some samples (Table 5, Appendix I) in which nitrification rates were critically depressed (Ross *et al*., 2004). A high C:N ratio (>22) was associated with drier soil types (yB_A and B_B) and dominant tree species in secondary forests (*Quercus serrata* and *Pinus densiflora*), although not all samples collected from these soil types or dominant tree species had such high C:N ratios. High bulk density of fine soil (>0.8 Mg m^{-3}) was found in soils from secondary forests (Appendix I, site Nos. 2, 3, and 11). Soil samples with high bulk density of fine soil had relatively low values for most N status indices and intermediate values of net ammonification (Appendix II). These soil samples had a very low C:N ratio (<16) and a relatively high pH (3.76−4.22; Appendix I), which is inconsistent with findings from soils with low N status indices in previous studies (Chapin *et al*., 2002; Venterea *et al*., 2003). One possible explanation is that the high bulk density of fine soil lowered the N status indices through drier soil conditions, a secondary component regulating nitrification (Hirobe *et al*., 1998). This explanation is supported by negative correlations between bulk density of fine soil and WCMR ($r = -0.63$, $p < 0.0001$) and MWHC ($r = -0.71$, $p < 0.0001$).

For all three forest types, the CV of initial NO_3^--N concentration was larger than that of initial inorganic N concentration, and the CV of net nitrification potential was larger than that of net N mineralization potential, especially in secondary forests (Table 4). These results indicate that the *in situ* and potential nitrification indices vary more widely than do the N mineralization indices. This is consistent with the finding that nitrification rate shows a bimodal distribution during laboratory incubation in *Cryptomeria japonica* (Hirai *et al*., 2006). These results indicate that the N cycle in secondary forests varied most widely at the nitrification step, thus highlight the relative importance of nitrification in the inorganic N economy, which has been previously discussed by Booth *et al*. (2005). This insight suggests that nitrification is a key process in order to understand N cycles; therefore, in situ and/or potential nitrification rates are useful indices to evaluate regional variation in N leaching potential. In this context, our findings suggest several implications for further study area. Much attention should be paid to the high nitrification activity in *Cryptomeria japonica* stands, the considerable variation in the depth of the A layer in conifer plantations, and geomorphological and physicochemical soil conditions in which secondary forests show high nitrification activity when evaluating the likely consequences of continued N deposition on N cycles and their social and environmental impacts.

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矢作川流域の森林土壌における窒素無機化特性
－森林タイプによる比較－

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要 旨

本報では矢作川流域に分布する主要な３種類の森林タイプ（天然林・針葉樹人工林・二次林）における鉱質表層土壌 (0-5 cm) の窒素無機化に関する指標を、窒素循環に関係する土壌の理化学的特性値と併せて報告する。記載した窒素無機化に関する指標は、全窒素含有率、無機態窒素現存量、アンモニア態窒素現存量、硝酸態窒素現存量、室内培養法で測定した窒素無機化ポテンシャル、アンモニア態窒素生成ポテンシャル、硝化ポテンシャルの７項目である。室内培養においては一般的な培養条件である 30℃恒温条件下における４週間の培養とした。加えて、窒素動態研究の基礎的データベースとするため、付帯資料として土壌採取地の地勢的特性を記載した。窒素無機化に関する指標は天然林、針葉樹人工林、二次林の順に大きい傾向が認められ、特に硝化ポテンシャルで違いが著しかった。天然林における硝化ポテンシャルは B_D 型土壌で高く、B_B 型土壌で低い傾向が認められた。同様にブナ林で高く、ミズナラ林で低い傾向が認められた。土壌型の違いは C:N 比および pH と、優占樹種の違いは土壌水分指標の違いとそれぞれ関連が認められた。針葉樹人工林では A 層の深さと最大容水量に大きなばらつきが認められた。二次林では土壌が乾燥する傾向が一様に認められた。一方で C:N 比には大きなばらつきが認められた。

キーワード：窒素循環　室内培養　無機態窒素　硝酸態窒素　アンモニア態窒素　矢作川　土壌特性

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Appendix I. Physicochemical soil properties.

Site No.	Total C	C:N ratio	pH[a]	Bulk density of fine soil	Depth of A layer	WCMR[b]	MWHC[c]	WSR[d]	Rock mass[e]
1	98.5	16.9	3.85	0.68	5.0	0.257	0.813	0.316	0.06
2	39.8	13.9	3.99	1.00	5.0	0.283	0.687	0.412	0.02
3	32.9	12.9	4.22	0.92	5.0	0.307	0.666	0.462	0.17
4	79.8	14.5	4.53	0.54	5.0	0.543	0.968	0.561	0.18
5	58.4	13.9	3.60	0.63	5.0	0.390	1.012	0.385	0.08
6	130.3	19.9	3.47	0.47	22.0	0.668	1.429	0.468	0.09
7	102.6	22.3	3.29	0.47	11.0	0.513	1.191	0.431	0.04
8	114.1	18.8	4.19	0.58	31.0	0.592	1.048	0.565	0.10
9	36.1	19.2	3.77	0.53	5.0	0.063	0.478	0.132	0.44
10	40.6	20.6	3.57	0.55	5.0	0.035	0.299	0.116	0.58
11	54.3	15.6	3.76	0.87	15.0	0.053	0.513	0.103	0.20
12	67.4	17.9	3.77	0.56	5.0	0.195	0.749	0.260	0.17
13	158.8	27.2	2.59	0.30	5.0	0.132	0.890	0.148	0.20
14	152.2	25.4	2.69	0.37	5.0	0.179	0.909	0.197	0.26
15	34.0	13.3	3.61	0.48	5.0	0.194	0.794	0.244	0.34
16	71.7	19.5	3.26	0.48	5.0	0.144	0.469	0.306	0.49
17	92.5	25.5	2.98	0.39	5.0	0.155	0.437	0.355	0.13
18	89.9	23.0	2.84	0.49	5.0	0.156	0.433	0.360	0.48
19	73.3	21.1	3.55	0.58	5.0	0.171	0.492	0.348	0.06
20	57.0	16.0	3.57	0.73	5.0	0.241	0.709	0.341	0.16
21	41.8	13.5	5.17	0.72	8.5	0.274	0.669	0.409	0.14
22	59.2	18.5	3.35	0.73	16.0	0.356	0.831	0.429	0.09
23	62.5	20.4	3.51	0.54	7.0	0.235	0.918	0.256	0.15
24	91.0	23.5	3.14	0.55	6.0	0.230	0.814	0.283	0.14
25	47.8	19.4	3.80	0.63	6.0	0.091	0.315	0.289	0.28
26	98.4	30.6	2.78	0.46	8.0	0.140	0.678	0.206	0.07
27	56.0	18.8	3.49	0.46	5.5	0.234	0.849	0.276	0.14
28	136.4	21.0	3.45	0.41	33.0	0.481	1.153	0.417	0.14
29	134.4	19.0	3.38	0.43	28.0	0.579	1.472	0.393	0.19
30	72.9	15.3	4.61	0.55	18.0	0.283	0.782	0.361	0.21
31	162.9	18.1	3.95	0.32	50.0	0.765	1.815	0.421	0.04
32	119.4	16.9	4.52	0.51	40.0	0.520	1.174	0.443	0.23
33	107.7	13.5	3.89	0.43	6.0	1.201	1.924	0.624	0.03
34	164.7	16.1	3.53	0.34	11.0	1.485	2.269	0.655	0.02
35	183.5	15.3	3.50	0.27	9.0	1.948	2.926	0.666	0.01
36	213.5	16.0	3.35	0.31	10.0	1.528	2.323	0.658	0.03
37	162.9	16.0	3.61	0.28	17.0	1.423	2.721	0.523	0.03
38	159.9	15.2	3.69	0.32	15.0	1.388	2.144	0.648	0.03
39	196.8	17.6	3.45	0.34	14.0	0.975	1.873	0.521	0.04
40	169.6	18.5	3.37	0.28	7.0	1.481	2.575	0.575	0.02
41	152.2	16.2	3.35	0.30	12.0	1.275	2.296	0.555	0.00
42	217.2	19.1	2.96	0.19	7.0	1.162	2.630	0.442	0.00
43	197.7	20.9	3.33	0.38	25.0	0.831	1.511	0.550	0.01
44	107.4	18.7	3.19	0.28	13.0	1.131	2.262	0.500	0.01
45	85.6	15.1	3.85	0.44	13.0	0.980	1.759	0.557	0.02
46	143.1	19.0	3.50	0.28	15.0	1.379	2.309	0.597	0.01
47	85.9	15.3	3.64	0.49	14.0	0.710	1.292	0.549	0.02
48	122.5	15.8	3.47	0.41	9.0	0.848	1.534	0.552	0.08
49	61.8	12.7	3.61	0.53	7.0	0.606	1.212	0.500	0.05
50	146.9	15.9	3.55	0.36	5.0	0.975	1.816	0.537	0.01
51	145.9	19.8	3.54	0.38	15.0	0.807	1.757	0.460	0.11
52	86.5	16.9	3.50	0.51	12.0	0.682	1.454	0.469	0.05
53	100.3	15.4	3.83	0.46	5.0	0.796	1.638	0.486	0.02
54	83.3	15.3	3.83	0.58	5.0	0.624	1.155	0.541	0.10
55	109.4	17.3	3.38	0.33	5.0	0.639	1.682	0.380	0.20
56	60.5	15.1	3.62	0.56	5.0	0.485	1.224	0.396	0.19

[a]pH in 1 M KCl. Initial value before incubation. [b]water content mass ratio, kg water kg dry soil^{-1}. [c]maximum water holding capacity, kg water kg dry soil^{-1}. [d]water saturation ratio, ratio of water content mass to maximum water holding capacity. [e]Gravimetric rock abundance by soil volume.

Units: Total C, mg C g soil^{-1}; C:N ratio, dimensionless; Bulk density of fine soil, Mg m^{-3}; Depth of A layer, cm; WCMR and MWHC, kg water kg dry soil^{-1}; WSR, dimensionless; Rock mass, Mg m^{-3}.

Appendix II. N status indices.

		in situ N status indices			potential N transformation indices		
Site No.	Total N	Initial inorganic N concentration	Initial NH_4^+ concentration	Initial NO_3^- concentration	Net N mineralization	Net ammonification	Net nitrification
1	5.8	24.3	14.8	9.5	112.9	90.4	22.5
2	2.9	15.1	12.4	2.7	92.8	63.3	29.5
3	2.6	11.8	10.0	1.8	83.6	59.8	23.8
4	5.5	14.4	14.0	0.4	80.8	16.9	63.9
5	4.2	90.4	13.3	77.2	84.9	-1.3	86.1
6	6.5	28.0	13.9	14.1	95.4	68.2	27.2
7	4.6	26.6	15.4	11.3	88.1	67.8	20.3
8	6.1	13.5	12.6	0.9	107.5	-1.5	109.0
9	1.9	10.6	8.0	2.6	22.1	14.0	8.1
10	2.0	13.9	7.0	7.0	35.8	30.3	5.6
11	3.5	12.3	8.7	3.7	54.0	35.1	18.9
12	3.8	15.7	11.7	4.0	71.8	45.2	26.6
13	5.8	28.1	17.5	10.6	81.4	53.1	28.4
14	6.0	17.1	10.7	6.4	106.4	83.0	23.4
15	2.6	10.6	7.1	3.5	79.8	34.6	45.1
16	3.7	14.0	7.9	6.1	49.2	37.9	11.3
17	3.6	17.5	9.4	8.1	41.7	24.1	17.5
18	3.9	14.0	7.5	6.5	70.0	54.0	16.0
19	3.5	16.7	10.6	6.1	34.6	21.0	13.6
20	3.6	13.0	7.9	5.1	54.4	7.6	46.9
21	3.1	18.2	5.5	12.7	48.8	1.4	47.5
22	3.2	10.1	7.2	2.9	42.2	31.9	10.3
23	3.1	13.1	6.5	6.6	39.9	31.4	8.5
24	3.9	13.6	6.9	6.6	38.0	25.1	13.0
25	2.5	10.6	6.1	4.5	34.0	26.1	8.0
26	3.2	14.4	6.9	7.5	38.6	18.6	20.0
27	3.0	13.8	6.9	6.8	44.3	33.0	11.2
28	6.5	19.8	15.3	4.5	97.0	74.3	22.8
29	7.1	24.1	14.8	9.3	131.8	70.4	61.4
30	4.7	8.1	7.8	0.2	71.5	1.4	70.1
31	9.0	12.8	11.2	1.6	97.6	77.0	20.6
32	7.1	15.8	10.5	5.3	93.8	0.2	93.6
33	8.0	9.9	9.9	-	209.5	4.3	205.3
34	10.2	54.9	23.4	31.5	265.6	96.9	168.7
35	12.0	26.4	20.9	5.5	380.7	135.5	245.2
36	13.4	38.4	14.2	24.2	231.7	68.7	163.1
37	10.2	26.7	15.4	11.3	221.4	32.2	189.2
38	10.5	32.0	18.8	13.2	210.2	6.8	203.3
39	11.2	22.5	17.8	4.7	228.5	114.8	113.7
40	9.2	24.8	23.3	1.6	171.2	105.2	66.0
41	9.4	29.0	16.0	13.0	249.3	74.0	175.3
42	11.4	38.3	31.1	7.2	190.3	138.1	52.2
43	9.4	19.9	16.0	3.9	111.4	86.2	25.2
44	5.8	34.6	22.7	12.0	102.2	71.6	30.6
45	5.7	13.8	13.8	-	134.1	45.7	88.3
46	7.5	35.8	22.4	13.4	162.6	114.7	47.9
47	5.6	39.7	16.2	23.5	180.2	73.0	107.2
48	7.8	23.8	8.1	15.7	173.4	71.8	101.6
49	4.9	16.6	12.7	4.0	165.5	58.8	106.8
50	9.3	35.1	18.9	16.1	221.6	15.5	206.0
51	7.4	24.1	5.6	18.4	107.1	93.2	13.9
52	5.1	32.1	11.4	20.6	129.6	47.5	82.1
53	6.5	26.6	8.2	18.3	130.8	8.0	122.8
54	5.4	18.4	9.9	8.5	119.4	4.7	114.8
55	6.3	38.5	13.2	25.2	99.9	85.8	14.1
56	4.0	16.2	7.9	8.3	93.6	5.9	87.7

Units: Total N, mg N g soil^{-1}; Initial concentrations of inorganic N, NH_4^+-N and NO_3^--N, mg N kg soil^{-1}; Net N mineralization, net ammonification and net nitrification, mg N kg soil^{-1} 28day^{-1}.