Nutrient cycling in an Alpine tundra ecosystem on Changbai Mountain, Northeast China

Gang Wu, Jing Wei^{*}, Hongbing Deng, Jingzhu Zhao

*Key Lab of Systems Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences,
18 Shuangqing Road, Haidian District, Beijing 100085, PR China*

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Abstract

Nutrient availability regulates the responses of high-latitude ecosystems to climate change but nitrogen, phosphorus and sulfur biogeochemistry, especially, phosphorus and sulfur cycles, are poorly understood in Alpine tundra ecosystem. This study examines the cycling of nutrients in a 302-year-old Alpine tundra ecosystem in which litter has accumulated through compartment methods. Samples of the vegetation, litter and soil components were collected and chemically analyzed for nitrogen (N), phosphorus (P) and sulfur (S). Overall, nutrient budgets for N, P and S pool sizes were determined. Although there were large reserves of N (24,640 kg hm⁻²), P (5860 kg hm⁻²) and S (10,018.7 kg hm⁻²) in soil layers (0–20 cm), the nutrient reserves within the litter and fine roots within surface soil layer (0–10 cm) were well balanced, indicating that a tightly closed plant–litter–soil–plant nutrient cycle was in operation for the cycling of N, P and S. The litter helped the retention of as many nutrients as possible in Alpine tundra system.

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1. Introduction

Future temperature changes in high-latitude regions are believed to be larger than for any other part of the globe. Although such predictions have uncertainties, it is suggested that by 2080, Arctic regions will experience temperature increases of 4–7.5 °C in summer and 2.5–14 °C in winter (Sven

et al., 1999; Hagen et al., 2001). Understanding the response of high-latitude ecosystems to climate warming requires detailed information on soil nutrients, because despite the harsh climate, biological productivity is often limited by nutrient availability (Benjamin et al., 2004). Phosphorus is a primary limiting nutrient in high-latitude soils, although the degree of limitation varies markedly across the heterogeneous tundra landscape (Schmidt et al., 1999). For example, in the North American Arctic, net primary productivity in moist tussock tundra tends towards co-limitation by nitrogen and phosphorus,

^{*} Corresponding author. Tel.: +86 10 62849184;
fax: +86 10 62943822.

E-mail address: weijingrcees@126.com (J. Wei).

whereas wet sedge tundra is typically phosphorus-limited (Nadelhoffer et al., 2002). Mesic tundra sites, probably, tend towards nitrogen limitation, although the biological demand for phosphorus in all tundra environments is likely to be enhanced by the current low rates of reactive nitrogen deposition from the atmosphere (Gordon et al., 2001). In addition, there is increasing evidence that, for a number of forests, phosphorus is immobilized in the first stages of decomposition to a significantly greater extent than nitrogen. Furthermore, most plant nitrogen was tied into perennial, woody stems or coarse roots and contributed little to the annual cycling of nutrients between plants and soil (Jonasson et al., 1996).

The tundra landscape is characterized by a mosaic of wet, dry and mesic areas, which form in response to variations in topography, soils and hydrology. In Alpine tundra ecosystems, most organically bound nutrients were fixed in the soil and litter and a low proportion was in the plant biomass. For instance, the vegetation contained <35% of the ecosystem nitrogen pool, while the remaining 65% was fixed in the recalcitrant soil organic matter and in the litter in Swedish Arctic tundra. As in mesic dwarf shrub tundra and in *Betula*- and *Salix*-dominated shrub tundra, the percentage nitrogen in the soil plus litter increased to between 90 and 95% and hence, only $5 \pm 10\%$ of the ecosystem pool was incorporated in the plant biomass (Jonasson and Michelsen, 1996). Consequently, although these ecosystems often contain large pools of nutrients, these are tied into re-calcitrant soil organic matter or, when absorbed by plants, a high proportion is locked into tissue with a slow turnover. It is not surprising, therefore, that ecosystem productivity is generally nutrient-limited and that the dominant plants are mostly species or functional groups of low nutrient requirement or species with a conservative use of nutrients (Chapin et al., 1995). Across the Arctic tundra, numerous studies of plant community responses to experimental addition of nutrients have shown that both community productivity and plant species composition are sensitive to changes in the soil pools of plant available nutrients, mostly nitrogen and phosphorus. This suggests that any changes in the input or cycling of these nutrients, for instance, from air-borne pollutants or increased rate of nutrient mineralization caused by a predicted future warming of the Arctic (Cattle and Crossley, 1995), will change

the species composition and, most likely, increase plant productivity. Most studies of nutrient cycling in tundra ecosystems have either addressed questions of plant nutrient acquisition or of decomposition and mineralization processes, while few studies have attempted to integrate processes in both the soil and plant compartments. There is currently limited information on the nitrogen and phosphorus cycling of high-latitude regions. It is important to better understand nitrogen and phosphorus biogeochemistry and potential tundra ecosystem response to warming in such regions.

The aim of this research is to examine the nutrient (nitrogen, sulfur and phosphorus) dynamics and pools of Changbai Alpine tundra in which litter has accumulated. The nutrient dynamics of N, P and S within the system were examined, as N is regarded as most limiting in vegetation succession (Johannisson et al., 1999; Piatek and Allen, 1999). To establish a nutrient budget and cycling pattern within and between, the soil, litter and plant compartments for a high-middle altitude 303-year-old tundra vegetation the nutrient levels of aboveground, belowground components, litter and soil were measured. This could be to provide information for the effective management of the systems. The applied significance of the work is that annual bio-cycling pattern in tundra ecosystems is important for evaluating sustainable management of ecosystem and region.

2. Methods

2.1. Study site

The study site was located at altitudes from 1950 to 2650 m on northern slope of Changbai Mountain, Northeast China ($42^{\circ}24'N$, $128^{\circ}28'E$). The annual mean temperature in the area was $-7.4^{\circ}C$ and the sub-Alpine climate was affected by monsoon (Jiang et al., 2003). The annual precipitation was 900–1340 mm. The total tundra area was 15,195 hm^2 . The topographical, geomorphic and hydrological conditions had clear variation, resulting five soil types: peat Alpine tundra soil, meadow Alpine tundra soil, grey Alpine tundra soil, lithic Alpine tundra soil and cold desert Alpine tundra soil. The dominant plant communities were shrubs, herbaceous plants, moss,

lichen, etc. The dominant shrub species are *Dryas octopetala* var. *asiatica*, *Vaccinium jliginosum* var. *alpinum*, *Vaccinium vitis-idaea*, *Rhododendron confertissimum*, *Rhododendron chrysanthum*, *Phyllodoce caerulea*, *Vaccinium uliginosum*, etc.

2.2. Sampling

In August 2002 and 2003, at each vegetation type characterized with similar aboveground conditions, such as similar plant species composition and geomorphic and hydrological conditions, four transects were randomly allocated. There were four sample plots at each altitude along each transect at an interval of 100 m from 1950 to 2650 m of altitude. Each plot was sized 0.2 m × 0.2 m. Vegetation biomass (including roots) and litter biomass were collected with the harvest method at each plot. The soil bulk density were measured at the depths of 5 and 15 cm and the data of soil bulk densities, which were adjusted for stone content at each vegetation type. Four soil samples (>200 g), at each depth of 0–10 and 10–20 cm, were collected from each profile to analyze the content of nitrogen, phosphorus and sulfur. A total of 128 vegetation samples, 128 litter samples and 256 soil samples were measured each year.

2.3. Chemical analysis of vegetation, litter and soil components

The vegetation, litter and soil samples were put into sealed hop-pockets, respectively and kept at 4 °C until they were used to analyze the nutrients by standard procedures. These samples were analyzed for total nitrogen using Kjeldahl procedure followed by colorimetric analysis (Anderson and Ingram, 1989); for total, phosphorus and total sulfur using an inductive coupled plasma spectrometry (ICPS) after digestion with HNO₃/HClO₄. The precision of all measurements was 0.01 units. The average of soil bulk densities, nutrient concentrations and their standard deviations were used in this study.

2.4. Nutrient budget calculations

Using the mean nutrient values from Tables 1 and 2 and the biomass figures, it was possible to determine the size of the nutrient pools. The soil nutrient pools

(kg hm⁻²) were calculated using the following formula (Guo and Gifford, 2002):

$$P = 100 \times NC \times BD \times D \quad (1)$$

where NC is the nutrient concentration converted to g kg⁻¹; BD the bulk density in g cm⁻³ and *D* is the soil depth in cm. The soil depth measured at this site was 20 cm.

2.5. Data analysis

The nutrient concentrations of the different components were statistically analyzed. When significant differences were evident, multiple range tests of the least significant differences were conducted. All the analyses were performed with SPSS11.0, a computer statistics software package.

3. Results

3.1. Nutrient concentrations of vegetation components

Among the vegetation components, leaves had the highest concentration of N, P or S, with nitrogen being the major nutrient (Table 1). Although there were no significant differences in the concentration of either P or S among roots, stems and leaves for each vegetation type, the concentrations of P and S were at least 1.5–2 times higher in leaves or aboveground than in roots or belowground.

3.2. Nutrient concentrations of litter and soil

The litter had a relatively higher nutrient concentration than the soil (Tables 2 and 3). Litter N had higher concentrations than litter P or S. Significant differences in the distribution of N throughout the litter/soil layers were evident (*p* < 0.01), which can be attributed to the significantly lower nitrogen concentrations in soil layers than those found in the litter layers. No significant differences were found in the distribution of S between litter and soil layers, while there were significant differences in the distribution of P (*p* < 0.05) between litter and soil layers. The percentage of P in the litter of rocky tundra (RT) and typical tundra (TT) was significantly higher

Table 1

Nutrient concentrations of different parts in Alpine tundra on Changbai Mountain (g kg^{-1})

Vegetation type	Components	Total nitrogen	Total phosphorus	Total sulfur	Total
Rocky tundra	Belowground	2.91 ± 1.2	0.5 ± 0.2	2.2 ± 1.2	5.6 ± 0.5
	Aboveground	10.7 ± 7.8	1.3 ± 0.3	1.4 ± 0.2	13.4 ± 0.7
Stony tundra	Belowground	5.3 ± 1.4	2.7 ± 1.6	1.8 ± 0.8	9.8 ± 0.6
	Aboveground	15.2 ± 11.0	3.8 ± 4.3	1.3 ± 1.1	20.3 ± 1.0
	Root	5.5 ± 0.5	0.9 ± 0.4	1.0 ± 0.6	7.4 ± 0.2
Typical tundra	Stem	5.0 ± 2.3	0.9 ± 0.7	1.5 ± 1.0	7.4 ± 0.6
	Leave	8.2 ± 3.4	1.2 ± 0.9	2.0 ± 1.2	11.4 ± 0.9
	Root	3.6 ± 1.2	1.2 ± 0.8	0.8 ± 0.4	5.6 ± 0.3
Meadow tundra	Stem	2.7 ± 1.3	0.8 ± 0.3	1.7 ± 1.2	5.2 ± 0.7
	Leave	6.6 ± 2.1	1.2 ± 1.1	1.8 ± 0.9	9.6 ± 0.2
	Root	5.4 ± 2.3	0.5 ± 0.4	1.1 ± 0.7	7.2 ± 0.4
Swamp tundra	Stem	5.2 ± 1.3	0.7 ± 0.4	1.9 ± 1.1	7.8 ± 0.7
	Leave	5.6 ± 3.6	1.5 ± 1.1	1.9 ± 1.6	8.8 ± 0.2

Table 2

Litter nutrient distribution at different vegetation types

Vegetation type	Nitrogen		Phosphorus		Sulfur		Total (kg hm^{-2})
	Concentration (g kg^{-1})	Content (kg hm^{-2})	Concentration (g kg^{-1})	Content (kg hm^{-2})	Concentration (g kg^{-1})	Content (kg hm^{-2})	
Rocky tundra	8.1 ± 2.1	11.16	3.1 ± 1.1	4.27	0.8 ± 0.2	1.10	16.54
Stony tundra	3.5 ± 1.1	4.95	1.2 ± 0.4	1.71	0.7 ± 0.1	0.99	7.65
Typical tundra	4.8 ± 0.9	11.31	3.2 ± 1.4	7.54	1.9 ± 0.8	4.48	23.33
Meadow tundra	4.8 ± 2.1	10.34	1.3 ± 0.3	2.80	1.4 ± 0.3	3.02	16.16
Swamp tundra	3.3 ± 0.4	8.17	1.9 ± 0.9	4.70	2.2 ± 0.6	5.45	18.32
Total	4.9 (Average)	45.93	2.1 (Average)	21.02	1.4 (Average)	15.04	81.99

Fig. 1. The N cycle of Alpine tundra on Changbai Mountain in which litter has accumulated. Nutrient pools are in t N and arrows represent the nutrient fluxes t N per year with the area of 15,195 hm^2 . The broken arrows were not analyzed in this study.

than the plant, indicating a re-translocation of P prior to litter. But the percentage of P in the litter of meadow tundra (MT) and swamp tundra (WT) was not significantly different from that in the plant (root, stem and leave). The concentration of soil N was greater than soil P and S. But the percentage of N, P and S of MT soil was significantly different among RT, stony tundra (ST), TT and WT ($p < 0.05$) (Table 3).

3.3. Nutrient cycle

For N (Fig. 1), P (Fig. 2) and S (Fig. 3), soil pool was the major nutrient pool, followed by the plant and litter pools for N and S cycle, while followed by litter and plant pools for P cycle.

Alpine soils under tundra and birch forest contained a diverse mixture of inorganic and organic N and P compounds. Although there were no significant differences for soil total N and S at different vegetation types except for MT types, C:N and C:S ratios varied contrarily with respect to N and S, with highest concentrations of N and S in MT; for soil P except for WT types, lowest C:P ratio with highest concentration of phosphorus in WT (Table 4).

3.4. Nutrient reserves

The N and P reserves in the soil pool in this study (Table 3) were higher than the three values given by Aaron et al. (2001). The N, P and S reserves of Changbai Alpine tundra were presented in Table 5.

4. Discussion

4.1. Biomass nutrient content of plant components

The contents of plant in different vegetation types are summarized in Table 6. During the vegetation restorations after volcano eruption in 1702, nutrients were probably transferred from aboveground to belowground (root), N and P are mobile in the stem (xylem) and can be re-translocated within the plant. The mobility of S from cell to cell and within the phloem is, however, restricted. This needs to be further studied. Joanna et al. (2002) reported root N concentrations were 0.90–1.13% and P were 0.08–0.12%, which considerably lower than the values

Table 3
Soil nutrient distribution at different soil types

Nutrients	Soil depth (cm)	Rocky concentration (g kg ⁻¹)	Tundra content (t hm ⁻²)	Stony concentration (g kg ⁻¹)	Tundra content (t hm ⁻²)	Typical concentration (g kg ⁻¹)	Tundra content (t hm ⁻²)	Meadow concentration (g kg ⁻¹)	Tundra content (t hm ⁻²)	Swamp concentration (g kg ⁻¹)	Tundra content (t hm ⁻²)
Nitrogen	0–10	3.4 (0.7)	3.33	3.2 (0.3)	2.62	3.2 (0.2)	2.49	5.4 ^a (1.5)	4.1	3.3 (1.4)	2.05
	10–20	2.2 (0.2)	2.02	2.4 (0.3)	1.94	2.3 (0.2)	1.63	3.4 ^a (0.3)	2.55	1.8 (0.3)	1.01
Phosphorus	0–10	0.6 (0.5)	0.59	0.3 (0.2)	0.25	0.8 (0.6)	0.62	1.0 (0.6)	0.76	1.8 ^a (0.3)	0.62
	10–20	0.5 (0.3)	0.46	0.3 (0.1)	0.24	0.9 (0.4)	0.64	1.2 (0.3)	0.9	1.4 ^a (0.6)	0.78
Sulfur	0–10	1.2 (0.1)	1.18	1.1 (0.2)	0.9	1.1 (0–1)	0.86	1.7 ^a (0.4)	1.29	1.1 (0.3)	0.68
	10–20	0.8 (0.1)	0.74	1.2 (0.6)	0.97	1.1 (0.4)	0.78	3.0 ^a (3.6)	2.25	0.6 (0.1)	0.34
Total	0–20	–	113.65	–	115.36	–	128.19	–	162.05	–	108.1

Values with parentheses are standard deviation.

^a Represents the significant difference among different vegetation types when $p < 0.05$.

Fig. 2. The P cycle of Alpine tundra on Changbai Mountain in which litter has accumulated. Nutrient pools are in t P and arrows represent the nutrient fluxes t P per year with the area of 15,195 hm^2 . The broken arrows were not analyzed in this study.

reported in this study (Table 1). Although Joanna et al. (2002) and this study both examined roots within the various litter/soil layers, the time of root sampling may be relevant as in this study roots were sampled only once, during the active growing season. Ideally, roots should be monitored throughout the year to adequately assess biomass, nutrient concentrations and uptake.

4.2. Nutrient content of litter and soil

Litter accumulation would influence the nutrient cycling in any vegetation ecosystem, as well as its

long-term productivity and sustainability during future management. But the sustainable management of vegetation ecosystem was important to ensure that there were sufficient nutrient reserves to allow for the growth of succeeding plant communities (Hüttel and Schaaf, 1995). Generally, no significant relationship existed between litter production and altitude. Litter accumulation was shown to increase with stand age and increasing altitude (Dames et al., 1998). However, in this study, litter accumulation was not shown to increase with increasing altitude (Table 7), which was not all consistent with the results of Dames et al.

Fig. 3. The S cycle of Alpine tundra on Changbai Mountain in which litter has accumulated. Nutrient pools are in t S and arrows represent the nutrient fluxes t S per year with the area of 15,195 hm^2 . The broken arrows were not analyzed in this study.

Table 4
Soil C:N, C:P and C:S ratios at different vegetation types in Alpine tundra

Vegetation types	0–10 cm			10–20 cm		
	C:N	C:P	C:S	C:N	C:P	C:S
Rocky tundra	17.8	100.7	50.3	17.1	75	46.9
Stony tundra	16.18	172	46.9	15.5	124.33	31.1
Typical tundra	17.4	69.8	50.7	16.2	41.4	33.9
Meadow tundra	15.2	82.2	48.4	16.7	47.3	18.9
Swamp tundra	19.3	63.8	58	17.1	22.1	51.5

(1998). This phenomenon was mainly relevant to vegetation coverage and dominant species of ST and RT types.

Litter has frequently been found to decompose in two phases: (1) an initial stage characterized by rapid loss of labile compounds and mass and (2) the long-term, slower decomposition of more re-calcitrant compounds (Wendy et al., 2004). However, another important, but poorly understood, control on nutrient transformations is the effect of living plants on litter

Table 5
Reserves of nitrogen, phosphorus and sulfur in Changbai Alpine tundra (kg hm^{-2})

Nutrients	Compartments	Rocky tundra	Stony tundra	Typical tundra	Meadow tundra	Swamp tundra	Total
Nitrogen	Plant	0.46	2.06	17.22	11.42	17.41	48.57
	Litter	11.16	5.3	11.31	10.34	8.17	46.28
	Soil	5350	4560	5020	6650	3060	24640
	Total	5361.62	4567.36	5048.53	6671.76	3085.58	24734.85
Sulfur	Plant	0.1	0.41	4.23	3.43	5.45	13.62
	Litter	1.1	1.06	4.47	3.01	5.44	15.08
	Soil	1920	1870	1640	3540	1020	9990
	Total	1921.2	1871.47	1648.7	3546.44	1030.89	10018.7
Phosphorus	Plant	0.06	0.73	2.88	3.22	3.4	10.29
	Litter	4.27	1.81	7.54	2.81	4.71	21.14
	Soil	1050	490	1260	1660	1400	5860
	Total	1054.33	492.54	1270.42	1666.03	1408.11	5891.43

Table 6
Biomass nutrient contents at different vegetation types (kg hm^{-2})

Vegetation type	Components	Vegetation Biomass	Nitrogen	Phosphorus	Sulfur	Total
Rocky tundra	Belowground	23.82 ± 2.84	0.07	0.01	0.05	0.13
	Aboveground	36.18 ± 7.18	0.39	0.05	0.05	0.48
Stony tundra	Belowground	177 ± 23.91	0.94	0.45	0.32	1.73
	Aboveground	73 ± 13.81	1.12	0.28	0.09	1.48
Typical tundra	Root	1160.32 ± 110.8	6.34	1.09	1.21	8.63
	Stem	1204.72 ± 98.6	6.02	1.08	1.81	8.92
	Lave	594.96 ± 75.2	4.86	0.71	1.21	6.78
Meadow tundra	Root	1722.6 ± 110.45	6.20	2.07	1.38	9.65
	Stem	655.4 ± 98.4	1.77	0.52	1.11	3.41
	Leave	522 ± 32.17	3.45	0.63	0.94	5.01
Swamp tundra	Root	833.98 ± 212.7	4.67	0.42	0.92	6.00
	Stem	753.48 ± 78.3	3.92	0.53	1.43	5.88
	Leave	1632.54 ± 213.7	8.82	2.45	3.10	14.37
Total		9390	48.55	10.33	13.61	72.46

Table 7

Litter biomass and nutrient contents at different vegetation types ($\text{kg hm}^{-2} \text{a}^{-1}$)

Vegetation type	Litter biomass	Nitrogen	Phosphorus	Sulfur	Total
Rocky tundra	1.378 ± 0.78	11.16	4.27	1.1	16.53
Stony tundra	1.415 ± 0.21	5.3	1.81	1.06	8.17
Typical tundra	2.356 ± 3.41	11.31	7.54	4.47	23.32
Meadow tundra	2.154 ± 2.17	10.34	2.81	3.01	16.16
Swamp tundra	2.476 ± 0.89	8.17	4.71	5.44	18.32
Total	1.98 (Average)	46.28	21.14	15.08	82.5

and soil organic compounds breakdown. Plants may affect decomposition by altering soil moisture, temperature and other soil physical and chemical properties. The effects of plant activity on decomposition processes have been primarily investigated in agricultural systems in relation to soil quality (Cheng and Coleman, 1990). Elucidating the effects of plants on decomposition in nonagricultural ecosystems is necessary for better understanding of global biogeochemical cycles. However, the effects of living plants on decomposition remain unclear as evidence has been found for both priming and conserving effects of plants on litter and soil organic compounds decomposition (Cheng and Coleman, 1990; Bottner et al., 1999).

Aaron et al. (2001) measured the soil nutrient concentrations of *P. aristata* and *P. engelmannii* Alpine tundra having the depths of 10 cm, respectively. These values are presented in Table 8 for comparison. It is clear that soil N and P concentrations in Alpine tundra on Changbai Mountain were significantly higher than *P. aristata* krummholz and *P. engelmannii* tundra. Although differences in soil

nutrients could be a result of heterogeneous soil conditions, we suggested that a more plausible explanation is that *R. chrysanthwn* and *R. confertissimum* tree islands are altering the soil chemistry of the Alpine predominantly by their existence and growth in this Alpine environment.

4.3. Nutrient cycle

Joanna et al. (2002) reported that the nutrient capital of N and P was mainly distributed in the litter floor pool followed by the soil and tree pools, while Singh (1982) in descending order, among the soil, tree and litter pools. However, from this study, it is evident that the nutrient capital is mainly distributed in the soil pool followed by the litter and plant pools.

4.3.1. The N cycle

There are two sources of inorganic N taken up by plant roots, nitrate and ammonium. Nitrate is mobile in the xylem and can be stored in vacuoles until required. Ammonium is immediately incorporated into organic compounds, such as amino acids and amides, in the roots (Marschner and Persson, 1995). The N pool in the soil layer (0–20 cm) is approximately 600 times greater than the N pool in the litter or tree (Fig. 2).

The net N cycling was, though it varied somewhat with plant community and species, consistent with other studies on tundra mineralization (Weintraub and Schimel, 2003). In a moist Alpine tundra, it appeared that there was an increase in N levels during the early snow period, when some plants produce overwintering roots. The reason for increase is two-fold; it was low the next August, the end of the growing season. Soil immobilized N throughout both winter (slowly) and the growing season, though soil showed

Table 8

Soil total N and P concentrations and its contrast with Aaron et al. (2001) (g kg^{-1})

Sites	Nitrogen	Phosphorus
Aaron et al. (2001)		
<i>P. aristata</i>	1.6 ± 0.2	0.275
<i>P. engelmannii</i>	2.3 ± 0.3	0.35
Alpine tundra	1.9 ± 0.3	0.315
Rocky tundra	2.7 ± 0.9	0.55 ± 0.41
Alpine tundra of Changbai		
Stony tundra	2.9 ± 0.6	0.31 ± 0.21
Typical tundra	3.1 ± 0.4	0.87 ± 0.57
Meadow tundra	4.8 ± 1.2	0.91 ± 0.66
Swamp tundra	2.9 ± 0.9	1.72 ± 0.73

slight mineralization at thaw in May. Thus, N was most available for plant uptake in the fall in the moist tundra. The amounts of N available in fall were substantially relative to annual plant N demand for total aboveground production in Alpine tundra. Cold season N cycling was generally tardigrade under the ambient snow conditions, presumably because the extremely cold soil temperatures prevent any substantial microbial activity.

In Alpine tundra, soils of Changbai Mountain, it appeared that the bulk of the N that had been mineralized over the previous winter was immobilized at thaw. It is important to note that N was immobilized at thaw even though the soil was isolated in cores and therefore, inaccessible to plants. Despite the ability of soil microbes to almost completely immobilize the nitrogen mineralized over the winter, it is likely that plants would, in fact, take up a fraction of the available N if roots were present. [Bilbrough et al. \(2000\)](#) showed that both vascular and nonvascular plants take up N during thaw and [Schmidt et al. \(1999\)](#) concluded that plants take up some of the N that is otherwise immobilized in a buried bag type incubation in tundra soils. The mineralization that occurred in the tundra soils during the growing season represents a major change in N cycling and may reflect multiple years of wintertime activity.

4.3.2. The P and S cycles

Alpine soils under tundra and birch forest contained a diverse mixture of inorganic and organic P and S compounds. The P and S pool in the soil layers is approximately 177.9 and 488.9 times greater than the P and S pool in the litter or tree ([Figs. 2 and 3](#)). A similar P composition has been reported for high organic matter peats and the humic acids extracted from them ([Makarov et al., 1997; Turner et al., 2003](#)). But the S cycle was almost not reported in previous research. High organic matter soils tend to contain a relatively rich P composition, because degradation of the more labile compounds is slowed under conditions unfavorable for microbial activity ([Makarov et al., 1997](#)). Organic matter degradation is certainly slowed by the harsh climate on Changbai Mountain, but other factors, such as soil pH, may also be important in determining the persistence of some compounds.

The abundance of phosphorus compounds considered relatively labile in temperate environments

suggests that Alpine tundra soils contain a large pool of potentially bio-available soil organic phosphorus. This further suggests that P availability is unlikely to limit ecosystem productivity, at least on the relatively N-limited mesic tundra, although other more P-limited environments in the heterogeneous tundra landscape would be expected to respond differently to environmental change. However, there is no information on the potential bio-availability of the various organic and inorganic phosphorus compounds. Some plant species in high-latitudes can directly assimilate organic forms of N ([Näsholm et al., 1998](#)), but there is no such evidence for the uptake of organic P or S compounds into the cytoplasm. It is, thus, generally assumed that organic and condensed phosphorus compounds must first be hydrolyzed by phosphatase enzymes prior to plant uptake, although hydrolysis of simple orthophosphate esters has been shown to occur within the cell walls of mosses ([Turner et al., 2001](#)) and seems likely to occur in many other plants. It also remains unclear how much of the potentially labile compounds are actually contained within living microbes. The microbial biomass represents a dynamic pool of soil P that is sensitive to small changes in the ambient environment, including elevated CO₂, temperature and ultra-violet radiation ([Johnson et al., 2002](#)). Therefore, even small changes in microbial biomass size or activity could have a major impact on plant nutrient availability, at least in the short term ([Jonasson et al., 1996](#)), although this may benefit or inhibit productivity depending on the strategies employed by tundra plants to obtain nutrients. Rapid immobilization of nutrients within microbial cells when high-latitude soils is warm could inhibit plant growth, whereas wetting and drying or freezing and thawing cycles may turn microbes into a source of P for plant uptake ([Lipson and Monson, 1998; Turner and Haygarth, 2001](#)). The latter processes may be common in Arctic tundra soil, because there is evidence that Arctic plants are adapted to access P from pulses in their environment ([Kielland and Chapin, 1994](#)). Furthermore, studies in the Canadian sub-Arctic tundra revealed that hair-forming cyanobacteria are indicative of a highly variable supply of organic phosphorus in the environment ([Whitton, 1988](#)). Clearly, understanding phosphorus and sulfur biogeochemistry in Alpine tundra ecosystems

requires detailed temporal and spatial studies of soil phosphorus and sulfur composition and bio-availability in the various microenvironments within the heterogeneous tundra landscape, especially, in tundra with being formed by periodic volcano eruption.

5. Conclusions

Changbai Alpine tundra not only has accumulated lots of litter, but also acquired a certain proportion of ecosystem nutrients, especially, P and S from litter layers. That is because the distribution of roots occurs mainly within the litter pool. Nutrients in Changbai Alpine tundra ecosystem are, therefore, being cycled through a plant–litter–soil–plant pattern that emphasizes the importance of the litter layers. Our results indicate relatively small and subtle N, P pool dynamics compared to previous studies. Alpine tundra exhibited considerable variation due to climate, substrate and disturbance regimes, which appeared to limit microbial activity and N mineralization and S sulfuration, it was likely that plants would only take up a small fraction of the available N from over-wintering roots with effectively uptake and therefore, a large amount of soil N was inaccessible to plants. In addition, it suggests that Changbai tundra soils contain a large pool of potentially bio-available soil organic phosphorus. Therefore, the N mineralization and S sulfuration would have long-term effects on ecosystem structure, which has feedback on nutrient availability (Joshua et al., 2004). In order to understand the effects of different dominant species on the Alpine tundra, future comparisons should specially focus on the role of dominant species in different Alpine tundra belts, as well as better understanding about general conclusions regarding nutrient biogeochemistry in Alpine tundra, which may not hold for cross site comparisons. Although it is still not clear what the vegetation of Alpine tundra was like during the last glacial maximum, the N and P contents from large Pleistocene dune fields (such as RT and ST) are evidence that eolian processes were a dominant aspect of Changbai tundra formation. Studies should focus on dominant species shift, spatio-temporal change of litter, nitrogen availability, soil microbial activity, N mineralization rate, S sulfuration rate, P

re-location and causes of soil nutrient difference among different vegetation types in future.

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