Nutrients and biomass spatial patterns in alpine tundra ecosystem on Changbai Mountains, Northeast China

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Abstract

Biomass and nutrients were investigated in 2003, 2004 and 2005 growing seasons by using a chronosequence of five vegetation types in alpine tundra on Changbai Mountains. The objective of this study was to test whether nutrients at biointerfaces were significant differences among five vegetation types. The biomass and elevation are highly related ($\text{biomass} = -237.3 \ln(\text{elevation}) + 494.36$; $R^2 = 0.8092$; $p < 0.05$). There were no significant differences in phosphorus (P) and sulphur (S) concentrations of roots, stems and leaves among five vegetation types while there are significant differences in nitrogen (N) and P stocks of roots, stems and leaves and in S stock of stems and leaves among typical alpine tundra vegetation (TA), meadow alpine tundra vegetation (MA), and swamp alpine tundra vegetation (SA) ($p < 0.05$). Vegetation nutrients stock is averagely 72.46 kg hm^{-2} , and N, P, S stocks are 48.55, 10.33 and 13.61 kg hm^{-2} , respectively. Soil N and S concentrations in MA are significantly higher than those in other four soil types. P is higher in SA ($p < 0.05$). Soil nutrients stock (0–20 cm) is averagely 39.59 t hm^{-2} , and N, P, S stocks are 23.74, 5.86 and 9.99 t hm^{-2} , respectively.

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1. Introduction

The climate change has been one of hotspots in global environment issues. Future temperature changes in high latitude regions (alpine tundra) are believed to be larger than any other part of the globe. Although such predictions have uncertainties, it is suggested that by 2080 arctic regions will experience

temperature increases of $4\text{--}7.5^\circ\text{C}$ in summer and $2.5\text{--}14^\circ\text{C}$ in winter [1,2]. Although alpine tundra is one of the most sensitive ecosystems to global climate change in the world, most of studies were only focused on tropical areas [3–5], and few studies were done on change of soil carbon stock associated with soil nutrients in temperate alpine tundra ecosystems previously [6,7]. The last volcano eruption undergone by alpine tundra on Changbai Mountains in 1702 year constitutes a major recurring disturbance and leads to the establishment of shrubs or herbs communities. Now alpine tundra on Changbai Mountains is covered with abundant gramineous grasses, low shrubs or subshrubs, weeds, mosses and lichens [8]. Many studies have shown that in pioneer stages of succession, dominant species modify their environment in the short- or long-term, with effects on the vegetation dynamics [9]. Whereas the post-volcano successions have mainly been studied from a floristical and structural point of view, biomass or nutrients approaches to explain the vegetation dynamics are scarce. Because of the harsh climate of alpine tundra, vegetation productivity is often limited by

Abbreviations: FA, Felsenmeer alpine tundra vegetation; LA, lithic alpine tundra vegetation; TA, typical alpine tundra vegetation; MA, meadow alpine tundra vegetation; SA, swamp alpine tundra vegetation; NPP, net primary productivity; N, nitrogen; P, phosphorus; S, sulphur; CDS, cold desert alpine tundra soil; LS, lithic alpine tundra soil; GS, grey alpine tundra soil; MS, meadow alpine tundra soil; PS, peat alpine tundra soil; UNESCO, United Nations Educational, Scientific, and Cultural Organization

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nutrients availability [10,11]. High rates of productivity depend strongly on species selection, nutrients availability, nutrients use efficiency, etc. Nutrients limitations are common during plant growth, especially for N and P. In general, biomass and soil nutrients change substantially with plant age. Biomass over time may differ among species, which is due to in part nutrients availability of different species over time [9,12]. P is the primary limiting nutrients in alpine tundra, although the degree of limitation varies markedly across the heterogeneous tundra landscape [13,14]. For instance, in the North American arctic, NPP in moist tussock tundra tends towards co-limitation by N and P whereas wet sedge tundra is typically P-limited [15,16]. Mesic tundra probably tends towards N limitation, although the biological demand for P in all tundra environments is likely to be enhanced by the current low rates of reactive N deposition from the atmosphere [17–20]. Otherwise, there is increasing evidence that, for a number of forests, P is immobilized in the first stages of decomposition to a significantly greater extent than N. Furthermore, most plant N was tied into perennial, woody stems or coarse roots and contributed little to the annual cycling of nutrients between plant and soil [21,22]. Most organically bound nutrients were fixed in the soil and litter and a low proportion was in biomass in any alpine tundra ecosystem. For instance, the vegetation contained <35% of ecosystem N 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, N percentage in soil plus litter increased to between 90 and 95% and only $5 \pm 10\%$ of ecosystem was incorporated into vegetation biomass [22,23]. Consequently, although alpine tundra often contains large pools of nutrients, these are tied into recalcitrant 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 alpine tundra productivity is generally nutrients limited and that dominant plants are mostly species or functional groups of low nutrients requirement, or species with a conservative use of nutrients [23,24]. Most studies of alpine tundra have either addressed questions of nutrients acquisition or of decomposition and mineralization processes [24–26] while few studies have attempted to integrate processes in both biomass and nutrients. There is currently limited information on nutrients cycling of alpine tundra ecosystems, whereas it is important to better understand nutrients spatial pattern and potential alpine tundra response to environment change in such regions. Alpine tundra occurs on heavily weathered, nutrients-poor soils, and tends to have lower nutrients budgets and a higher proportion of nutrients contained in the living material of ecosystem [27]. Data on biomass and nutrients storage in alpine tundra are limited, and have been the subject of considerable controversy. Clearly, there is a need for additional studies of biomass and nutrients in alpine tundra, and of factors that cause natural variability in biomass and nutrients. Very few studies have assessed effects of soils nutrients on biomass, although investigators have often searched for relationships between soil or drainage features and vegetation composition [28–30].

The aim of this research is to examine nutrients concentrations and stocks of vegetation and soil in alpine tundra on

Changbai Mountains in which litter has accumulated, as N or P is regarded as most limiting in vegetation development [1–8] and to study change of biomass and nutrients, therefore we investigated biomass and nutrients in alpine tundra on Changbai Mountains. The above- and below-ground biomass was harvested and soil samples were collected in permanent plots at the end of growing seasons in 3 successive years.

2. Materials and methods

2.1. Study site

Changbai Mountains Nature Reserve (42°24'N, 128°28'E) is the best-preserved mountainous ecosystem in China, perhaps even in the world and is a designed UNESCO Biosphere Reserve. It is the most representative upland forest ecosystem, containing a range of soils, vegetation, and climate, with distinct altitudinal distributions. The Reserve contains 1337 vascular plant species, including 1250 seed plant species [39], and four vegetation zones [9]: sub-alpine vegetation, evergreen coniferous forest, mixed broadleaf-conifer forest, and larch forest. The alpine tundra on Changbai Mountains lies in 41°53'–42°04'N, 127°57'–128°11'E between 1950 and 2690 m a.s.l. and its total area is 15,860 hm², in which, the area of vegetation coverage is 15,190 hm², accounting for 95.78% of the entire alpine tundra area [30]. The physiognomy includes mainly volcanic physiognomy, glacier physiognomy and ice edge physiognomy. There are many snow packs on the peak. The mean annual radiation is 506.6 J cm⁻² a⁻¹, the mean annual light time is 2295 h, the mean annual temperature is -7.4 °C, January mean temperature (the coldest month) is -23.8 °C, July mean temperature (the warmest month) is 8.4 °C, the highest temperature is 19.2 °C, and the lowest temperature is -44 °C. The mean annual rainfall is 900–1340 mm. The sampling sites are located at elevations from 1950 to 2650 m on the northern slope of Changbai Mountains (Figs. 1 and 2).

2.2. Sampling

Sampling collection and measurements were conducted in late July and early August of 2003, 2004 and 2005. We selected sampling sites by visual inspection of vegetation, selecting sites subject to minimal anthropogenic disturbances. Four representative transects were allocated with similar aboveground conditions, geomorphic and hydrological conditions in each vegetation type. There were four quadrats in each transect. Each quadrat was sized 1.0 m × 1.0 m. Plants (including roots) were collected with the harvest method at each plot. Nearly all collected plants were in growing season (the most biomass). The soil bulk density was 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. Soil samples at each depths of 0–10 and 10–20 cm were collected from each profile to analyze N, P, and S concentrations. In all, a total of 128 plant samples and 256 soil samples were collected and measured per year.

Fig. 1. The sketch of Changbai Mountains Nature Reserve, showing main vegetation types. The sampling sites were located at the elevation from 1950 to 2650 m. The area of studied tundra is 15,195 hm^2 , including five vegetation types and five soil types. Vegetation types are Felsenmeer alpine tundra vegetation, lithic alpine tundra vegetation, typical alpine tundra vegetation, meadow alpine tundra vegetation, and swamp alpine tundra vegetation. Soil types are cold desert alpine tundra soil, lithic alpine tundra soil, grey alpine tundra soil, meadow alpine tundra soil, and peat alpine tundra soil.

2.3. Chemical analysis and data

These samples of plants and soil were collected, placed in paper envelopes and hop-pockets, respectively, and dried in the sun. These samples were oven-dried at 65 °C upon returning to the laboratory. Dried samples were ground to a fine powder using a ball mill. After that, the plant and soil samples were used to analyze nutrients by standard procedures. Total N was determined using Kjeldahl procedure followed by colorimetric analysis [12] while total P and S using an inductive coupled plasma spectrometry (ICPS) after digestion with $\text{HNO}_3/\text{HClO}_4$. We used the regression approach to the analysis of variance (ANOVA) in the SPSS statistical software package version 11.0. The significance of effects was tested with the F -ratios between mean squares of effects and residuals. When significant differences were evident, multiple range tests of the least significant differences were conducted.

2.4. Biomass and nutrients budget

Using biomass of plots and areas of different vegetation types, it could determine vegetation biomass, vegetation carbon storage, and NPP. Using dry weight of plant species and its density, it could calculate the mono-species biomass using the following formula [8]:

$$W = \frac{\sum w_j n_j}{1000} \quad (1)$$

where W is mono-species biomass (kg hm^{-2}), w_j the average dry weight of the j plant species (g ind.^{-1}) and n_j is the number of j plant species (ind. hm^{-2}). Using mean values of nutrients and biomass, it could determine vegetation nutrients pools while soil nutrient pools (kg hm^{-2}) were calculated using the following formula [27]:

$$P = 100 \times \text{NC} \times \text{BD} \times D \quad (2)$$

where NC is the nutrient concentration converted to g kg^{-1} , BD the soil bulk density in g cm^{-3} and D is the soil depth in cm. The soil depth measured at this site was 20 cm.

3. Results

3.1. Biomass pattern in alpine tundra on Changbai Mountains

3.1.1. Patterns of vegetation

There is significant differences of plot biomass in both FA and LA, either aboveground or belowground parts ($p < 0.05$). Root plot biomass in SA is significantly smaller than those in TA and MA while leaves in SA bigger than in TA and MA and stem in TA bigger than in MA and SA ($p < 0.05$) (Table 1). The biomass of 5 vegetation types spatially distributes as follows: $\text{SA} > \text{TA} > \text{MA} > \text{LA} > \text{FA}$ in alpine tundra on Changbai Mountains.

Fig. 2. Relationship between vegetation biomass and elevation in alpine tundra on Changbai Mountains. The t -test showed that there are two points largely deviated from the fitted curve. The two points are located at the elevations of 2250 and 2450 m. The t -test values are 3.456 (at the elevation of 2250 m) and 4.357 (at the elevation of 2450 m) ($n = 7$, $p < 0.05$, $t_{\text{standard}} = 1.895$), respectively.

Table 1
Vegetation biomass pattern in alpine tundra ecosystem on Changbai Mountains

Vegetation type	Components	Plot biomass ^a (kg hm ⁻²)	Area (hm ²)	Vegetation biomass (t hm ⁻²)	NPP (t hm ⁻² year ⁻¹)	Total carbon storage (t)
FA	Belowground	23.82 ± 2.84	85	0.06	0.06	5.1
	Aboveground	36.18 ± 7.18				
LA	Belowground	177 ^b ± 23.91	4160	0.25	0.25	1040
	Aboveground	73 ^b ± 13.81				
TA	Root	1160.32 ± 110.8	10870	2.96	1.48	32175.2
	Stem	1204.72 ^b ± 98.6				
	Leaves	594.96 ± 75.2				
MA	Root	1722.6 ± 110.45	65	2.9	1.45	188.3
	Stem	655.4 ± 98.4				
	Leaves	522 ± 32.17				
SA	Root	833.98 ^b ± 212.7	15	3.22	1.61	48.3
	Stem	753.48 ± 78.3				
	Leaves	1632.54 ^b ± 213.7				
Total		9389.9	15195	2.21	1.14	33456.9

^a Mean value and standard deviation of plot biomass are reported, values behind ± sign are standard deviation.

^b Significant differences at $p < 0.05$.

3.1.2. Relationship between biomass and elevation

The biomass and elevation are highly related (biomass = $-237.3 \ln(\text{elevation}) + 494.36$; $R^2 = 0.8092$; $p < 0.05$), which shows that vegetation biomass is mainly affected by elevation. From Fig. 2, there are two points largely deviated from the fitted curve by t -test values ($t_{2250\text{m}} = 3.456$; $t_{2450\text{m}} = 4.357$, $n = 7$, $p < 0.05$, $t_{\text{standard}} = 1.895$), which are biomass at both elevations of 2250 and 2450 m (Fig. 2). From the field investigation on the spot and analysis, the deviated points at the elevations of 2250 and 2450 m are mainly from the reasons that there are many dominant species from high elevation (such as LA and FA) distributed in weather ridge and steep slope at the elevations of 2250 m and 2450 m and that there are strong aeolian erosion and snow patch erosion in somewhere and that vegetation coverage is below 20% in weather ridge and steep slope.

In order to study the correlativity between organ biomass and elevation, it takes an example of dominant species from *Ericaceae* (such as *Rhododendron chrysanthum* and *Vaccinium uliginosum* var. *alpinum*) to analyze organ biomass distribution. There are significantly different patterns of roots, stems, and leaves biomass along elevation gradient. The root biomass percentage gradually increases along increasing elevation while

leaves markedly decreases and stem changes irregularly (Fig. 3). Organ biomass of *Vaccinium uliginosum* var. *alpinum* (mainly distributed below elevation of 2350 m) distributed along increasing elevation as follows: stems > roots > leaves while that of *Rhododendron chrysanthum* (mainly distributed above elevation of 2450 m) roots > stems > leaves. The subtle differences are from different organs of different dominant species long-term adaptation to aeolian or snow erosion.

3.2. Vegetation nutrients pattern in alpine tundra on Changbai Mountains

Among the plant components, leaves have the highest N, P, and S concentrations, with N being the major nutrients. Although there were no significant differences in P and S concentrations among roots, stems and leaves at each vegetation type, P and S concentrations are at least 1.5–2 times higher in leaves or aboveground than in roots or belowground. But plant N, P, and S stocks in both FA and LA, either aboveground or belowground part, are significantly different ($p < 0.05$). There are significant difference in N and P stocks of root, stem, and leaves ($p < 0.05$) while there are only significant difference in S stock of stem and leaves among the TA, MA, and SA (Table 2). There are similarly spatial patterns about N, P, and S concentrations or stocks among 5 vegetation types. Nutrients stock of vegetation is averagely 72.46 kg hm⁻², N, P, and S of which is 48.55, 10.33, and 13.61 kg hm⁻², respectively, in alpine tundra ecosystem on Changbai Mountains (Table 2).

3.3. Soil nutrients pattern in alpine tundra on Changbai Mountains

Soil N, P, and S concentrations or stocks are mainly accumulated at the depth of 0–10 cm. Soil N concentration is greater than soil P and S. But soil N and S concentrations in MA are

Fig. 3. Organ biomass gradient change of dominant species (i.e. *Ericaceae*) along elevation.

Table 2
Vegetation nutrients concentrations and stocks

Vegetation type	Parts	Total N ^a		Total P ^a		Total S ^a	
		Concentration (g kg ⁻¹)	Stock (kg hm ⁻²)	Concentration (g kg ⁻¹)	Stock (kg hm ⁻²)	Concentration (g kg ⁻¹)	Stock (kg hm ⁻²)
FA	Belowground	2.91 ± 1.2	0.07 ^b (0.003)	0.5 ± 0.2	0.01 ^b (0.001)	2.2 ± 1.2	0.05 ^b (0.003)
	Aboveground	10.7 ± 7.8	0.39 ^b (0.056)	1.3 ± 0.3	0.05 ^b (0.002)	1.4 ± 0.2	0.05 (0.001)
LA	Belowground	5.3 ± 1.4	0.94 (0.033)	2.7 ± 1.6	0.45 (0.04)	1.8 ± 0.8	0.32 (0.02)
	Aboveground	15.2 ± 11.0	1.12 (0.15)	3.8 ± 4.3	0.28 (0.06)	1.3 ± 1.1	0.09 (0.02)
TA	Root	5.5 ± 0.5	6.34 (0.06)	0.9 ± 0.4	1.09 (0.04)	1.0 ± 0.6	1.21(0.07)
	Stem	5.0 ± 2.3	6.02 ^b (0.23)	0.9 ± 0.7	1.08 ^b (0.07)	1.5 ± 1.0	1.81 ^b (0.10)
	Leaves	8.2 ± 3.4	4.86 (0.26)	1.2 ± 0.9	0.71(0.09)	2.0 ± 1.2	1.21(0.04)
MA	Root	3.6 ± 1.2	6.2 (0.13)	1.2 ± 0.8	2.07(0.03)	0.8 ± 0.4	1.38(0.12)
	Stem	2.7 ± 1.3	1.77 (0.13)	0.8 ± 0.3	0.52(0.04)	1.7 ± 1.2	1.11(0.03)
	Leaves	6.6 ± 2.1	3.45 (0.07)	1.2 ± 1.1	0.63(0.09)	1.8 ± 0.9	0.94(0.15)
SA	Root	5.4 ± 2.3	4.67 ^b (0.49)	0.5 ± 0.4	0.42 ^b (0.03)	1.1 ± 0.7	0.92(0.09)
	Stem	5.2 ± 1.3	3.92 (0.11)	0.7 ± 0.4	0.53(0.23)	1.9 ± 1.1	1.43(0.34)
	Leaves	5.6 ± 3.6	8.82 ^b (0.78)	1.5 ± 1.1	2.45 ^b (0.97)	1.9 ± 1.6	3.1 ^b (0.57)
Total		–	48.55	–	10.33	–	13.61

^a Mean value and standard deviation of plant nutrient concentrations or stocks are reported at each component of each vegetation type. Values within parentheses or behind ± sign are standard deviation.

^b Significant differences at $p < 0.05$.

significantly higher than those in other four soil types while P concentration in SA higher ($p < 0.05$) (Table 3). Difference of N concentration throughout the soil layers is not evident ($p < 0.05$), but there is similar pattern between 0–10 and 10–20 cm. P concentration or stock at the depth of 10–20 cm soil layer is evidently greater than that at the depth of 0–10 cm among FA, LA, TA, and MA. S concentration or stock at the depth of 0–10 cm soil layer is evidently greater than that at the depth of 10–20 cm among FA, LA, TA, and SA. Nutrients stock of soil (0–20 cm) is averagely 39.59 t hm⁻², N, P, and S of which is 23.74², 5.86, and 9.99 t hm⁻², respectively, in alpine tundra ecosystem on Changbai Mountains (Table 3).

4. Discussion

4.1. Change of vegetation nutrients

Plant N, P, and S concentrations or stocks in 5 vegetation types are summarized in Table 2. Although N stock is the most in TA and SA while P in MA or SA and S in SA, respectively, N is mainly concentrated in root parts of TA and SA while P in roots of MA or leaves of SA and S in leaves of SA. On one hand, the nutrients stock differences of 5 vegetation types are from the reason that different dominant species of 5 vegetation types and their organs have the different selective absorption coefficients

Table 3
Soil nutrients concentrations and stocks

Vegetation type	Soil type	Soil depth (cm)	Total N ^a		Total P ^a		Total S ^a	
			Concentration (g kg ⁻¹)	Stock (t hm ⁻²)	Concentration (g kg ⁻¹)	Stock (t hm ⁻²)	Concentration (g kg ⁻¹)	Stock (t hm ⁻²)
FA	CDS	0–10	3.4 ± 0.7	3.33	0.5 ± 0.3	0.46	1.2 ± 0.1	1.18
		10–20	2.2 ± 0.2	2.02	0.6 ± 0.5	0.59	0.8 ± 0.1	0.74
LA	LS	0–10	3.2 ± 0.3	2.62	0.3 ± 0.2	0.24	1.1 ± 0.2	0.9
		10–20	2.4 ± 0.3	1.94	0.3 ± 0.1	0.25	1.2 ± 0.6	0.97
TA	GS	0–10	3.2 ± 0.2	2.49	0.8 ± 0.6	0.62	1.1 ± 0.1	0.86
		10–20	2.3 ± 0.2	1.63	0.9 ± 0.4	0.64	1.1 ± 0.4	0.78
MA	MS	0–10	5.4 ^b ± 1.5	4.1	1.0 ± 0.6	0.76	1.7 ^b ± 0.4	1.29
		10–20	3.4 ^b ± 0.3	2.55	1.2 ± 0.3	0.9	3.0 ^b ± 3.6	2.25
SA	PS	0–10	3.3 ± 1.4	2.05	1.8 ^b ± 0.3	0.62	1.1 ± 0.3	0.68
		10–20	1.8 ± 0.3	1.01	1.4 ^b ± 0.6	0.78	0.6 ± 0.1	0.34
Total		0–20	–	23.74	–	5.86	–	9.99

^a Mean value and standard deviation of soil nutrients concentration and stock are reported at different soil depths of each soil type. Values behind ± sign are standard deviation.

^b Significant differences at $p < 0.05$.

to N, P, and S nutrients. For instance, *Polygonum ochotense* (main dominant species) is abundant of N in TA (0.48%) and SA (0.33%) while *Rhododendron confertissimum* of P in MA (0.13%) or SA (0.19%) and *Dryas octopetala* var. *asiatica* of S in SA (0.22%)[5,31,32]. The other possible reason is that nutrients are probably transferred from aboveground to belowground (root) during the vegetation development after volcano eruption in 1702a. For instance, N and P are mobile in the stem (xylem) and can be re-translocated within the dominant plant while the mobility of S from cell to cell and within the phloem is restricted. This needs to be further studied. Joanna et al. [31] reported root N concentration was 0.90–1.13% and P was 0.08–0.12% in sub-arctic and arctic ecosystems and in a *Pinus patula* plantation in South Africa, which is considerably lower than the values reported in this study (Table 2). Although Joanna et al. [31] 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 per year, during the active growing season. Ideally, roots should be monitored throughout the year to adequately assess biomass, nutrients concentration and uptake.

4.2. Change of soil nutrients

Soil nutrients change after human disturbance or natural disaster mainly because (1) human activities and natural disaster could directly affect soil nutrients decomposition and loss; (2) soil moisture is easily affected by climate (e.g., the addition of water to dry soil caused large pulsed of CO₂, NO and N₂O emissions [33–38]); (3) pioneer plants or dominant species have different nutrients requirements, exploit nutrients with varying efficiency and store or convert nutrients at different rates [39–41].

Soil N pattern has a close relation with root system distribution (root clumping and root free zone) [31,33]. Many studies have shown that N-fixing species can significantly increase soil N levels [34], while others found no correlation between the presence of N-fixing species and total N accumulation in the surface soil [35,37]. Aron et al. [10] measured soil nutrients concentration of *P. aristata* and *P. engelmannii* alpine tundra at the depth of 10 cm, respectively. It is clear that soil N concentration in alpine tundra on Changbai Mountains is significantly higher than those in *P. aristata* and *P. engelmannii* alpine tundra (Table 4). In this study we found that surface soil (0–10 cm) in FA and MA was abundant of N. This possible reason is that N of plant and litter is very high while N use efficiency is relatively low [5]; that there is higher net N mineralization rate from rock weathering during forming soil after volcano eruption; that root system in fixing N has special spatial pattern.

Differences in soil P may result from change of biological and geochemical processes at different depths after volcano eruption [38,39]. In soil mycorrhizal symbionts and other microorganisms closely couple decomposition and uptake processes contributing to soil P retention. Biological controls on P include root growth patterns, amounts and quality of detritus inputs, extracellular enzyme activity, production of organic chelates and mycorrhizal activity [40,41]. Soil P does not significantly change

Table 4

Contrast soil N and P concentrations in this study with Aron [10] (g kg⁻¹)

Sites	Alpine tundra	N ^a	P ^a
Aron et al. [10] sites	<i>P. aristata</i>	1.6 (0.2)	0.275
	<i>P. engelmannii</i>	2.3 (0.3)	0.35
	Average	1.9 (0.3)	0.315
Alpine tundra on Changbai Mountains	FA	2.7 (0.9)	0.55 (0.41)
	LA	2.9 (0.6)	0.31 (0.21)
	TA	3.1 (0.4)	0.87 (0.57)
	MA	4.8 (1.2)	0.91 (0.66)
	SA	2.9 (0.9)	1.72 (0.73)
	Average	3.28 (1.25)	0.872 (0.78)

^a Values within parentheses are standard deviation.

at 5 vegetation types in alpine tundra on Changbai Mountains. The soil P is lower in LA while higher at the depth of 10–20 cm in MA. So there is large storage of soil P in MA and SA (Table 4). The details of soil P change at 5 vegetation types appear different and complicated. But it is clear that soil P concentration in alpine tundra on Changbai Mountains is significantly higher than those in *P. aristata* and *P. engelmannii* alpine tundra [34,37] (Table 4). Although differences in soil nutrients could be a result of heterogeneous soil conditions, we suggested that a more plausible explanation was that *R. chrysanthum* and *R. confertissimum* tree islands were altering soil chemistry of tundra predominantly by their existence and growth in the alpine tundra environment [5–7].

S is considered an essential plant macronutrient. The factors that control the rate of S reduction have not been identified with certainty in the various environments because many factors are involved, such as, oxygen and sulphate concentrations, temperature and organic matter availability [23,26]. Soil S would come from the mineralization of litter, soil organic matter and rock in alpine tundra on Changbai Mountains. We also found that S and P stocks in dominant plants were very high while in soil relatively low, which showed that use efficiency of S and P was significantly high and that S and P were the most limited factors of plant growth in alpine tundra on Changbai Mountains [6,7]. Further research should be done to elucidate the relative contribution of soil S and P during vegetation development after gigantic volcano eruption in 1702a. The ratios of C:N, C:P, C:S and C:N:P were often used as indicators of soil nutrient condition [8,26,27]. Soil N and S concentrations are lower in SA while soil P is lower in LA and higher in MA of alpine tundra on Changbai Mountains, respectively. The possible reason is that after volcano eruption, soil is mainly oriented with physical weathering. Furthermore, after vegetation restoration, although plants grow slowly under low temperature, the anaerobic and reductive soil is against decomposition of litter and microorganism, which makes alpine tundra soil abundant of humus or turf bed. Although soil sampling replications were limited in this study, the sampling size satisfied the minimum requirement (5 × 4) in most of ecological field studies by statistical rule of thumb. However, certain cautions are needed when extending the reported findings in this study.

5. Conclusions

The similarities in biomass or soil nutrients between LA and FA or among TA, MA, and SA would be difficult to anticipate without census information showing the proportionally large number of shrubs and herbs in the community. The sampling area, times, depth and harvesting method may account for the fact that there is significant differences of plant plot biomass in both FA and LA ($p < 0.05$); that root plot biomass in SA is significantly smaller than those in TA and MA while leaves in SA bigger than in TA and MA and stem in TA bigger than in MA and SA ($p < 0.05$); that soil N and S concentrations in MA are significantly higher than those in other four soil types while P in SA higher ($p < 0.05$).

In order to understand effects of different dominant species on alpine tundra of Changbai Mountains, future comparisons should specially focus on the role of dominant species in different alpine tundra types, as well as better understanding about general conclusions regarding nutrients spatial pattern in alpine tundra, which may not hold for cross site comparisons. Future studies should focus on dominant species shift, spatial-temporal pattern change of biomass and litter, nutrients availability, soil activity, N, S, and P re-location and causes of plant or soil nutrients differences in alpine tundra on Changbai Mountains.

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