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Comparative Assessment of Tundra Vegetation Changes Between North and Southwest Slopes of Changbai Mountains, China, in Response to Global Warming

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Abstract: Vegetation in high altitude areas normally exhibits the strongest response to global warming. We investigated the tundra vegetation on the Changbai Mountains and revealed the similarities and differences between the north and the southwest slopes of the Changbai Mountains in response to global warming. Our results were as follows: 1) The average temperatures in the growing season have increased from 1981 to 2015, the climate tendency rate was 0.38℃/10yr, and there was no obvious change in precipitation observed. 2) The tundra vegetation of the Changbai Mountains has changed significantly over the last 30 years. Specifically, herbaceous plants have invaded into the tundra zone, and the proportion of herbaceous plants was larger than that of shrubs. Shrub tundra was transforming into shrub-grass tundra. 3) The tundra vegetation in the north and southwest slopes of the Changbai Mountains responded differently to global warming. The southwest slope showed a significantly higher degree of invasion from herbaceous plants and exhibited greater vegetation change than the north slope. 4) The species diversity of plant communities on the tundra zone of the north slope changed unimodally with altitude, while that on the tundra zone of the southwest slope decreased monotonously with altitude. Differences in the degree of invasion from herbaceous plants resulted in differences in species diversity patterns between the north and southwest slopes. Differences in local microclimate, plant community successional stage and soil fertility resulted in differential responses of tundra vegetation to global warming.

Keywords: global warming; Changbai Mountains tundra; vegetation change; species diversity patterns

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1 Introduction

Climate change has become a pertinent global environmental issue. Areas at high latitude and altitude are sensitive to climate change, and are likely to experience greater changes in temperature (Symon et al., 2005; IPCC, 2007; Wei et al., 2007). Alpine areas are known as the most important for detecting and assessing impacts of climate change (Dai et al., 2002). In the context of global climate change, alpine vegetation is considered to be highly sensitive (Theurillat and Guisan, 2001; Dirnböck et al., 2003; Erschbamer et al., 2011), and in many mountainous regions, changes in climate have induced vegetation responses (Henry and Molau, 1997;

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DeChaine and Martin, 2004; Lesica and McCune, 2004; Huelber et al., 2006; Inouye, 2008). Monitoring data from Alps confirmed that climate warming caused the migration of species to higher altitudes, leading to an upward shift in the vegetation vertical zone and forest line, resulting in increased species richness (Grabherr et al., 1994; 1995; Bahn and Körner, 2003; Pauli et al., 2003; 2007; Walther et al., 2005; Holzinger et al., 2008; Parolo and Rossi, 2008; Erschbamer et al., 2009, 2011; Gottfried et al., 2012; Pauli et al., 2012). At relatively low altitude mountain summits suffering plant invasion from the lower altitudes, competition for space has resulted in biodiversity loss greatly (Grabherr et al., 1995; Pauli et al., 2003; Stanisci et al., 2005; Kazakis et al., 2007). Observed changes in tundra plant communities have been related to interactions between plant species and the local environment (Mitchell et al., 2009), but long-term changes associated with warming are difficult to infer from short-term studies. Such changes are detectable only over long periods of time (Vittoz et al., 2008, Britton et al. 2009). There are lack observations from sites in remote high latitude and altitude mountainous regions (Danby, 2011).

At high altitudes, temperature is a key factor in controlling the environment which explains the distribution of species and even the limits of life, such as the formation of forest lines and chilling lines (Körner, 1998; Körner and Paulsen, 2004). Climate warming altered the physical environment of alpine plants and promoted plant migration and invasion, leading to changes in vegetation composition, structure and diversity (Erschbamer et al., 2011). As the temperature rises, species distribution tends to shift toward higher altitudes. Some species that are sensitive to elevated temperatures migrate first, while others may lag behind (Parmesan and Yohe, 2003). As climate change continues, entire communities begin to migrate. Alpine vegetation contains a high proportion of endemic species and their diversity is subject to spatiotemporal variation of climate changes (Heikkinen and Neuvonen, 1997; Gough et al., 2000; Moser et al., 2005).

Altitude is an important biodiversity factor because it reflects the availability of resources such as water and heat (Körner, 2000). Reported studies about plant diversity patterns have demonstrated that altitude plays an important role in species diversity (Kessler, 2000; Grytnes, 2003; Oommen and Shanker, 2005).

It has been generally accepted that species diversity decreases with increasing altitude. For instance, von Haller (1742) studied the changes in quantity of vascular plant species with altitude and established a conceptual model, which is consistent with the polarization from the equator to the poles (Körner, 2000; Lomolino, 2001). However, recent studies have questioned the linear relationship between vascular plant diversity and altitude, and have found that there is an intermediate peak in plant diversity (Colwell and Hurtt, 1994; Rahbek, 1995; Odland and Birks, 1999; Grytnes, 2003; Bruun et al., 2006). Species diversity reflects the balance between species decreases caused by local processes such as competition, and species increases resulting from the spread of the regional species pool (Ricklefs, 1989). Competition is particularly important in benign environments, but is less intense under conditions of environmental stress (Grime, 1973a; 1973b; 1979; Sammul et al., 2000; Callaway et al., 2002). In low altitude areas, the regional species pool is large, but the local species diversity is strictly restricted by competitive exclusion. While in middle altitude areas, the regional species pool is small, but competition is weak, and the diversity of local species is higher. In high altitude areas, the regional species pool is small, and as result the richness of local species is low (Bruun et al., 2006). Therefore, the species diversity normally changes unimodally with altitude.

Besides temperature, other factors also play important roles in tundra vegetation changes, such as the precipitation and temperature co-affecting the diversity of mountain vegetation (Engler et al., 2011), the terrain, particularly slope, affecting the local climate in terms of radiation, snow, wind, etc., which may enhance climate warming (Bruun et al., 2006). A study on the changes in the tundra vegetation of the Ruby Range Mountains of southwest Yukon in Canada showed that the diversity of species has increased significantly over the last 42 years (Danby et al., 2011). Furthermore, changes in community composition were also observed. This study found that some new species of graminoids appeared, and also found that the direction and magnitude of vegetation change varied with the slope aspect. In particular, increases of the species diversity of the Southeast and Southwest aspects were greater than that of the North and East aspects. Erschbamer et al. (2011) showed that alpine endemic species of the south side disappeared much faster among four sides in the Dolomites (northern Italy).

Alpine tundra is the most highly distributed vegetation, and it is predicted that climate change will lead to a reduction in areas of global alpine tundra. The threat of climate warming to alpine tundra vegetation is particularly serious (Diaz and Eischeid, 2007; Ackerly et al., 2010). The Changbai Mountains is identified a typical mountain tundra region in Asia (Huang and Li, 1984). Qian and Zhang (1980), Huang and Li (1984), and Qian (1990) investigated the community structure and identified the dominant species in the tundra (except east slope within the territory of North Korea). Qian's survey in 1977 showed that there were seven dominant species in the tundra zone of the Changbai Mountains, including six shrub species, one herbaceous species. Seven dominant plants were *Rhododendron aureum*, *Vaccinium uliginosum*, *Vaccinium vitis-idaea*, *Phyllodoce caerulea*, *Dryas octopetala* var. *asiatica*, *Rhododendron confertissimum*, *and Sanguisorba sitchensis* (Qian and Zhang, 1980). There were very few herbaceous plants, mostly existing only in a few shrub clusters, and the herbal height (10−15 cm) was lower than that of shrubs (20 cm). Huang's survey in 1984 suggested that the tundra community was simple, comprising shrub-moss lichen tundra with only two layers consisting of shrub and moss lichens. The shrub layer was about 8−22 cm high. The rise in altitude is associated with the lower shrub layer and the smaller overall coverage. Among the nine dominant species of tundra vegetation recorded, the six species were shrubs. Meadow tundra was recorded to have developed in the snow depression (Huang and Li, 1984). Qian (1990) divided the tundra into 59 clusters based on the survey, including 38 shrub-moss-lichen clusters, three shrub-herb clusters and 18 herb clusters. The herbs were mainly distributed in the snow depression. No previous studies have addressed the differences of tundra vegetation between the north and the southwest slopes. The associated tundra vegetation has changed significantly since 1990 (Xu and Zhang, 2010). Low-altitude herbaceous plants have invaded the tundra, resulting in degradation of the original vegetation and replacement by herbaceous plants (Jin et al., 2016). To date, studies of changes in the tundra vegetation of the Changbai Mountains have focused on the herbaceous plant expansion of southwest slope (Zong et al., 2013; 2014; Jin et al., 2016). Jin et al. (2016 and 2017) suggested that herbaceous species have encroached on the alpine tundra zone of southwest slope and become the co-dominant plant species, with shrubs becoming fragmented and patchy and the tundra seeming to be transforming into alpine meadows.

Noticeably, we have observed the differences on tundra vegetation changes between the north and the southwest slopes of the Changbai Mountains. However, differences of vegetation changes have remained unknown. Are the differences of tundra vegetation changes between the north and southwest slopes because of different species composition or because of the different change patterns response to climate change? What are the possible change processes for the differences? All of these are worth exploring. We compared recent survey data with data collected from previous years (Qian and Zhang, 1980; Huang and Li, 1984; Qian, 1990) to analyze the changes in tundra vegetation. In view of the high uniformity between temperature and altitude, we analyzed the altitudinal changes in tundra vegetation diversity between the southwest and the north slopes, and studied the similarities and differences of vegetation in order to detect the differential responses to global warming.

2 Materials and Methods

2.1 Study area

The Changbai Mountains is situated at 41°23'N–42°36'N, 127°55'E–129°00'E, reaching an elevation of 2744 m. Located in the temperate continental monsoon climate zone, the vegetation types are characterized by coniferous and broad-leaved mixed forest, mountain coniferous forest, subalpine birch forest and alpine tundra.

Affected by the East Asian monsoon, the north slopes is the windward of the winter monsoon, while the southwest slopes is the windward of the summer monsoon. The climatic differences between the north and the southwest slopes are relatively large for low and middle elevation region. The annual average temperature and precipitation of the southwest slopes are higher than those of the north slopes (Yang, 1981). The high mountain climate is characterized with low temperature, strong wind, plenty of precipitation and high humidity. Unlike at the lower altitudes, there are no significant differences in climate on top of the mountain among the slopes (Table 1). The Tianchi Meteorological Station is located in the tundra zone at an elevation of 2623 m above sea level, where the average annual temperature is –7.4℃ and the annual average precipitation is 1372.5 mm.

The tundra surface mostly comprises weathered alkaline rough rock and a small amount of volcanic ash. The landform of the volcanic cone slope has been transformed by water. The soil comprises a thin layer of tundra soil that is rich in organic matter, skeletal, shallow and without prominent stratification (Meng, 1982). The north slope is steeper than that of the southwest slope, and the soil thickness of the north slope is thinner than the southwest slope (Jin et al., 2013).

According to the literature, polar or alpine species account for about 80% of the tundra plants of the Changbai Mountains. *Rhododendron aureum* and *Vaccinium uliginosum* communities are the most common plant communities in the tundra zone, with shrubs and moss-lichens constituting the two community layers, and with an herbal layer generally lacking (Qian and Zhang, 1980).

2.2 Data collection

Observed climatic data from 1959 to 2015 (the Tianchi Meteorological Station, 42°01′N, 128°05′E, 2623 m) were provided by China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). We performed quality control based on the method by Alexander et al. (2006) and performed homogeneity test using the RHtestV4 software (Wang and Feng, 2013). The data proved to be homogeneous by this test.

Plots were set up on tundra zone of the north and southwest slopes of the Changbai Mountains (Fig. 1) at elevations ranging from 2000 m to 2600 m in 2015. The 100 m-long sampling transects were set at intervals of 25 m of the altitudinal gradient from low to high elevation, with a 5 m-wide blank spacer left on both sides. Four 1 m × 1 m quadrants were set at intervals of 30 m. Each side contained a total of 25 × 4 = 100 sampling plots. The latitude, longitude, altitude, slope, aspect, plant species composition, height, coverage, as well as the number of plants of each species were recorded.

2.3 Data analysis

(1) Trends of temperature and precipitation in the growing season. Monthly values of temperature and precipitation from June to September were used. The trends in temperature and precipitation in the growing season were estimated by simple linear regression in the past 50 years.

(2) Determination of dominant species. The importance value index (IV), that describes which species are the most important within the studied area, was also determined according to Mueller-Dombois and Ellenberg formulas (1974).

Importance value = [relative density + relative frequency + relative coverage] / 3, where the relative density = number of individuals of a plant / total number of plants × 100; the relative frequency = frequency of a plant population / sum of all population frequencies × 100; the relative coverage = population coverage of a plant / sum of all population coverage × 100.

(3) Ecological dominance D. Simpson dominance index was used to determine shrub and herb ecological dominance in tundra communities between the north and the southwest slopes.

$$D = \sum_{i=1}^{s}\left(\frac{n_i}{N}\right)^2 \tag{1}$$

where S is the number of species; n_i represents the importance value of the ith species; N represents the sum of importance value of all species.

(4) Community covariance CP. Jaccard index was used to determine degree of species co-occurrence of communities in tundra communities between the north and the southwest slopes. The equation is as follows:

$$CP = \frac{c}{a+b-c} \tag{2}$$

Table 1 Climatic differences on tundra zone between north and southwest slopes of Changbai Mountains in growing season in 2015 at elevation of 2300 m

Site	Wind direction of winter half year	Wind direction of summer half year	Average annual precipitation (mm)	Average annual temperature (℃)	>5℃ accumulated temperature
North slope	NW	SE	1013	7.9	946
Southwest slope	SW	SW	1116	8.2	984

Notes: NW, north-west; SE, south-east; SW, south-west

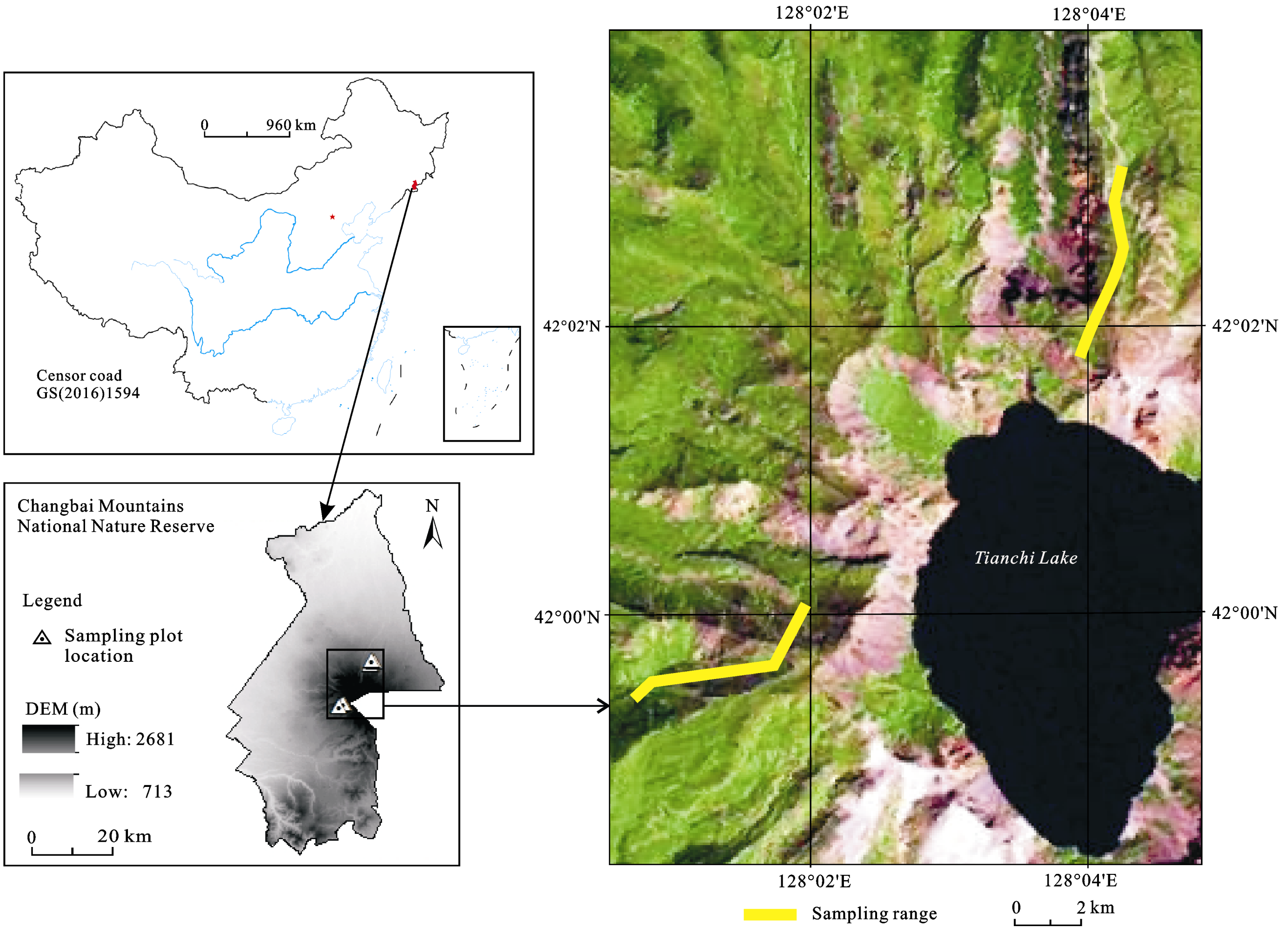

Fig. 1 Sampling transect location map

where *a* is the number of species in the north side community; *b* is the number of species in the southwest side community; *c* is the common species of both; and $a + b - c$ is the total number of species on the north and southwest slopes .

The range of *CP* value represents the similarity, e.g., 0.00–0.25, 0.25–0.50, 0.50–0.75 and 0.75–1.00 represent very dissimilar, moderately dissimilar; moderately similar; and very similar, respectively.

(5) Community α diversity. We used the Margalef species richness index for representing species dominance, the Shannon-Wiener species diversity index for representing community diversity, and the Pielou evenness index for representing the uniformity of the community.

The Margalef species richness index (*MI*) is expressed as:

$$MI = \frac{S-1}{\ln N} \tag{3}$$

where S is the number of species and N is the total number of individuals of all species.

The Shannon-Wiener species diversity index (*SW*) is expressed as:

$$SW = -\sum_{i=1}^{S} P_i \ln P_i \tag{4}$$

where P_i represents the diversity ratio of the ith species, i.e. $P_i = \frac{N_i}{N}$, where N_i is the total number of individuals of the ith species.

The Pielou evenness index (E) is expressed as:

$$E = \frac{1 - \sum_{i=1}^{S} \left(\frac{N_i}{N} \right)^2}{1 - \frac{1}{S}} \tag{5}$$

where S, N, and N_i are the same as above.

(6) Relationship between species diversity and altitude. Scatter plots were used to show the data of altitude

and α diversity index. Linear regression analyses were firstly used to explore the relationships between altitude and diversity index. Once the linear relationship was insignificant ($P > 0.05$), the Binary Linear Regression Models were used. We have chosen to only consider *P*-values smaller than 0.05 as significant.

3 Results

3.1 Trends of temperature and precipitation

Climate change in the alpine tundra of the Changbai Mountains has been observed, and the average temperature in the growing season from June to September has significantly increased from 1959 to 2015. The tendency rate is 0.23℃/10yr from 1959 to 2015, −0.17℃/10yr from 1959 to 1980, and 0.38℃/10yr from 1981 to 2015 (Fig. 2). However, there is no obvious change in precipitation observed from June to September in the past 50 years (Fig. 3).

3.2 Changes in tundra vegetation

The survey conducted in 2015 showed that the herb layer appeared in the tundra vegetation. The relative abundance of the herbaceous plant was greater than 50%, and the relative coverage was more than 30% for the north and southwest slopes (Table 2). In terms of dominant tundra species, compared with previous results (Qian and Zhang, 1980; Huang and Li, 1984; Qian, 1990), shrubs decreased while herbaceous dominant species increased, particularly, and ecological domi-

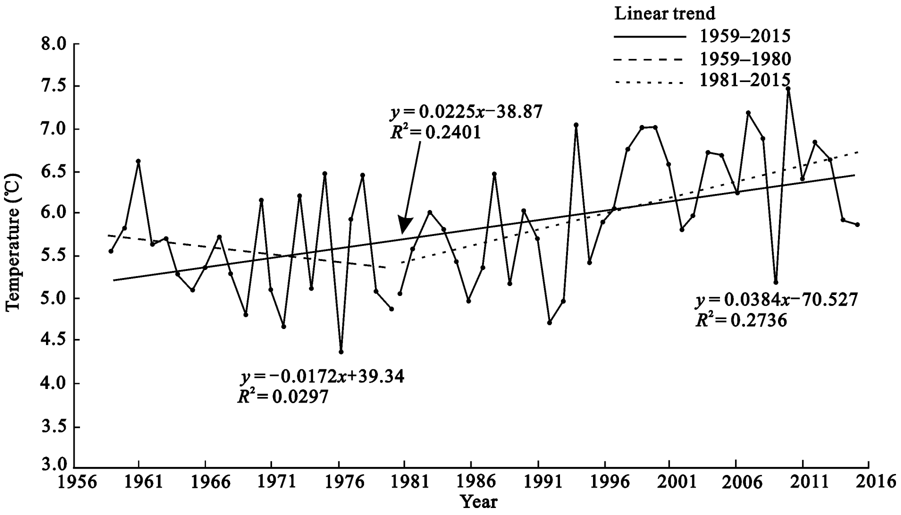

Fig. 2 Trend of average temperature from June to September at Tianchi Meteorological Station from 1959 to 2015

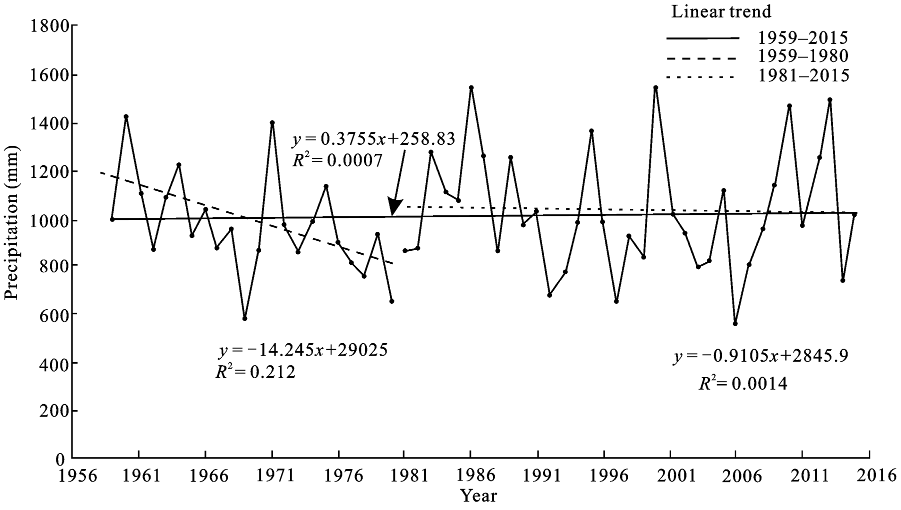

Fig. 3 Trend of precipitation from June to September at Tianchi Meteorological Station from 1959 to 2015

nance of herb increased (Table 2). In summary, the tundra vegetation in the Changbai Mountains has already changed, and the shrub tundra has been transformed to shrub-herb tundra.

3.3 Differences in species composition of tundra vegetation

Our investigation showed that there were 94 species of flowering plants in the tundra vegetation on the north slope of the Changbai Mountains, and 71 species on the southwest slope. Forty-seven species are shared between the two slopes. The similarity coefficient CP of the species composition of the two slopes was 39.83%, and was representative of moderate dissimilarity.

The dominant species of the tundra zone of the north slope include four shrub species (*Vaccinium uliginosum*, *Dryas octopetala*, *Rhododendron aureum*, and *Rhododendron confertissimum*) and three herb species (*Polygonum viviparum*, *Saussurea tomentosa* and *Carex pseudo-longerostrata*). The dominant species of the tundra zone of the southwest slope include two shrubs (*Rhododendron aureum* and *Vaccinium uliginosum*) and five herbs (*Sanguisorba parviflora*, *Sanguisorba stipulata*, *Calamagrostis angustifolia*, *Saussurea tomentosa*, and *Ligularia jamesii*). The dominant species shared between the two slopes include *Rhododendron aureum*, *Vaccinium uliginosum* and *Saussurea tomentosa* (Table 3).

The dominant species on the tundra zone of the north slope were mostly shrubs with relatively high importance values, and *Vaccinium uliginosum* was the most dominant species. The dominant species on the tundra zone of the southwest slope were mostly herbaceous, and of the two shrubs, *Rhododendron aureum* was the main dominant species, while *Vaccinium uliginosum* has a lower importance value (Table 2 and Table 3). The shrubs and herbs on the tundra zone of the north slope accounted for 42.54% and 57.46% of the total number of plants, while those on the tundra zone of the southwest slope accounted for 36.92% and 63.08% of the total number of plants in the survey area (Table 4). The proportion of shrubs on the tundra zone of the north slope was greater than that of southwest slope, indicating the encroachment of herbaceous species into the tundra was more severe on the southwest slope. The plant density of the tundra zone of the north slope was less than half of that of the southwest slope (Table 4).

3.4 Vegetation diversity

The Margalef species richness index and Shannon-Wiener species diversity index of the north slope were unimodally distributed (hump-shaped) with altitude ($P < 0.01$), with the peak in the middle of the tundra zone around 2300 m above sea level and decreasing towards the lower and higher altitudes (Fig. 4 and Fig. 5). The Margalef species richness index and Shannon-Wiener species diversity index of the southwest slope decreased monotonically ($P < 0.01$), and the diversity degree was higher at lower altitudes and decreased gradually towards higher altitudes ($P < 0.05$). The Pielou evenness index of the tundra zone of the north slope did not vary significantly with altitude ($P > 0.05$), suggesting high uniformity. The Pielou evenness index of the tundra zone of the southwest slope showed a significant decrease with altitude ($P < 0.01$), and lower altitudes were more uniform than the higher altitudes (Fig. 6).

The Margalef species richness and Shannon-Wiener species diversity indexes of the tundra shrub and herb layers of the north slope were unimodally distributed with altitude ($P < 0.01$). However, the peak positions differed slightly, in that the herb diversity peak with altitude was lower than the shrub peak (Fig. 7). The Margalef species richness and Shannon-Wiener species diversity indexes of the tundra shrub and herb layers of the southwest slope differed with altitude. Both the Margalef species richness index and the Shannon- Wiener species diversity index of the shrub layer were unimodally distributed ($P < 0.01$), while that of the herbaceous layer decreased with altitude ($P < 0.01$) (Fig. 8).

Table 2 Comparison of the dominant herbs and shrubs of the north and southwest slopes tundra zone in 2015

	Shrub relative abundance (%)	Herb relative abundance (%)	Shrub relative coverage (%)	Herb relative coverage (%)	IV of shrub dominant species	IV of herb dominant species	Shrub dominant species quantity	Herb dominant species quantity	D of Shrub	D of Herb
North slope	42.5	57.5	66.1	33.9	35.80	14.51	4	3	0.029	0.013
Southwest slope	36.9	63.1	33.4	66.6	24.31	32.38	2	5	0.045	0.028

Notes: IV, the importance value index; D, ecological dominance

Table 3 Comparison of dominant species in plant community of tundra zone of north and southwest slopes

Species	Life form	IV	
		North slope	Southwest slope
Vaccinium uliginosum	Shrub	13.0050	3.4724
Dryas octopetala	Shrub	8.5966	
Rhododendron aureum	Shrub	7.6627	20.8425
Polygonum viviparum	Herb	6.7534	
Rhododendron confertissimum	Shrub	6.5372	
Saussurea tomentosa	Herb	4.6169	3.9360
Carex pseudo-longerostrata	Herb	3.1367	
Sanguisorba tenuifolia	Herb		9.0828
Sanguisorba stipulata	Herb		8.4665
Calamagrostis angustifolia	Herb		7.5457
Ligularia jamesii	Herb		3.3467

Note: IV, importance value index

Table 4 Statistics of species in plant community of tundra zone of north and southwest slopes

Family	North slope			Southwest slope		
	Genus	Species	Number of plants	Genus	Species	Number of plants
Gramineae	9	10	858	7	8	2256
Compositae	8	9	1044	7	9	2704
Ericaceae	4	8	3406	3	4	8465
Rosaceae	5	6	1453	3	4	4924
Cyperaceae	2	6	723	2	6	382
Polygonaceae	1	5	1199	1	3	424
Ranunculaceae	5	5	79	4	4	1170
Liliaceae	4	4	709	2	2	39
Leguminosae	4	4	414	2	2	318
Umbelliferae	4	4	408	4	5	332
Lycopodiaceae	4	4	101	3	3	71
Crassulaceae	2	3	79	1	1	699
Saxifragaceae	2	3	24	2	2	177
Juncaceae	1	2	12	1	1	29
Violaceae	1	2	76	1	1	18
Orchidaceae	1	2	6	1	1	5
Gentianaceae	1	2	89	1	2	313
Caryophyllaceae	2	2	193	1	1	82
Papaveraceae	2	2	24	–	–	–
Cupressaceae	1	1	7	1	1	28
Valerianaceae	1	1	20	–	–	–
Primulaceae	1	1	15	1	1	8
Onagraceae	1	1	7	–	–	–
Pyrolaceae	1	1	8	1	1	5
Geraniaceae	1	1	128	1	1	663
Caprifoliaceae	1	1	45	–	–	–
Cruciferae	1	1	7	–	–	–
Scrophulariaceae	1	1	11	2	2	23
Salicaceae	1	1	230	1	2	44
Iridaceae	1	1	14	1	1	10
Campanulaceae	–	–	–	1	1	13
Urticaceae	–	–	–	1	1	27
Tofieldiaceae	–	–	–	1	1	71
Shrub subtotal			4845			8602
Shrub proportion (%)			42.54			36.92
Herb subtotal			6544			14698
Herb proportion (%)			57.46			63.08
Total	93	94	11389	57	71	23300

4 Discussion

4.1 Changes of tundra vegetation pattern

Vegetation in many alpine and subalpine areas has changed over the last few decades, and a thermosphilization trend has been observed. For instance, lower altitude species near the forest line or below the forest line have appeared in higher altitude areas (Klanderud and Birks, 2003; McDougall et al., 2005; Danby and Hik, 2007; Beckage et al., 2008; Kelly and Goulden, 2008; Parolo and Rossi, 2008; Frei et al., 2010; Odland et al., 2010). The upward expansion of herbaceous plants is particularly obvious (Walther et al., 2005; Danby and Hik, 2007; Pauli et al., 2007; Danby et al., 2011), and these changes are overwhelmingly the result of climate warming (Hughes, 2000; Walther, 2003; Thuiller et al., 2006).

The Changbai Mountains tundra was dominated by shrubs 30 years ago, with very few herbs recorded (Qian and Zhang, 1980). Currently, the importance value of most of the dominant shrub species in the north and southwest slopes have decreased and herbaceous plants have spread into this area, forming an herbaceous plant layer. Most of these herbaceous plants were migrating from the birch forest zone. Some of these herbaceous plants were originally rare species that had existed in the tundra zone before 30 years ago. These herbaceous plants formed patches of herbs, and become common and even dominant species in many tundra habitats recently (Xu and Zhang, 2010; Zong et al., 2013; Jin et al.,

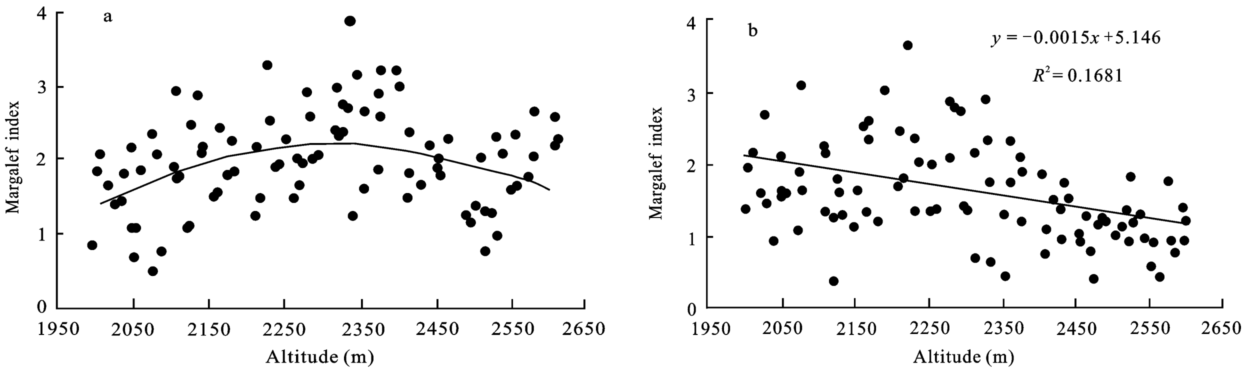

Fig. 4 Changes of Margalef species richness index of tundra zone of north slope (a) and southwest slope (b) with altitude

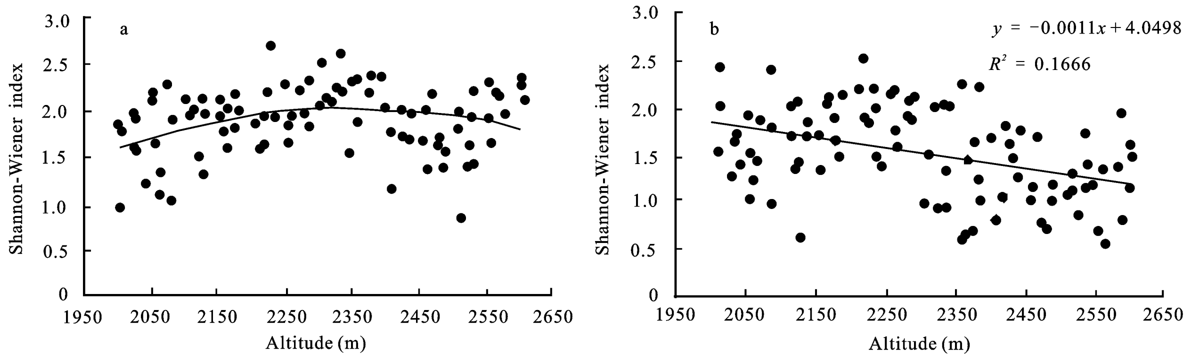

Fig. 5 Changes of Shannon-Wiener species diversity index of tundra zone of north slope (a) and southwest slope (b) with altitude

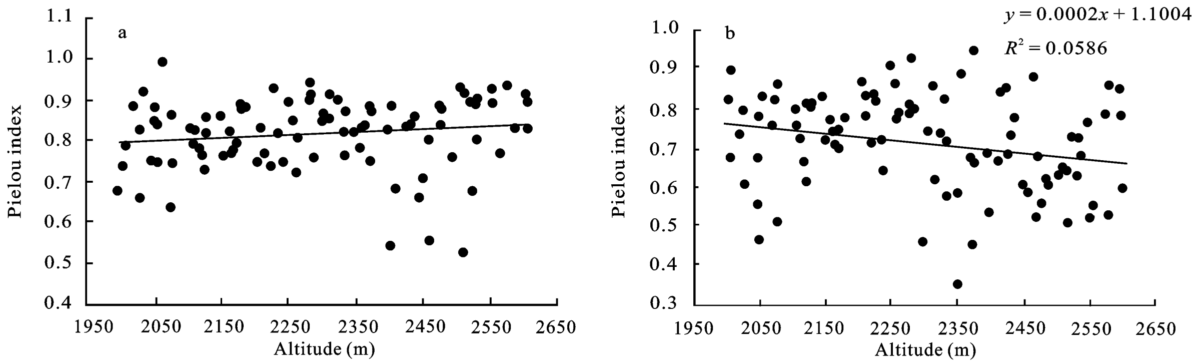

Fig. 6 Changes of Pielou evenness index of tundra zone of north slope tundra zone (a) and southwest slope (b) with altitude

2016). And there was a much greater shift in species rankings in the north and southwest slopes. Changes in the Changbai Mountains alpine tundra are correlated with alpine tundra changes in other areas, suggesting that the invasion of herbs into the tundra is a general response to global warming (Danby et al., 2011; Erschbamer et al., 2011).

4.2 Changes in tundra species diversity with altitude

If the vegetation is in an undisturbed and stable situation, plant diversity changes with altitude are mostly unimodal, with the largest diversity of plants occurring at intermediate altitudes (Colwell and Hurtt, 1994; Rahbek, 1995; Odland and Birks, 1999; Grytnes, 2003; Bruun et al., 2006). However, if there is persistent strong invasion from low-altitude plants, the biodiversity will increase significantly and will change the plant diversity distribution patterns. Our study showed that the species diversity is unimodally distributed on the tundra zone of the north slope of Changbai Mountains, indicating that the distribution pattern has not been

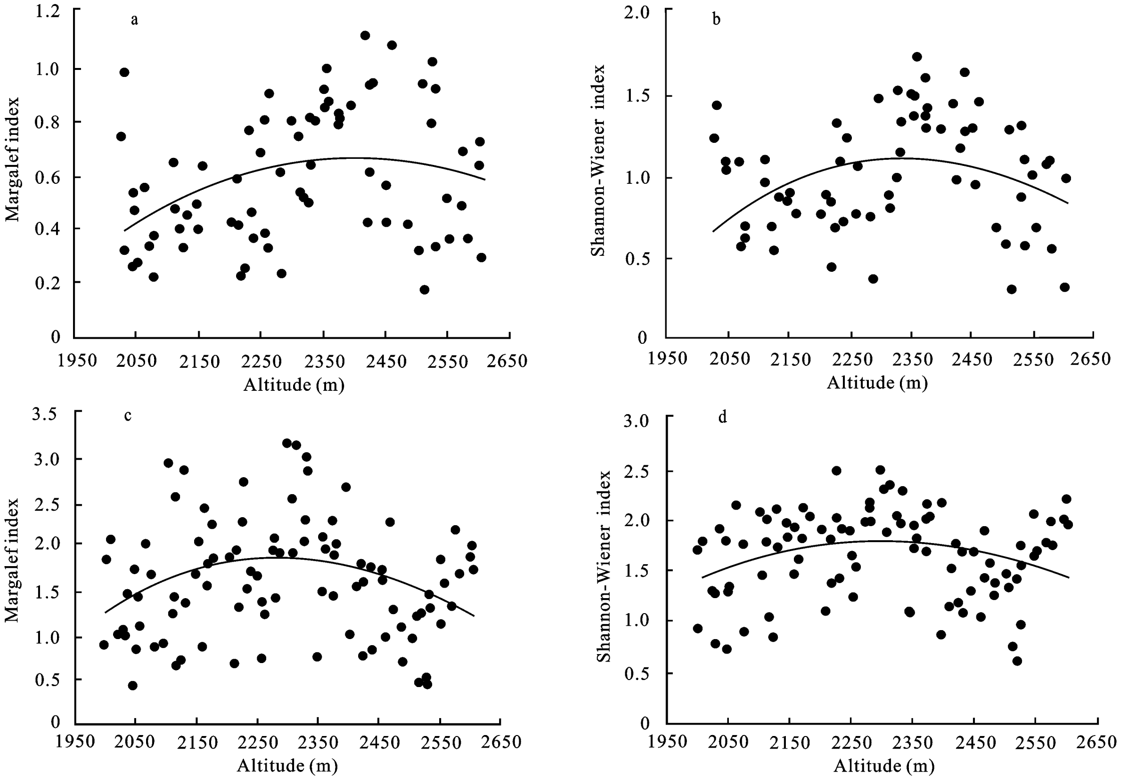

Fig. 7 Changes of Species α diversity of tundra zone shrub layer (a, b) and herb layer (c, d) of north slope with altitude

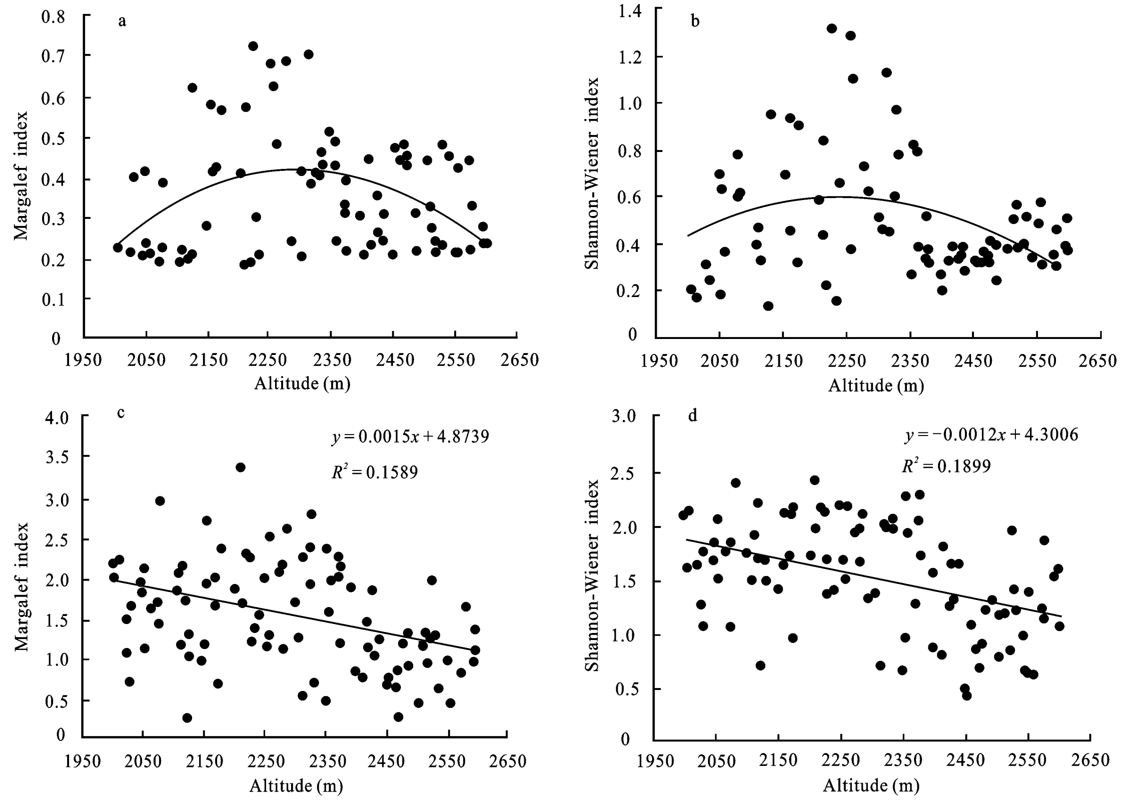

Fig. 8 Changes of Species α diversity of tundra zone shrub layer (a, b) and herb layer (c, d) of southwest slope with altitude

affected by the invasion of herbaceous plants. While the invasion degree of herbaceous plants on the southwest slope is high, the distribution pattern has obviously been altered, with species diversity decreasing linearly with altitude. This change pattern of southwest slopes is consistent with the change pattern of plant diversity at high altitudes on the Qinghai-Tibet Plateau (Shimono et al, 2010). The invasion of herbaceous plants increased the species diversity at low altitudes in the tundra zone, but there was a difference in the invasion degree of herbaceous plants in different slope areas, leading to the north and southwest slopes possessing different species diversity patterns with altitude. It can be inferred that if invasion from herbs increases on the north slope, the species diversity distribution pattern with altitude will change from unimodal to a linear decrease.

Species diversity patterns also differed between the shrub and herbaceous layers. The species diversity of shrub and herbaceous layers of the north slope were both unimodal, indicating that herbaceous plant invasion is currently in a stable state. The diversity index of the tundra shrub layer of the southwest slope is still unimodal, but the herbaceous layer diversity index decreased with increasing altitude, suggesting that herbaceous plant invasion was continuous and that the herbaceous layer was transforming.

4.3 Effects of multiple factors on changes in tundra vegetation

The Changbai Mountains tundra is located on a small area of the uppermost section of the volcanic cone. Therefore, the temperature and precipitation of the tundra zone should not be significantly different, and vegetation response to climate warming should generally be consistent. Furthermore there should not be any significant differences in the distribution pattern of species diversity among different slopes. So other factors as well a rise in temperature must play important roles in the changes of tundra vegetation.

The micro-terrain associated with the slope aspect strengthens the differences in microclimate. In comparison to the northern slopes, soil temperature of the southwestern slopes is higher in mountains of northernmost Fennoscandia (Bruun et al., 2006; Scherrer and Körner, 2011). So the warmer micro-habitats in the southwest slope are more than that of the north slope on tundra zone of the Changbai Mountains. And the precipitation of the southwest slope is higher than that of the north slope since southwest slope is windward slope in the growing season. Furthermore, smaller slope, thicker soil, and better fertility in the southwest slope resulted in relatively denser vegetation compared to those of the north slope, which is more intensely response to climate change. This is in accordance with the existing literature (Danby et al., 2011; Engler et al., 2011; Erschbamer et al., 2011).

The vegetation of the Changbai Mountains is also affected by volcanic eruptions, and the vegetation succession stages on different slopes differ. The deposition thickness of the volcanic ash and pumice on different slopes differs due to the impact of volcanic eruption angle and the strong high-altitude westerly winds. The eastern slope is most thick, followed by the southern and western slopes, while the northern slope is the least thick. The volcanic ash and pumice form loose parent soil material, which is continuously eroded by water. This has a long-term impact on the succession of destructed vegetation in that each slope manifests a different distribution. The northern slope was the first to experience a volcanic eruption, and the vegetation succession began on a solid geological basis (bedrock). It is currently in the middle and later stages of vegetation succession, and thus the tundra vegetation development is more advanced. The southwestern slope is in the middle stages of succession (Jin et al., 2013). The different stages of vegetation succession are the basis for the changing tundra vegetation patterns. The vegetation of the north and southwest slopes was moderately dissimilar, and the fact that there were more species on the north slope despite the poor water and heat conditions also verified this view. In the later stages of succession, the plant community structure is more complex and stable, and the anti-interference ability is strong (Grime, 1998). Therefore, the invasive degree of herbaceous plants on the north slope is lower than that of the southwest slope. The later the succession stage, the weaker the response to climate warming is.

In addition, the role of snow is also important as climate change has brought about changes in parameters such as a decline in snow cover and an advance in snowmelt timing, resulting in moss lichens in the snow depression being replaced by herbs (Danby et al., 2011). The increased prevalence of herbs in the Changbai Mountains tundra may also be associated with this.

More snow has accumulated on the southwest slope, and the spatial distribution of snow patch and the timing of snowmelt differ greatly between the two slopes. The effect of changes in snow as a result of climate change on vegetation change increase with altitude, such that the evenness index decreases significantly with altitude. In other words, the higher the altitude, the more evident the herbaceous patchiness on the southwest slope due to decreasing permanent snow patches.

The species diversity distribution pattern of the north slope of the Changbai Mountains tundra does not change with the altitude, indicating that some factors may slow down the effects of climate warming, and the dramatic changes of the southwest slope indicate that some factors may enhance the effects of climate warming.

4.4 Indicators of alpine tundra vegetation change

Tundra vegetation is highly susceptible to global warming, with changes in alpine tundra being recorded first (Danby and Hik, 2007; Bjorkman et al., 2015). Changes in alpine tundra vegetation are therefore indicative of global climate change. Studies have shown that a rise in temperature occurred in the tundra zones of Eurasia and North America, which was associated with the forest expanding into the tundra zone in the north (Myers-Smith et al., 2011). At the same time, the phenomenon of herb invasion may occur whereby herbs infiltrate the tundra zone, causing changes in species composition and diversity, which may lead to changes in surface energy balances, primary productivity, nutrient cycling and nutrient interactions. In view of the significant differences of the tundra in terms of the complex terrain, hydrothermal conditions, carbon balance, snow coverage, soil fertility, etc., the associated vegetation changes would be diverse. In the absence of long-term monitoring in the Arctic region, changes in the tundra vegetation of the Changbai Mountains, especially with regards to the responses of differential slopes, could provide a reference for the prediction of vegetation changes in the Arctic.

5 Conclusions

1) The average temperatures in the growing season have increased from 1981 to 2015, and there was no obvious change in precipitation observed tundra zone of the Changbai Mountains. 2) The elevated temperature of tundra zone resulted in the invasion of thermophilic herbs. Over the past 30 years, the tundra vegetation of the Changbai Mountains has changed significantly as herbaceous plants have invaded and so as the community composition. The proportion of herbaceous plants has become higher than that of shrubs. In the context of global warming, the shrub tundra is transforming to shrub-herb tundra. 3) The tundra vegetation responses of the north and southwest slopes to global warming differed greatly. The tundra zone of the southwest slope exhibited a significantly higher degree of herbaceous plant invasion and vegetation change than that of the tundra zone of the north slope. 4) The species diversity of the tundra zone of the north slope showed a unimodal change with altitude, while the species diversity of the southwest slope decreased monotonously with altitude. The differences in the degree of herbal invasion prompted changes in tundra species diversity patterns on the north and southwest slopes. 5) The differences in local microclimate, plant successional stage, fertility and other factors superimposed with the effects of climate warming resulted in differential responses of tundra vegetation on different slopes to global warming.

There are both similarities and differences in the change patterns of tundra vegetation on different slopes of the Changbai Mountains. For instance, there is a common response to global warming, but there are differences in the response patterns. Global warming, differences in local conditions, vegetation characteristics and other factors are all contributing factors to the differences in vegetation response patterns.

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