Postprint: The Relationship Between Herbaceous Plant Invasion and Soil Environment in the Changbai Mountain Tundra

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Date: 2018-03-08T00:00:00+00:00

Abstract

Based on vegetation surveys and soil sampling analysis of 132 quadrats within a transect on the western slope of the alpine tundra in Changbai Mountain, this study employed Redundancy Analysis (RDA) and Canonical Correlation Analysis to investigate the relationship between the degree of herbaceous plant invasion in the tundra zone and the physicochemical properties of tundra soil as well as environmental factors. The results indicated that the degree of herbaceous invasion on the western slope of the Changbai Mountain tundra zone exhibited significant regional variation, which could be classified into five distinct invasion grades; ten soil environmental factors including elevation, slope gradient, total potassium content, clay content, and organic matter content were significantly correlated with the degree of herbaceous plant invasion. RDA analysis demonstrated that soil environmental factors could explain 93% of the plant species abundance information, with organic matter content, clay content, and slope gradient being the primary soil factors influencing herbaceous plant invasion; the first pair of canonical variables revealed that organic matter content was positively correlated with the abundance of Rhododendron chrysanthum and negatively correlated with the abundance of Sanguisorba stipulata, whereas clay content exhibited the opposite relationship; the second pair of canonical variables showed that elevation and available nitrogen content were negatively correlated with the abundance of Vaccinium uliginosum and Geranium baishanense. Herbaceous plants on the western slope of the Changbai Mountain tundra zone were spatially distributed in a discrete, patch-like pattern. This indicates that herbaceous plant invasion exhibits habitat selectivity. The positive correlation between soil organic matter content and shrub abundance suggests that soil organic matter content decreases during the process of herbaceous invasion; or alternatively, in areas where organic matter content declines, shrub growth degenerates, thereby facilitating herbaceous invasion and establishment.

Full Text

Relationship Between Herbaceous Plant Invasion and Soil Properties in the Changbai Mountain Tundra

ACTA ECOLOGICA SINICA, Vol. 38, No. 4, Feb. 2018 DOI: 10.5846/stxb201701050046

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Abstract

The alpine tundra of Changbai Mountain, located on the upper slopes of the volcanic cone (2000–2500 m), represents the only typical alpine tundra in eastern China. Due to its environmental similarities with polar tundra, this ecosystem holds significant scientific value. Herbaceous species invasion has been documented in both polar and alpine tundra worldwide, likely driven by climate change. Vegetation and soil are closely correlated in tundra ecosystems, with changes in vegetation community structure directly or indirectly altering soil properties. The progression of herbaceous invasion has resulted in decreased organic matter content. Tundra vegetation growth is constrained by both temperature and soil composition (i.e., nutrients), while plant community composition affects local soil processes. The Changbai Mountain tundra vegetation is undergoing significant changes in response to global climate change, particularly on the western slopes where herbaceous plants have become invasive and expanded their distribution, substantially reducing the dominance of shrubs.

This study investigated the relationship between herbaceous plant invasion and soil properties across 132 plots within a 100 m × 1600 m transect on the western slope of Changbai Mountain tundra in August 2014. Plot coordinates (latitude, longitude, elevation) were measured using GPS, while slope, aspect, and position were recorded with a compass. Plant community characteristics (species, height, density, coverage) and soil thickness were documented in the field. Physicochemical properties (n = 12) of sieved soil samples (0–10 cm) were analyzed in the laboratory.

Redundancy analysis (RDA) and canonical correlation analysis revealed that herbaceous invasion degree varied significantly and could be categorized into five invasion levels. Ten soil factors (e.g., elevation, slope, total potassium, clay content, organic matter content) showed significant correlations with herbaceous invasion degree. Samples with higher herbaceous invasion were primarily located in areas with lower elevations, steeper slopes, relatively low mineral and organic nutrient contents, low sand and silt contents, and relatively high clay content.

However, no obvious relationship was found between herbaceous invasion and available nutrient contents (available N, available P, available K).

RDA indicated that soil factors explained 93% of the variation in plant species abundance, with organic matter content, clay content, and slope being the main factors affecting herbaceous invasion, while shrub growth was primarily influenced by organic nutrient content. The distributions of herbaceous plants *Sanguisorba stipulata* were related to soil thickness and clay content, respectively. Canonical correlation analysis showed that soil factors and plant species abundance were significantly correlated, with different herbaceous species exhibiting distinct habitat preferences. Specifically, the first canonical variable indicated that organic matter content was positively correlated with *Rhododendron chrysanthum* abundance and negatively correlated with *Sanguisorba stipulata* abundance, while clay content showed the opposite relationship. The second canonical variable revealed that elevation and available nitrogen content were negatively correlated with the abundance of *Vaccinium uliginosum* and *Geranium baishanense*.

Keywords: herbaceous plant invasion; physicochemical soil properties; soil factor; alpine tundra soil; Changbai Mountain

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1. Study Area and Methods

1.1 Study Area Overview

The alpine tundra of Changbai Mountain is located on the upper portion of the volcanic cone (2000–2500 m) in southeastern Jilin Province, representing the only typical alpine tundra in eastern mainland China. The study area is situated in the core region of the western slope tundra belt (41°58 -41°59 N, 127°59 -128°01 E). The climate is temperate continental monsoon, with an annual average temperature of only -5.87°C and mean annual precipitation of 1340 mm concentrated primarily in June–September, accounting for approximately 70% of annual precipitation. The growing season (June–September) has a mean daily temperature of 7.3°C. Soils are classified as tundra soils, characterized by weak profile development and distinct coarse skeletal properties [14].

1.2 Field Survey and Sampling

In August 2014, we established a 100 m × 1600 m transect on the western slope of the Changbai Mountain tundra belt, spanning elevations from 2046 to 2291 m. Sample plots (1 m × 1 m) were set up at 100 m intervals along the main transect direction, with three parallel sub-transects creating a total of 132 plots (33 × 4 = 132). For each plot, we measured geographic coordinates (latitude, longitude, elevation) using GPS, recorded slope, aspect, and position using a compass, and documented soil thickness and plant community metrics (species composition, height, density, coverage). Surface soil samples (0–10 cm) were collected from each plot using a soil auger, with three replicates per plot. Samples were sieved to remove roots and stones before laboratory analysis.

[Figure 1: see original paper] **Fig. 1** Location map of transect sampling sites

1.3 Laboratory Experiments

Soil physicochemical indicators were measured using standard methods. Soil organic matter content was determined by the potassium dichromate volumetric method. Total nitrogen (TN) and total phosphorus (TP) were measured using a continuous flow chemical analyzer (SKALAR SAN++) after digestion with H SO -HClO and H SO -HF, respectively. Available nitrogen was determined by the alkali diffusion method, available phosphorus by NaHCO extraction, and available potassium by ammonium acetate extraction followed by inductively coupled plasma optical emission spectrometry (ICPS-7500). Soil particle size distribution was measured using a laser particle size analyzer, with clay defined as particles <2 m, silt as 2–50 m, and sand as 50–2000 m. Fulvic acid carbon and humic acid carbon were extracted with sodium pyrophosphate and measured by the potassium dichromate oxidation method.

1.4 Data Processing

We used Excel and SPSS 19.0 software to calculate plant species density, frequency, and coverage. RDA was performed using Canoco 4.5 software. Canonical correlation analysis, a multivariate statistical method that examines relationships between two sets of variables through multiple canonical variables, was used to analyze correlations between soil factors and vegetation abundance. This method transforms the overall linear correlation between two original variable sets into relationships between extracted canonical variables, and has been widely applied in ecological research [15–17].

Let X and Y represent the two variable groups, with linear combinations V and W as canonical variables. The correlation coefficient between them is the canonical correlation coefficient.

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2. Results and Analysis

2.1 Classification of Herbaceous Invasion Levels in the Changbai Mountain Tundra

Historical records indicate that the western slope tundra was previously dominated by shrubs and moss-lichens, with few herbaceous plants [18–19]. Based on the ratio of herbaceous to shrub coverage, we classified the 132 sample plots into five invasion levels: no invasion (ratio 0.1), mild invasion (0.1<ratio 0.3), moderate invasion (0.3<ratio 0.6), severe invasion (0.6<ratio 0.9), and full invasion (0.9<ratio 1.0). The average coverage of each plant species across invasion

levels is shown in Table 1.

Table 1 Plant species and their coverage under different invasion degrees

2.2 Soil Characteristics Under Different Herbaceous Invasion Levels

Statistical analysis of soil factors across invasion levels revealed distinct patterns (Table 2). Soil factors included both physicochemical and environmental variables. Slope position was categorized as summit, upper, middle, lower, and foot slopes (assigned values 1-5), while slope aspect was classified as west, northwest, and southwest (assigned values 1-3). As herbaceous invasion intensity increased, elevation, organic matter content, and sand content showed clear decreasing trends, while clay content increased. Available nutrients fluctuated without clear directional changes.

Plots with heavy herbaceous invasion were primarily located in lower-elevation, steeper-slope areas of the tundra belt. These plots exhibited lower total nitrogen, total potassium, fulvic acid, and humic acid contents, with reduced sand content but increased clay and silt fractions. In contrast, available nutrients showed no significant changes across invasion levels.

Table 2 Average values of soil factors under different herbaceous invasion degrees

[Figure 2: see original paper] **Fig. 2** Trend of ten soil factors with increasing severity of herb invasion

2.3 Redundancy Analysis of Invasion Degree and Soil Factors

Detrended Correspondence Analysis (DCA) of major plant species data from the tundra belt indicated gradient lengths of 2.925, suggesting the data were suitable for RDA. Monte Carlo permutation tests showed that the first and second axes were highly significant ($P < 0.01$), with correlations between soil factors and plant species of 0.66 on the first axis and 0.42 on the second axis.

The first RDA axis explained 87.3% of the species-environment variation and was primarily correlated with organic matter content, clay content, and slope. The second axis explained 5.7% of the variation and was mainly associated with soil thickness, available potassium, and elevation. Therefore, the primary soil factors influencing herbaceous invasion in the Changbai Mountain tundra were organic matter content, clay content, and slope.

The RDA ordination diagram clearly showed the second axis as a boundary separating invasion levels: high-invasion plots were distributed on the left side (negative side) of axis 2, while low-invasion plots were on the right side (positive side). The two shrub species (*Rhododendron chrysanthum* and *Vaccinium uliginosum*) were positioned on the right side, while all herbaceous species except *Sanguisorba parviflora* and *Saussurea tomentosa* were on the left. Herbaceous invasion primarily varied along axis 1, indicating that factors correlated with axis 1 were the main drivers.

Rhododendron chrysanthum showed positive correlation with organic matter content, while *Vaccinium uliginosum* was positively associated with fulvic acid carbon content, suggesting shrub growth is influenced by soil organic nutrients. Among herbaceous species, *Sanguisorba stipulata* was clearly positively correlated with clay content, while *Deyeuxia angustifolia* and *Geranium baishanense* were positively associated with soil thickness.

Table 3 Summary statistics for RDA axes of alpine tundra, Changbai Mountain

[Figure 3: see original paper] **Fig. 3** RDA of plant species and soil factors in alpine tundra, Changbai Mountain

2.4 Canonical Correlation Analysis Between Soil Factors and Plant Abundance

Canonical correlation analysis examines overall correlations between two sets of indicators through comprehensive variable pairs, revealing intrinsic relationships more effectively than simple correlation analysis [20–22]. We selected nine soil environmental and physicochemical factors as independent variables and abundance and coverage ratios of herbaceous to shrubs plus abundance of nine plant species as dependent variables (Table 4).

Table 4 Selected variables in this study

Analysis yielded two significant canonical variable pairs ($P < 0.01$) with correlation coefficients of 0.753 and 0.676, respectively. The squared coefficients were 0.567 and 0.457, indicating that 56.7% and 45.7% of the information in the biological process variables could be explained by corresponding soil factors.

First canonical variable pair: V = 0.314X - 0.329X + 0.496X - 0.153X - 0.141X + 0.047X - 0.326X + 0.188X - 0.085X + 0.603X + 0.224X + 0.453X - 0.624X + 0.162 W = -0.846Y + 0.657Y - 0.859Y + 0.601Y - 0.688Y - 0.431Y - 0.166Y + 0.36Y + 0.182Y - 0.047

In this pair, organic matter (X) and clay content (X) had large weight coefficients in the independent variable set, while *Sanguisorba stipulata* abundance (Y) and *Rhododendron chrysanthum* abundance (Y) dominated the dependent set. This pair primarily explains the competitive relationship between *R. chrysanthum* and *S. stipulata*: organic matter content is positively correlated with *R. chrysanthum* abundance but negatively correlated with *S. stipulata* abundance, while clay content shows the opposite pattern.

Second canonical variable pair: V = 0.827X - 0.079X - 0.236X + 0.346X + 0.327X + 0.429X - 0.416X + 0.202X - 0.164X + 0.150X - 0.256X + 0.337X - 0.069X W = 0.359Y + 0.061Y + 0.292Y + 0.595Y - 0.513Y - 0.471Y - 0.184Y + 0.385Y + 0.364

In this pair, elevation (X) and available nitrogen content (X) had large weight coefficients in the independent set, while *Vaccinium uliginosum* abundance (Y) and *Geranium baishanense* abundance (Y) dominated the dependent set. This pair indicates that elevation and available nitrogen content are negatively correlated with the abundance of both *V. uliginosum* and *G. baishanense*.

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3. Discussion

3.1 Relationship Between Soil Environmental Factors and Herbaceous Invasion

Current research on herbaceous invasion in the Changbai tundra primarily attributes the phenomenon to temperature increases, nitrogen deposition, and seed rain intensity changes. Under these factors, herbaceous plants invade from low to high elevations, showing discrete spatial distributions and clear habitat selectivity. Soil represents a crucial habitat factor, and soil physicochemical properties are closely related to herbaceous invasion patterns, with complex feedbacks between vegetation and soil changes.

Wang Xiaodong et al. [9] found that *Deyeuxia angustifolia* dominates on gentle slopes (<5°), while *Rhododendron chrysanthum* dominates on steep slopes (>42°). Our results show non-invaded plots averaged 15.8° slope, while severely and fully invaded plots averaged 33.1° and 28.4°, respectively. This similarity suggests that steep slopes favor herbaceous establishment because shrub seeds struggle to colonize steep terrain, whereas herbaceous seeds have dispersal advantages better suited to such conditions. In the Changbai tundra, herbaceous plants initially establish on steep slopes before expanding gradually.

Zong Shengwei et al. [11,23] demonstrated that *D. angustifolia* and other herbaceous species gradually invade upward along elevation gradients, a phenomenon observed globally in alpine ecosystems [24]. Chen et al. [25] reported species migrating upward at 11 m per decade and poleward at 16.9 km per decade. Our study found heavily invaded plots concentrated in lower-elevation tundra zones, with canonical correlation analysis showing negative correlation between elevation and *Geranium baishanense* abundance. This aligns with the pattern of upward expansion from lower-elevation birch forests, constrained by seed dispersal limitations and increasingly harsh conditions at higher elevations. Slope aspect and position had relatively minor effects compared to elevation and slope, which primarily determine seed sources, temperature ranges, and colonization potential.

3.2 Relationship Between Soil Physicochemical Factors and Herbaceous Invasion

Soil particle composition critically affects water-holding capacity, which is essential for plant competition and predicting species responses to climate change in alpine regions [26]. Our results demonstrate that clay content significantly influences plant abundance patterns. In the Swiss Alps, Kämmer et al. [26] showed soil water storage capacity is a key factor affecting plant species diversity in high alpine vegetation.

Regarding soil organic nutrients, both shrub species showed positive correlations with soil organic content. Studies in the Qinghai-Tibet Plateau [27–29] similarly found that alpine meadow degradation reduces plant diversity, productivity, and surface soil fertility. As shrub vegetation degrades in Changbai tundra, soil organic matter content decreases significantly. Shrubs, with their abundant litter and taproot systems, provide more organic matter to soil than herbaceous plants. Root systems also significantly influence soil nutrients through phenolic compound exudation [30], particularly in alpine ecosystems.

For soil mineral nutrients, heavily invaded plots showed lower total nitrogen and total potassium contents, while available nutrients remained unchanged. Zamin et al. [31] found that experimental warming increased tundra soil nutrient content and plant biomass in Canadian mesic low arctic tundra. Michelson et al. [32] observed that nitrogen addition in Swedish tundra promoted grass growth (*Festuca ovina*) while dwarf shrub (*Vaccinium uliginosum*) cover changed little, indicating that warming and nitrogen deposition enhance herbaceous growth. However, under combined nitrogen deposition and herbaceous invasion, mineral nutrient changes in tundra soils are complex, showing no clear trends. Bret-Harte et al. [35] found that nitrogen deposition reduced moss biomass in Alaskan tundra, while Wang et al. [36] demonstrated that vascular plants absorb nitrate nitrogen more efficiently than mosses absorb ammonium nitrogen. As mosses decline with shrub tundra degradation, nitrogen exchange between soil and plants changes, reflecting the complex feedbacks between vegetation shifts and soil properties.

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4. Conclusions

Herbaceous invasion levels in the Changbai Mountain tundra show significant variation and can be classified into five distinct grades. Invasion degree is significantly correlated with elevation, slope, and clay content. Heavily invaded plots are concentrated in lower-elevation, steeper-slope areas with reduced mineral and organic nutrients, lower sand and silt contents, but higher clay content. Available nutrients show no significant changes.

RDA explained 93% of plant species variation, identifying organic matter content, clay content, and slope as the primary factors affecting herbaceous invasion, while shrub growth was mainly influenced by organic nutrients. *Deyeuxia angustifolia* distribution correlated with soil thickness, while *Sanguisorba* species distributions related to clay content, indicating distinct habitat selection among herbaceous species.

Canonical correlation analysis revealed two significant variable pairs explaining 56.7% and 45.7% of variation, respectively. The first pair showed organic matter content was positively correlated with *Rhododendron chrysanthum* abundance but negatively correlated with *Sanguisorba stipulata* abundance, with clay content showing the opposite relationship. The second pair demonstrated that elevation and available nitrogen content were negatively correlated with *Vaccinium uliginosum* and *Geranium baishanense* abundance.

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Note: Figure translations are in progress. See original paper for figures.