Vegetation Ecological Characteristics in the Permafrost Region on the Northern Slope of the Greater Khingan Mountains and Their Response to Permafrost Degradation (Postprint)

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Abstract

Permafrost and vegetation are crucial components of cold region ecosystems. As global warming progresses, permafrost is gradually degrading, leading to decreased soil moisture and organic matter content, which subsequently impacts aboveground vegetation. This study investigated the plant ecological characteristics of permafrost regions on the northern slope of the Greater Khingan Mountains and their response to permafrost degradation. The results showed that a total of 85 plant species were recorded across the 30 surveyed permafrost sites, belonging to 29 families and 55 genera. Among these, there was 1 fern species, accounting for 1.2% of the species composition; 1 gymnosperm species, accounting for 1.2%; and 83 angiosperm species, accounting for 97.6%. Among the four life forms, hemicryptophytes were the most diverse with 51 species, representing 60% of the total species count; geophytes and phanerophytes followed with 12 and 19 species respectively, representing 14.1% and 22.4%; chamaephytes were relatively scarce with only 3 species, representing 3.5%. Among the four water ecological types, mesophytes were the most diverse with 50 species, representing 58.8% of the total species count; hygrophytes followed with 26 species, representing 30.6%; helophytes accounted for 7 species (8.2%); and xerophytes were the least abundant with 2 species (2.4%). Within the active layer thickness range of 50–150 cm, the number of plant families, genera, and species was highest, followed by permafrost regions with thickness greater than 150 cm; when the active layer thickness was smaller (< 50 cm), the number of plant families, genera, and species was lowest. With increasing active layer thickness, i.e., permafrost degradation, the number of hemicryptophyte species increased significantly ($P < 0.05$), the number of phanerophyte species decreased significantly ($P < 0.05$), while the number of chamaephyte and geophyte species showed no significant change with active layer thickness. With increasing active layer thickness, the number of helophyte species decreased significantly ($P < 0.05$), the number of mesophyte species increased significantly ($P < 0.05$), while the number of hygrophyte and xerophyte species showed no significant change with active layer thickness, and community plant composition gradually shifted from hygrophytic to mesophytic.

Full Text

Preamble

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Title: Ecological Characteristics of Vegetation and Their Responses to Permafrost Degradation in the North Slope of Great Khingan Mountain Valley of Northeast China

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Abstract

Permafrost, defined as ground that remains below 0℃ for at least two consecutive years, is an important component of the cryosphere that is highly vulnerable to climate warming. Global warming has accelerated permafrost degradation, evidenced by thickening of the active layer, increasing ground surface temperatures, and the transition from continuous to island permafrost. Vegetation is a vital component of permafrost ecosystems and is particularly sensitive to permafrost degradation, which leads to changes in plant community characteristics such as species composition, diversity, vegetation cover, and biomass. The impacts of permafrost degradation on vegetation have become a key topic in climate change research. However, previous studies have focused primarily on permafrost distribution, with limited quantitative research on the mechanistic connections between permafrost and environmental factors and on how permafrost degradation affects vegetation ecological characteristics. Understanding these responses is therefore essential.

In this study, we investigated plant ecological characteristics and their responses to changing permafrost thaw depths on the north slope of the Great Khingan Mountain valley in northeast China. Our results showed that 30 plots contained 85 plant species belonging to 29 families and 55 genera. Angiosperms dominated, accounting for 97.6% of total species, while ferns and gymnosperms each comprised only 1.2%. Based on Raunkiaer' s life form classification, the flora included 51 hemicryptophytes (60%), 12 phanerophytes (14.1%), 19 geophytes (22.4%), and 3 chamaephytes (3%). Among hydro-ecotypes, mesophytes were most abundant with 50 species (58.8%), followed by hygrophytes (30.2%), helophytes (8.2%), and xerophils (2.4%).

Plant families, genera, and species all reached maximum richness at an active layer thickness (ALT) of approximately 50–150 cm. Taxonomic abundance was intermediate where ALT $>$ 150 cm and lowest where ALT $\leq$ 50 cm. Hemicryptophyte species increased significantly with increasing ALT, whereas phanerophyte species decreased significantly. Changes in geophyte and chamaephyte species numbers were not significant. Helophyte species decreased significantly with increasing ALT, while mesophytes showed an increasing trend. Hygrophyte and xerophil species showed no significant changes with ALT.

Our findings indicate that the study area experiences short summers and long, cold winters, with plant growth conditions tending toward moderation. This research provides a theoretical basis for predicting vegetation ecological characteristic variations under permafrost degradation and offers important insights for agricultural and forestry development in permafrost zones. Additionally, our observations may guide forest management and biodiversity conservation efforts in permafrost regions.

Keywords: Great Khingan Mountains; permafrost degradation; vegetation; ecological characteristic; active layer thickness

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1. Study Area Overview

The study area is located on the north slope of the Great Khingan Mountains (50°01 01 –53°26 25 N, 119°07 02 –121°49 17 E) and features a cold temperate continental monsoon climate. Winters are extremely cold and prolonged, with mean annual temperatures ranging from -4 to -1℃. Annual precipitation ranges from 350 to 550 mm, and the growing season lasts approximately 100 days. The flora is dominated by cold temperate species, with a minority of temperate species.

Sample plots were situated in the transition zone between grassland and forest ecosystems, where species composition is relatively rich. Plant communities exhibit relatively simple vertical structure with three distinct strata. The tree layer is dominated by Dahurian larch (*Larix gmelinii*), including some old-growth stands and scattered Asian white birch (*Betula platyphylla*). The shrub layer contains more species, including dwarf birch (*Betula fruticosa*), narrow-leaf Labrador tea (*Ledum palustre* var. *angustum*), and bog blueberry (*Vaccinium uliginosum*), which are characteristic of permafrost vegetation communities. The ground layer is primarily covered by various *Sphagnum* mosses such as intermediate bog moss and white-toothed peat moss. The herb layer contains the most species, including *Carex subpediformis*. Soils are mainly meadow and swamp soils, with loose texture, surface water accumulation, and high organic matter content.

1.1 Plot Setup

This study employed a space-for-time substitution approach. We selected 30 plots with similar habitat conditions across different active layer thickness (ALT) conditions. For each plot, we recorded plant species names, height, and other quantitative metrics, along with environmental factors including longitude, latitude, altitude, slope, soil water content, and ALT. Plots were classified into three ALT ranges: 0–50 cm, 50–150 cm, and >150 cm. Shrubs were surveyed in 2 m × 2 m quadrats, while herbs were surveyed in 1 m × 1 m quadrats. ALT was measured using the direct excavation method, with a maximum excavation depth of 150 cm. Detailed plot information is provided in Table 1.

2. Plant Life Form and Water Ecological Type Analysis

Plant life form represents the adaptive morphology that plants develop under long-term environmental influences. Using Raunkiaer' s life form system, which classifies plants based on dormant bud position during unfavorable seasons, permafrost community plants were categorized into four types: phanerophytes, chamaephytes, hemicryptophytes, and geophytes.

Based on plant-water relationships, plants were classified into hydro-ecotypes: hygrophytes (plants growing in moist environments that cannot tolerate prolonged water deficiency), mesophytes (plants in moderate moisture conditions), xerophils (plants that can tolerate long-term drought while maintaining water balance and normal growth), and helophytes (plants with only roots and basal parts submerged in water). Each species was classified according to both life form and water ecological type, with quantities and percentages calculated as indices for structural analysis.

3. Data Processing and Analysis

Origin 8.6 software was used for graphical plotting, and SPSS 18.0 software was used for statistical analyses.

3.1 Community Plant Composition Analysis

The survey of 30 permafrost plant communities revealed 85 plant species. Hemicryptophytes were the most abundant life form (60% of species), followed by geophytes (22.4%) and phanerophytes (14.1%), with chamaephytes being least common (3.5%). Angiosperms dominated the flora (97.6% of species), while ferns and gymnosperms each represented only 1.2%.

Among hydro-ecotypes, mesophytes were most abundant (58.8% of species), followed by hygrophytes (30.6%), helophytes (8.2%), and xerophils (2.4%).

In terms of importance values, phanerophytes ranked highest, followed by hemicryptophytes and chamaephytes. For water ecological types, hygrophytes showed the highest importance value, followed by helophytes and mesophytes, while xerophils had the lowest.

[Figure 1: see original paper]
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3.2 Changes in Plant Families, Genera, and Species with Active Layer Thickness

Across the three ALT ranges, the highest numbers of families, genera, and species occurred in the 50–150 cm zone (8–21 families, 27-43 genera, and 38–76 species). The second highest abundance occurred where ALT > 150 cm. Therefore, the most species-rich ALT range was 50–150 cm, while ALT < 50 cm had the lowest taxonomic richness. Both very shallow and very deep active layers were unfavorable for species richness.

3.3 Changes in Plant Life Forms with Active Layer Thickness

As ALT increased, hemicryptophyte species numbers increased significantly ($P < 0.05$), while phanerophyte species numbers decreased significantly ($P < 0.05$). Changes in geophyte and chamaephyte species numbers were not significant ($P > 0.05$). Analysis of importance values showed that hemicryptophyte importance values decreased significantly with increasing ALT ($P < 0.05$), while geophyte importance values increased significantly ($P < 0.05$). Phanerophyte and chamaephyte importance values showed no significant changes with ALT ($P > 0.05$), though both exhibited decreasing trends.

[Figure 5: see original paper]
[Figure 6: see original paper]

3.4 Changes in Plant Water Ecological Types with Active Layer Thickness

With increasing ALT, helophyte species numbers decreased significantly ($P < 0.05$), while mesophyte species numbers increased significantly ($P < 0.05$). Hygrophyte and xerophil species numbers showed no significant changes with ALT ($P > 0.05$), though hygrophytes exhibited a decreasing trend while xerophils showed an increasing trend. Xerophils first appeared in zones where ALT > 150 cm.

Analysis of importance values revealed that helophyte importance values decreased significantly with increasing ALT ($P < 0.05$), while mesophyte importance values increased significantly ($P < 0.05$). Hygrophyte and xerophil importance values showed no significant changes with ALT ($P > 0.05$), though hygrophyte importance values decreased while xerophil importance values increased with ALT.

[Figure 7: see original paper]
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4. Discussion

Permafrost is highly sensitive to climate change and has degraded to varying degrees under current global warming scenarios. Active layer thickness serves as a key parameter characterizing permafrost conditions and can reflect permafrost dynamics to some extent. This study established an ALT gradient sequence from small to large, assuming that this spatial pattern reflects environmental change trends as ALT increases in the study area, thereby implementing the predictive concept of space-for-time substitution. By analyzing how plant ecological characteristics change with ALT, we explored the impacts of permafrost degradation on plant community ecological characteristics.

The Great Khingan Mountains region has a cold temperate continental monsoon climate. Permafrost vegetation communities are stressed by severe cold and composed mainly of cold-resistant species. Compared to other climate zones, higher latitudes have fewer plant species due to temperature limitations. The short summer and limited exposed ground surface area, combined with summer surface water accumulation, allow only deep-rooted shrubs, various *Carex* species that can form tussocks, and a few herbs adapted to cold, wet environments to grow.

Life forms represent long-term adaptive responses to environmental conditions and often serve as indicators of regional bioenvironmental and topographic factors. In naturally growing communities, life forms are typically not singular but composed of several types, with one or a few dominant. In low-latitude regions with favorable water-heat conditions, phanerophytes dominate, while geophytes are abundant in cold regions. This study shows that hemicryptophytes dominate in the Great Khingan permafrost region, reflecting the local climate of short summers and long, severe winters. The high proportions of hemicryptophytes and geophytes indicate these are the most successful life forms adapted to harsh winter conditions. Although phanerophytes are not numerous, their high importance values indicate their significant role in the community. The combined importance values of helophytes and hygrophytes account for 76.2%, reflecting the moist habitat characteristics of permafrost, though soil conditions show a trend toward mesophytism.

During permafrost degradation, soil moisture content changes significantly across different ALT ranges, with soil water content decreasing markedly. Our results show that as ALT increases, helophyte species numbers and importance values decrease significantly, while mesophyte species numbers and importance values increase significantly. Moisture-loving species decline and are gradually replaced by mesophytes. Xerophils appear only where ALT > 150 cm. Similar studies have found that from continuous to island permafrost zones, helophyte importance values decrease significantly while mesophyte and xerophil importance values increase, indicating soil moisture conditions are becoming more mesic and even xeric. As permafrost degrades, surface water content decreases, providing opportunities for mesophyte invasion and altering community structure. With continued degradation and further groundwater decline, aquatic or hygric species disappear and xerophytes may emerge.

The response of vegetation to permafrost degradation is a gradual dynamic process. Whether in the Great Khingan Mountains, the Qinghai-Tibet Plateau, or Arctic regions, as permafrost degrades, helophytes decrease and are replaced by mesophytes, with xerophytes potentially appearing. The most suitable method for studying this dynamic response is long-term monitoring based on quadrat surveys. However, due to the lack of long-term observation systems in the Great Khingan region, this study used space-for-time substitution to explore vegetation responses to permafrost degradation. Future research should establish long-term monitoring systems in northeast permafrost regions and investigate the impacts of permafrost degradation on vegetation carbon pools.

5. Conclusion

Plant ecological characteristics represent long-term adaptations to the environment and serve as environmental indicators. The ecological characteristics of plants on the north slope of the Great Khingan Mountains indicate that the study area has short summers and long, severe winters. Within the 50–150 cm ALT range, soil nutrients and moisture conditions for plant growth are optimal, resulting in the highest species richness. Both shallower and deeper ALT zones are unfavorable for species richness. As permafrost degrades and ALT increases, soil moisture content decreases, moisture-loving plants decline, and are gradually replaced by mesophytes. This research on plant ecological characteristics and their responses to permafrost degradation provides valuable insights for further studies on environmental change and permafrost degradation in this region.

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