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Symbiosis of Marshes and Permafrost in Da and Xiao Hinggan Mountains in Northeastern China

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Abstract: Recently, the degradation of permafrost and marsh environments in the Da and Xiao Hinggan Mountains has become a great concern as more human activities and pronounced climate warming were observed during the past 30 years and projected for the near future. The distribution patterns and development mechanisms of the permafrost and marshes have been examined both in theories and in field observations, in order to better understand the symbiosis of permafrost and marshes. The permafrost and marshes in the Da and Xiao Hinggan Mountains display discernible zonations in latitude and elevation. The marsh vegetation canopy, litter and peat soil have good thermal insulation properties for the underlying permafrost, resulting in a thermal offset of 3℃ to 4℃ and subsequently suppressing soil temperature. In addition, the much higher thermal conductivity of frozen and ice-rich peat in the active layer is conducive to the development or in favor of the protection of permafrost due to the semi-conductor properties of the soils overlying the permafrost. On the other hand, because permafrost is almost impervious, the osmosis of water in marsh soils can be effectively reduced, timely providing water supplies for helophytes growth or germination in spring. In the Da and Xiao Hinggan Mountains, the permafrost degradation has been accelerating due to the marked climate warming, ever increasing human activities, and the resultant eco-environmental changes. Since the permafrost and marsh environments are symbiotic and interdependent, they need to be managed or protected in a well-coordinated and integrated way.

Keywords: marsh; permafrost; symbiosis; thermal offset; active layer; Da and Xiao Hinggan Mountains

1 Introduction

Recently, the degradation of permafrost and marsh environments in the Da and Xiao Hinggan (Xing'anling in Chinese) Mountains has become a great concern as more human activities and pronounced climate warming were observed during the past 30 years and projected for the near future. About 390,000km^2 of permafrost was mapped in the Da and Xiao Hinggan Mountains in the northeastern China before the 1970s (Zhou and Wu, 1965; Guo et al., 1981). However, the area of the permafrost has been in a rapid decline due to the combined influences of increasing human activities and climate warming since then (Zhou et al., 1996; Jin et al., 2000a; 2000b). The marshes in the Da and Xiao Hinggan Mountains have showed the similar trend as that of permafrost (Sun, 2000).

Since the later half of the 20th century, the qualitative relationship between the frozen ground and marshes in the Da and Xiao Hinggan Mountains were widely recognized (Zhou and Wu, 1965; Wang, 1998; Zhou et al., 2000; Jin et al., 2000a; 2000b). Many scholars believed that permafrost paludification would generally occur when water percolation was greatly reduced due to the existence of frozen soil as an aquiclude. Since the early 1960s, geocryologists have recognized the close rela-

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tionship between the freeze-thaw processes of soils and the development of marshes, the widespread concurrence of permafrost and marshes in the wide valleys in the Da and Xiao Hinggan Mountains, the good insulation properties of organic soils in marshes facilitating ice segregation in soils (Ding et al., 1987), and the assistance of permafrost in the development and protection of marshes (Wang, 1983; 1998; Sun, 2000). Many scholars studied spatio-temporal correlations and the inherent connection between the permafrost environment and marsh vegetation from the viewpoint of landscape ecology (Zhang, 1983; Lu, 1989; Yang, 1989; Chen and Yin, 1996). Sun (2000) preliminarily summarized the symbiotic mechanism of marshes and permafrost, and proposed that with more accumulation of peat, the thickness of permafrost increases and soils become less nutritious, accelerating the development and expansion of peat bogs. He further underlined that the permafrost and the freeze-thaw processes in the active layer have played very important roles in the formation, development, and protection of marshes in cold regions. On the other hand, it has been widely recognized that thermal and moisture properties and regimes of soils in marshes greatly impact the underlying permafrost (Kersten, 1949; Brown, 1963; Brown and Péwé, 1973; Ershov, 1998).

Recently, some national key projects of China, particularly those regarding soil and water conservation, expressway and China-Russia crude oil pipeline, and associated eco-environmental management, necessitated research on permafrost and marshes. In this paper, the symbiotic mechanisms of the permafrost and marshes in the Da and Xiao Hinggan Mountains in the northeastern China were further explored on the basis of theoretical analyses and observational evidence in the view of heat and water transfer.

2 Permafrost in Da and Xiao Hinggan Mountains

2.1 Study area

The permafrost in the Da and Xiao Hinggan Mountains is located in the vicinity of the southern limit of permafrost (SLP) of the Eurasian Continent (Fig. 1). The elevation in the northern Da and Xiao Hinggan Mountains ranges from 150 to 1529m. The vegetation mainly includes subarctic taiga forests, mixed coniferous and broadleaf forests, forest meadow and steppe. The mean annual air temperature (MAAT) ranges from –5℃ to 2℃, with a maximum annual range of temperature of 46℃. The SLP in the northeastern China largely coincides with the MAAT isotherm of –1℃ to 1℃ (Guo et al., 1981; Jin et al., 2006). The annual precipitation is 400–600mm, whereas the annual evaporation is about 1000mm. The persistent atmospheric inversion results in colder and thicker permafrost in lower landform (Jin et al., 2007). Although snow covers in the Da and Xiao Hinggan Mountains are generally thin, it can reduce the range of monthly mean ground surface temperature by 10–38℃ (Dai, 1982; Zhou and Guo, 1983; Zhou et al., 1993).

2.2 Permafrost features

The southern limit of permafrost (SLP) protrudes southwards in the Da and Xiao Hinggan Mountains, but shrinks by about 2º northwards on the edges of the Songnen Plain. The present SLP in the northeastern China falls between the MAAT isotherms of –1 and 1℃ (Guo et al., 1981; Zhou et al., 2000; Jin et al., 2006). To be more specific, 1) on the Hulun Buir Grassland, west of the Da Higgan Mountains, the SLP is between the isotherms of –1 and 0℃; 2) in the middle, including the northern part of the Songnen Plain and the southeastern and southwestern piedmonts of the Da Hinggan Mountains, the SLP largely coincides with the 0℃ isotherm; and 3) in the east, including the northern part of the Sanjiang Plain and the southeastern and southwestern piedmonts of the Xiao Hinggan Mountains, the SLP is between the isotherms of 0 and 1℃.

In the study area, annual precipitation declines northwestwards and soil moisture content decreases accordingly, and marshes are widespread in the northeastern part. Thus, in the northeastern part the concentrative precipitation (80%–90% of yearly total) and high soil moisture contents effectively dampen and retard the rising of soil temperature in summer, together with the evaporative cooling, helping the preservation of the underlying permafrost; in the northwestern part, however, ground temperature is more sensitive to climatic warming, and permafrost degrades more rapidly due to the drier soils.

The natural landscape in the permafrost zones in the northeastern China include the taiga forests in the northern and middle Da Hinggan Mountains, the mixed coniferous and broadleaf forests in the Xiao Hinggan Mountains, the forest-meadow in the northern Songnen Plain, and the steppes in the northern Inner Mongolia Plateau.

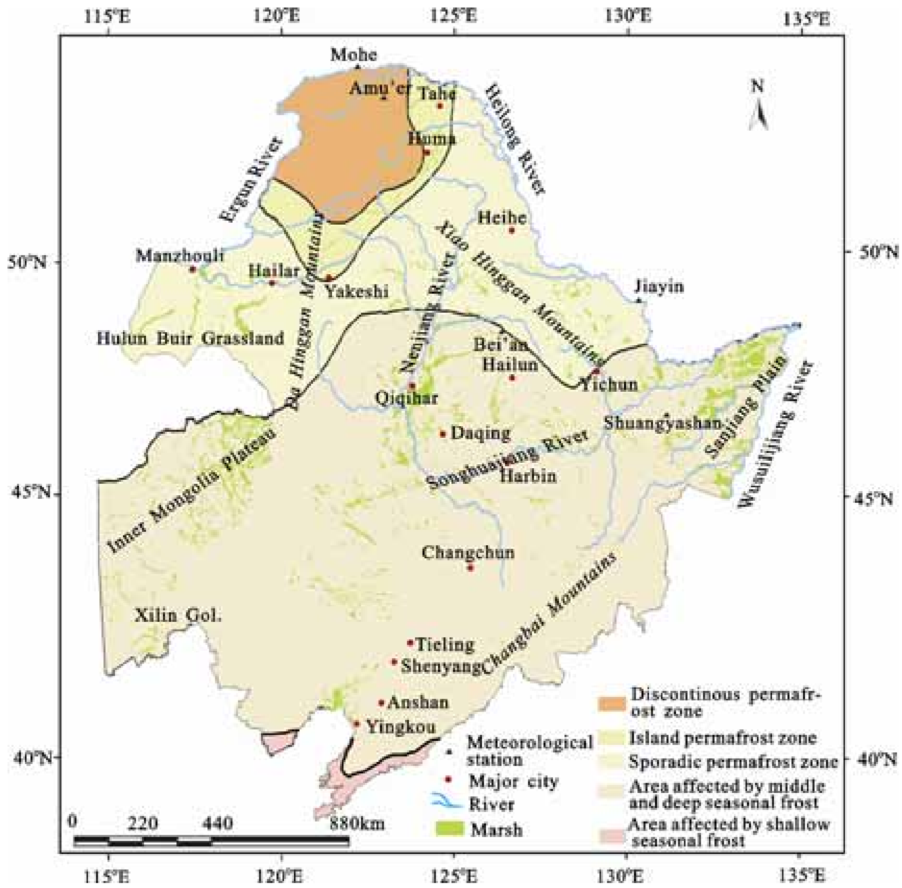

Fig. 1 Distribution of permafrost and marshes in northeastern China

The distribution of permafrost in the northeastern China is mainly controlled by latitudinal zonation. The statistics indicate that the distribution of the permafrost has a very good correlation (coefficient about 0.98) with mean annual air and ground surface temperature. From north to south, the MAAT increases from –5 to 0℃, and annual range of air temperature declines from 50℃ to 40℃. As a result, the area continuity of the permafrost is reduced from 70%–80% to 5%–30% (Table 1). The mean annual ground temperature (MAGT) rises southwards from –4℃ to 0℃. Correspondingly, the thickness of permafrost decreases southwards from about more than 100m to a few meters, even to less than 1m largely in the form of pure ground ice layer in marshes, and eventually disappears (Guo et al., 1981; Dai, 1982; Zhou et al., 1996; 2000; Jin et al., 2006) (Table 1).

The distribution laws of permafrost in the mountains are (Fig. 1):

Permafrost is distributed more extensively in the Da Hinggan Mountains than in the Xiao Hinggan Mountains. Discontinuous permafrost is largely found in the northern part of the Da Hinggan Mountains, and sporadic permafrost mainly exists in the southern part of the Da Hinggan Mountains and in the southeastern part of the Xiao Hinggan Mountains. SLP reaches 46º30′N in the Da Hinggan Mountains, but only about 47º48′N in the Xiao Hinggan Mountains. Permafrost temperature in the northeastern China is same or slightly lower than that in the southern part of Eastern Siberia at the similar latitudes because of relatively higher elevation of about 1000m in the Da Hinggan Mountains, and lower elevation of 350–400m in the eastern part of Trans-Baikalia. The areas adjacent to the Heilong-Amur River are roll-

Table 1 Basic feature of permafrost in northeastern China

Zone	MAAT (℃)	MAGT (℃)	Continuity (%)	Thickness (m)
Discontinuous	<-5	-4–0	70–80	50–100
Island	-5–-3	-2–0	30–70	20–50
Sporadic	-3–0	-1–0	5–30	5–20

Source: Zhou et al., 2000

ing hills of 200–800m in elevation. Therefore, the "W"-shaped SLP in the Da and Xiao Hinggan Mountains and the Songnen Plain displays the comprehensive influences of latitude and elevation.

2) Lowlands favor the development and protection of permafrost. In the discontinuous permafrost zone, the paludified areas with mosses and peat layers in basins, permafrost often is cold (-3℃ to -4℃), ice-rich (with layered ground ice), and thick (>100m), due to the influences of soil type, moisture content and persistent winter air stagnation over the intermontane lowlands.

3) The belt of sporadic permafrost is as wide as 200–400km. This is a transition zone between permafrost and the seasonal frost.

3 Evidences of Symbiosis of Marsh and Permafrost

Five major features are apparent in the development and distribution of marshes in the Da and Xiao Hinggan Mountains: 1) dominance of peat bogs; 2) complicated and/or mosaic marsh types; 3) development mainly on northern and western slopes of the mountains; 4) dominance of forest, meadow and permafrost paludification; and 5) conspicuous vertical and horizontal zonations.

The northern part of the Da and Xiao Hinggan Mountains is extensively paludified, because major types of marshes are distributed on almost all terrains, with apparent horizontal and vertical zonations.

Different types of marshes have their specific elevational zones. The *Larix*-*Pinus*-*Sphagnum* bogs are mainly distributed on the area above 1500m. The *Larix*-*Vaccinium*-*Sphagnum* bogs with patches of *Betula*-*Carex* and *Carex*-*Calamagrostis* swamps are at 1250–1350m (Lang, 1983). The *Larix*-*Rhododendron Sphagnum* bogs are concentrated on the terraces at 500–1000m.

Horizontal zonation of marshes is also recognized. In *Larix*-*Rhododendron*-*Sphagnum* bogs, *Sphagnum* plants form turfs as tall as 1.0 to 1.5m, with 100% coverage, and with a peat layer as thick as 0.5 to 1.5m. In addition to the shading effects of *Larix gmelinii* and *Pinus pumila* canopy, this type of soil structure effectively insulates the underlying permafrost from surficial thermal effects. This kind of marsh is mainly distributed in discontinuous permafrost zone with a continuity of permafrost of 70%–80%, and a total permafrost area of 50,000–60,000 km^2 (Guo et al., 1981). The landform is flat with dense, meandering river networks.Ground surfaces are wet, with the dense *Sphagnum* and *Carex* turfs underlain by permafrost. Generally, in the intermontane basin marshes, the thicknesses of permafrost vary from 60 to 80m, and sometimes exceed 90–100m. The permafrost temperature ranges from -1.5℃ to -3.5℃, occasionally to -4.2℃ (Northeastern China Permafrost Research Taskforce, 1983). In these marshes, the thick-layered ground ice is well developed. Even though the climate warms up sharply, the thawing of permafrost in these areas has been slow. The depths of maximum thaw penetration in this type of marshy soils are shallow (0.5–2.0m), compared with those of 1.5–4.5m in drier areas.

The *Larix*-*Vaccinium*-*Sphagnum* bogs are distributed south of the *Larix*-*Pinus*-*Sphagnum* bogs, but north of the Hailar and Heihe. The boundary of the *Larix*-*Vaccinium*-*Sphagnum* bogs largely coincides with the isotherms of -5℃ to -3℃ of the MAAT and -1.5℃ to -0.5℃ of MAGT. This kind of marsh is mainly distributed in island permafrost zone with a continuity of permafrost of 30%–60%, and a total area of the permafrost of 25,000–30,000km^2. The thicknesses of island permafrost vary from 20–50m. Compared to the discontinuous permafrost zone, which also coincides with the distribution of the *Larix*-*Pinus*-*Sphagnum* bogs, the development of island permafrost depends more on the favorable slope orientations and surface paludification.

The *Larix*-*Rhododendron*-*Sphagnum* bogs are distributed in more southward areas with MAATs at about -0.5 to 2.0℃ and MAGTs at -1℃ to 4℃. This kind of marsh is mainly distributed in sporadic permafrost zone including the areas north of Pinggang, Shuangshan, Bei'an and Xingdong, with a continuity of 5%–30% and a permafrost area of 28,000–32,000km^2.

The symposis of marshes and permafrost can be also found in some landforms. Sporadic permafrost can be found on the shadowy slopes or beneath the lowlands marshes, with a continuity of 5%–20%, and with a thickness generally less than 10m. River networks are well developed on the southeastern slopes of the Da Hinggan Mountains and western slopes of the Xiao Hinggan Mountains. Permafrost is sporadic on the floodplains, and on the lower terraces and shadowy slopes. Along the river floodplains, permafrost is distributed in the frequently disrupted stripes, and patches or lenses on the river terraces. In the vicinity of the southern limit of permafrost (SLP) and on the northern edge of the Songnen Plain, permafrost has degraded significantly due to strong human activities (Jin et al., 2007). The thickness of permafrost generally varies from 5 to 15m. In the low and rolling Xiao Hinggan Mountains, river valleys are wide and flat, rivers meander greatly and marshes are well developed. Permafrost patches can only be found on the densely vegetated, paludified valley bottoms, floodplains, and areas adjacent to the oxbow lakes on low terraces, with a continuity of about 5%–15%. The active layer consists of peat and clayey soils in the wet, lowland marshes, with the maximum thaw depths of 2.5–3.5m depending upon vegetative coverage.

4 Effect of Permafrost on Marsh

4.1 Promoting marsh plant growth

During the dry period of spring, snowmelt runoff in permafrost area can not permeate downwards, timely providing the badly needed water at plant root system for the early root-spreading or germination of mash plants. Therefore, plants start to grow about 20 days earlier in marsh than in dry lands, which would play an important role in the vegetation succession. In the mountains, seasonal frost penetrates down to 4m in taliks, the ground freezing starts almost immediately after the completion of thawing. Therefore, the frozen layer lasts for a long time to hold water for root system for plant growth.

4.2 Affecting marsh development and distribution

In the locations with poor drainage, ground surface is inundated from April to September. The low soil temperature and evaporation, and saturated conditions form reducing environment, resulting in low decomposition and subsequent high accumulation of organic matter, thus favoring the development and expansion of marsh. The freeze-thaw process also plays important roles in the expansion of marsh. In the process, the most important factors influencing marsh expansion include the depths and duration of ground freezing and thawing, and thermal and hydraulic properties of soils in the active layer.

In many paludified lowlands and intermontane basins in the mountains where moss and peat layers are thick, moisture content of soil containing ice layers can reach 520%–1200%. Soils are generally saturated at the lower active layer. Because of the presence of permafrost, the thawing process and areal continuity of permafrost control marsh types. The continuity and development of marshes increase northwards with rising continuity of permafrost. In the vicinity of SLP where permafrost is sporadic and seasonal thaw depths reach down to 2–4m, marshes generally develop on permafrost islands. In large expanse of discontinuous permafrost, where permafrost is thick, stable and relatively continuous, ground surface is inundated during the entire thawing season, so marshes develop in almost all terrains.

5 Effect of Marsh on Permafrost

5.1 Impacts of soil properties in marsh on freeze-thaw process

Near the ground surface, temperature and moisture content of soil vary substantially with the freeze-thaw processes (Wang, 1998). When soil is under a freezing and thawing cycle, its conductivity has significant changes, resulting in the temperature offset (the difference between the multi-year average temperature of the ground surface and the multi-year mean temperature at the bottom of the active layer, or the permafrost table). Therefore, permafrost can exist under warmer climate because of the temperature offset. The regions with continental climate, moist fine-grained soil and saturated peat have the largest temperature offset of about 3℃–4℃ (Garagulia, 1985).

The unique thermal and pedological structures of marsh lands can insulate or cool the underlying soils depending on the distribution of snow cover, standing waters and soil saturation conditions, vegetation coverage, and organic soil layers. In the northeastern China, land paludification mainly results in cooling of underlying soils and reducing of thaw depth. For example, in the discontinuous permafrost zone in the northern part (Amu'er) of the Da Hinggan Mountains, the paludified valley bottoms generally have MAGT from –4℃ to –2℃, and thaw depth of ≤1m (Table 2), whereas on slopes, the MAGT is about 1.5℃ to 4.0℃ higher than that in the valley bottoms, and permafrost is often vertically disconnected by a talik layer, or absent, with seasonal frost depth of 2.0–4.3m. In the island permafrost zone, surface paludification generally controls and indicates the occurrence of permafrost.

Table 2 Relationships between insulation conditions and permafrost table in Amu'er

Cover and thickness (Insulation condition)	Soil type	Permafrost table (m)		
		Good	Fair	Poor
Litter (0–0.1m)	Sand	0.7–1.2	1.3–1.7	1.8–2.2
	Gravel	1.2–2.0		2.1–3.5
	Pebble	2.0–2.8	2.9–3.5	3.6–4.3
Peat (0.2–0.4m)	Sand	0.5–1.1	1.2–1.6	1.7–2.0
	Sand and gravel	0.6–1.1	1.2–1.6	1.7–2.1
	Gravel	0.9–1.7		1.8–3.0
	Pebble	1.0–1.6	1.7–2.3	2.4–3.3
Peat (0.5–0.7m)	Sand	0.4–1.0	1.1–1.2	1.3–1.5
	Sand and gravel	0.4–1.0	1.1–1.2	1.3–1.4
	Pebble	0.4–1.1	1.2–1.7	1.8–2.2
	Peat	0.3–0.8	0.4–1.0	0.6–1.2

In the northern part of the Da Xinggan Mountains, permafrost is generally covered by a thick peat layer (0.5–1.5m). Taliks are generally associated with the gleyzation mires with a thin (0.5m or less) peat layer. Thick layers of peat are generally residuals of *Sphagnum* mosses, which form a multi-layer structure and are covered by shrubs or arbor trees.

The thermal offsets of peat soils can better protect permafrost by reducing annual amplitudes of soil temperature and depths of the active layer (Brown, 1963; 1965; Nelson et al., 1985). Observation in the Amuer area indicate that moss layers can lower soil temperature by 2.5–3.5℃ under similar other conditions (Table 3).

Table 3 Comparison of soil temperature of marsh with non-marsh in Amu'er

Depth (m)	*Larix* forest only (℃)		Forested *Larix-Rhododendron-Sphagnum* bog (℃)		Difference (℃)	
	Annual amplitude	Annual average	Annual amplitude	Annual average	Annual amplitude	Annual average
0.5	18.1	1.2	15.2	–2.3	2.9	3.5
1.0	9.1	0.7	8.6	–2.4	0.5	3.1
1.5	6.2	–0.2	7.7	–3.1	–1.5	2.9
2.0	3.2	0.8	5.2	–2.0	–2.0	2.8
2.5	2.3	0.7	4.1	–2.1	–1.8	2.8
3.0	2.2	0.6	2.9	–2.0	–0.7	2.6
3.5	2.0	–0.1	2.3	–2.6	–0.3	2.5

Source: Zhou et al., 1993

5.2 Shielding effects of marsh canopy on permafrost

The presence of vegetation and migration, convection and evaporation of surface water and/or soil moisture provide a marked thermal insulative effect for the underlying permafrost. In valley marshes of Amu'er area, the diurnal range of surface temperature of 18-cm-thick mosses is about 35℃ in July, while the range beneath the layer of mosses reduces by 1.5℃. Combined with the insulation effect of snow cover of about 20cm in winter, the net thermal effect of moss and litter layers result in a decrease of about 0.1℃–0.3℃ in the mean annual ground temperature (MAGT), and a reduction of annual range of surface temperatures by 2.4℃–5.2℃ in Gulian and Amu'er regions in the northern part of the Da Hinggan Mountains (Gu et al., 1994). The effects of dense and thick vegetation cover and moss layer result in a marked reduction in thaw penetration depths. In addition, peat bogs are forested and underlain by permafrost in many areas. The presence of forest has significant impacts on the thermal and moisture regimes of soils due to its roles in forming a unique microclimate.

6 Conclusions and Suggestions

The distribution patterns of marshes and permafrost in the Da and Xiao Hinggan Mountains of the northeastern

China coincide in general. These features display discernible zonations in latitude and elevation.

There is a mechanism for developing and maintaining the symbiosis of permafrost and marshes in the Da and Xiao Hinggan Mountains. The frozen ground and periodical freeze-thaw processes have significant effects on the development, distribution and protection, or degradation of marshes. In the vicinity of the southern limit of permafrost (SLP), marshes are largely associated with isolated patches of permafrost. In the discontinuous permafrost zones with extensive taliks, or in sporadic permafrost regions, marshes and permafrost are generally found in lowlands or shaded slopes with less insolation and/or higher soil moisture. In the northern part of the Da Hinggan Mountains, marshes can develop on almost all terrains.

As an almost imperious layer, permafrost can effectively retain soil moisture in plant root system during the germination or spreading period of root in spring, which is critical for helophytes to begin growing. Permafrost inhibits downward water percolation until the rainy season in June, timely providing water supplies for plant growth during the spring drought.

The dense vegetation cover of marshes and litter/peat layers are good thermal insulators with strong thermal offsets of about 3℃–4°C. In addition, as a thermal diode due to the substantial differences of peat under the frozen and thawed states, the marshes actually facilitate the formation or protection of permafrost. The effect of thermal offset can substantially buffer the thermal disturbances from the atmosphere and surface and protect the underlying permafrost because of the reduced amplitudes of temperature changes. In addition, snow cover delays the warming of permafrost in late spring and early summer.

In the Da and Xiao Hinggan Mountains, the degradation of permafrost has been accelerating due to the rapid environmental changes, marked climate warming and ever increasing human activities. Since the permafrost and marsh environments are symbiotic and interdependent, they need to be managed or protected in a integrated way. However, there is a long way to go to adequately understand the symbiotic relationships to develop practical solutions for retarding or reversing the degradation of the permafrost-marsh environments in the Da and Xiao Hinggan Mountains.

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