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Thermal impacts of boreal forest vegetation on active layer and permafrost soils in northern Da Xing'anling (Hinggan) Mountains, Northeast China

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Abstract

A comprehensive observing system was established at the Da Xing'anling (Hinggan) Mountains Station (Gen'he) of China Forest Ecological Research Network (CFERN) in Northeast China in 2009 and gradually improved since in order to evaluate the influences of boreal forest vegetation with complex structures and various components on the thermal regimes of active layer and shallow permafrost soils. At three selected typical forest sites with similar micro-reliefs, soils, and drainage conditions, the soil temperatures on the ground surface and at various depths ranging from 0.05 to 5.0 m were measured with thermistor cables permanently installed in boreholes. The temperature data were compared and contrasted for various vegetative features. In a control experiment, trees and shrubs were removed to better understand the hydrothermal effects of vegetation removal. Results show that: (1) The vegetative layer provides an evident effect of thermal insulation on the ground. The ground temperature at the same depth was lower at a stand with denser vegetation when other conditions are held the same. (2) The ground warms up when the vegetation degrades, and the ground temperature rises from the vegetation degradation could reach much deeper in winter than in summer. (3) In cases of extensive vegetation degradation, the resultant ground warming persists for a long time, resulting in a deepening active layer.

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Introduction

Permafrost occupies approximately 24% of the exposed land surface in the Northern Hemisphere under present climate conditions (Zhang et al., 2003). Induced by climate warming and human activities, permafrost has been degrading extensively in recent decades (Osterkamp and Romanovsky, 1999; Wang et al., 2000; Jin et al., 2007; Thibault and Payette, 2009; Yang et al., 2010). Permafrost degradation may lead to substantial, or even drastic, changes in the terrestrial ecosystems, hydrological processes, carbon cycles, land use, and infrastructures (Schuur et al., 2009; Schaefer et al., 2011; Runyan and D'Odorico, 2012; Wang et al., 2012).

Among many regulating factors, vegetation—and forest vegetation in particular—plays important roles in the energy and mass transfer near the ground surface (Shur and Jorgenson, 2007). In general, the vegetative layer protects the permafrost. Disturbance in the vegetative layer will lead to permafrost changes. The influences of vegetation on the thermal regimes of permafrost are mainly displayed in five ways. (1) By shading, the vegetation canopy reflects and absorbs much of the downward solar radiation and reduces its incidence onto the soil surface (Chasmer et al., 2011). (2) The canopy structure and its physiological functions change the meteorological conditions in the vegetation, which in turn affects the heat and moisture exchange between the atmosphere and the soil (Benninghoff, 1952; Tyrtikov, 1959; Price, 1988; Pomeroy et al., 1998; Wang, 1999). (3) The presence of vegetation promotes the accretion of an organic layer at the surface with low bulk density and low thermal conductivity, which effectively insulates the mineral soil from the atmosphere (Bonan and Shugart, 1989). (4) The vegetative layer also results in a decline of soil moisture contents due to the precipitation interception and high rates of evapotranspiration in summer, which releases notable latent heat and reduces the thermal conductivity of organic soils (Vitt et al., 2000; Yuan et al., 2010). (5) It is universally recognized that the snow accumulation differs substantially between forested and open environments because of the difference in interception, sublimation, and wind redistribution (Pomeroy et al., 1998).

Collectively, the presence of vegetation exerts an insulating effect on the soil and preserves the permafrost layer by maintaining lower ground temperatures (Shur and Jorgenson, 2007). Changes in vegetation cover and structure have distinct effects on the hydrothermal dynamics of soils. Several researchers have suggested that the loss of vegetation canopy induced by wildfires in Arctic regions has increased the thaw depth (Harden et al., 2006; Liu and Randerson, 2008). Wang et al. (2009) found that when the vegetative coverage decreased, the hydrothermal sensitivity of soils to climate change was amplified.

In the northern hemisphere, permafrost is almost always overlain by boreal forest or grasslands vulnerable to disturbances induced by wildfire (Bonan and Shugart, 1989), and deforestation due to timber industry and agricultural expansion (Hobson et al., 2002). It is important to measure and understand the impacts of vegetation on the regimes of ground temperature, which is critical to better forecast the impacts of climate change and human activities on permafrost in forested areas (Shur and Jorgenson, 2007; Guglielmin et al., 2008; van der Velde et al., 2009; Kokelj et al., 2010; Savva et al.,

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2010; Chasmer et al., 2011). In addition, the vegetative influences on the thermal regimes of permafrost and active layer vary with time and space. Even at a given forest stand, some components have greater influences than others (Bakalin and Vetrova, 2008; Cannone and Guglielmin, 2009). Therefore, efforts should be made to identify the dynamic influences of vegetation with complex structures and various components on the ground thermal regime. However, these effects are still poorly understood, partly owing to the difficulty of properly distinguishing the vegetative effects from those of other factors only based on statistical analysis.

To achieve the above-mentioned targets, comprehensive observational system and proper control experiments are essential. Observations in conditions of different vegetation types and states with similar microenvironments are also necessary. The northern Da Xing'anling Mountains in Northeast China are typical and ideal regions to investigate the interactions between vegetation and the underlying permafrost. A monitoring system for the influences of vegetation on ground thermal regime and permafrost degradation has recently been established in the Da Xing'an Mountains Ecological Station (DXMES) (50°49′ to ~50°51′N, 121°30′ to ~121°31′E; 790–850 m a.s.l.) at Gen'he, Inner Mongolia Autonomous Region, a member of China Forest Ecological Research Network (CFERN), and observations have been conducted intensively and regularly (Sun, 2000; Jin et al., 2007; Sun et al., 2008; He et al., 2009; Chang et al., 2011; Wei et al., 2011). Supported by the observations and control experiment, this paper aims at (1) analyzing the seasonal and annual variations of ground temperatures beneath different vegetation types under similar microclimate in forests in the study region, and (2) identifying the impacts of vegetation dynamics (or disturbance) on ground temperatures and permafrost.

This paper is organized as follows. First, the study region and monitoring system, as well as the control experiment of vegetation removal, are introduced in detail in the material and methods section. Then, the results and discussions are presented in the followed section. In the end, some conclusions are drawn on these analyses and some unresolved issues are prospected for future studies.

Material and Methods

STUDY REGION AND MONITORING SYSTEM

The DXMES is located at Gen'he in the western flanks of the Da Xing'anling Mountains in northern Northeast China. As a member both in China Forest Ecosystem Research Network (CFERN) and China National Ecosystem Research Network (CERN), it has a typical landscape of boreal coniferous forest on rolling mountains and in intermontane basins (Fig. 1). The study region is characterized by a cold temperate continental monsoon climate. Based on the meteorological records from 1 January 2001 to 31 December 2010, annual precipitation ranges from 350 to 550 mm, with snowfall (snow water equivalent) accounting for about 12%–20% of annual total precipitation. Snow usually starts to accumulate on the ground in October and disappear the next March. The maximum yearly snow depths during the past 10 years range from 10 to 40 cm. The mean annual air temperature is –3.0 °C, and mean monthly air temperatures vary from –31.7 °C (January 2001) to 19.5 °C (July 2002). The extreme maximum mean daily air temperature (MDAT) was 27.4 °C (27 June 2010) and minimum MDAT was –41.3 °C (10 January 2001). The station is in a region with discontinuous permafrost in the northern vicinity of the southern limit of permafrost. The areal extent of permafrost is approximately 60%–75% (Jin et al., 2007). As inferred from ground temperatures at shallow depths from 1 January 2009 to 20 May 2011, the thickness of the active layer varies from 0.5 to 2.0 m in this region.

In order to investigate the effects of different landscapes on permafrost, nine boreholes were installed in the vicinity of the study plots, including forest, wetland, grassland, and urban sites. However, this paper focuses on the hydrothermal effects of vegetation on ground temperatures. Some boreholes in forests with different vegetative features and similar microenvironments (in climate, soil, and drainage) were selected for comparative analysis.

The vegetation in the study region is primarily larch forest (*Larix gmelinii*), which can be subdivided into various sub-types based on the dominant understories and ground cover. Three representative sub-types were identified and boreholes were installed for long-term ground temperature monitoring, including a larch forest site with an understory of *Ledum* (*Larix dahurica-Ledum palustre* var. *dilatatum*, hereafter borehole P1 for short), a larch forest site with an understory of *Ledum* and *Betula* (*Larix dahurica-Ledum palustre* var. *dilatatum–Betula fruticosa*, P2), and two larch forest sites with an understory of *Betula* (*Larix dahurica–Betula fruticosa*, P3 and P4, described in detail in the Control Experiment Section) (Fig. 2).

The detailed characteristics of the three investigated plots are listed in Table 1. The longest plot pair-distance is less than 1 km (between P3 and P2), and there is also little difference in elevation among these plots (see Table 1). In addition, only one automatic weather station (AWS) was installed close to plot P2. Therefore, it is assumed that the variations in air temperature between these plots are minor, which is also supported by Figure 7 later in this report.

The vertical vegetation structures in the three selected plots can be evidently divided into tree, shrub, and ground cover layers. Larch is the dominate species. The tree density is similar at plots P1 and P2, and a little denser at P3. The average height of trees are 5.9, 6.1, and 5.5 m at P1, P2, and P3, respectively. The dominant species of the shrub layer is *Ledum* at P1 with average height of 1.02 m, *Ledum* and *Betula* at P2 with average height of 0.97 m, and *Betula* at P3 with average height of 1.75 m. The shrub density at the selected plots is in an ascending order of P1, P2, and P3. The ground cover at P1 and P2 is *Bryum*. While at P3, the dominant species of the ground cover layer is *Deyeuxia angustifolia* with an average height of 30–40 cm. The ground coverage is also much denser than P1 and P2. The soil texture profiles of these four plots are illustrated in Figure 3, which were recorded when drilling the boreholes. As it is known, soil texture has strong spatial heterogeneity. However, according to the similarity of the four recorded profiles, two groups can be identified: one at plots P1 and P2, and another at plots P3 and P4. The soil texture difference is greater between plots in different groups than that between plots in the same group. Because plots P3 and P4 are very close to each other, the soil texture profiles are very similar, especially in the active layer shallower than 1.6 m. The soil moisture conditions are similar, too. Volumetric soil moisture content was measured by a Hydro Sense portable soil moisture meter at the depth of 20 cm at these plots in September 2011, listed in Table 1.

At each selected plot, a borehole was installed and ground temperatures at various depths (0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, and 4.0 m) were monitored by thermistor cables. All the thermistors (made by the State Key Laboratory of Frozen Soils Engineering, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences) have an accuracy of ±0.05 °C in the temperature ranging from –30 to +30 °C, and ±0.1 °C in the temperature from –45 to –30 °C and +30 to +50 °C. From 3 January 2009 on, the data were recorded manually once a week on Saturday between 10:00 and 12:00 with a multimeter Fluke 189. Meteoro-

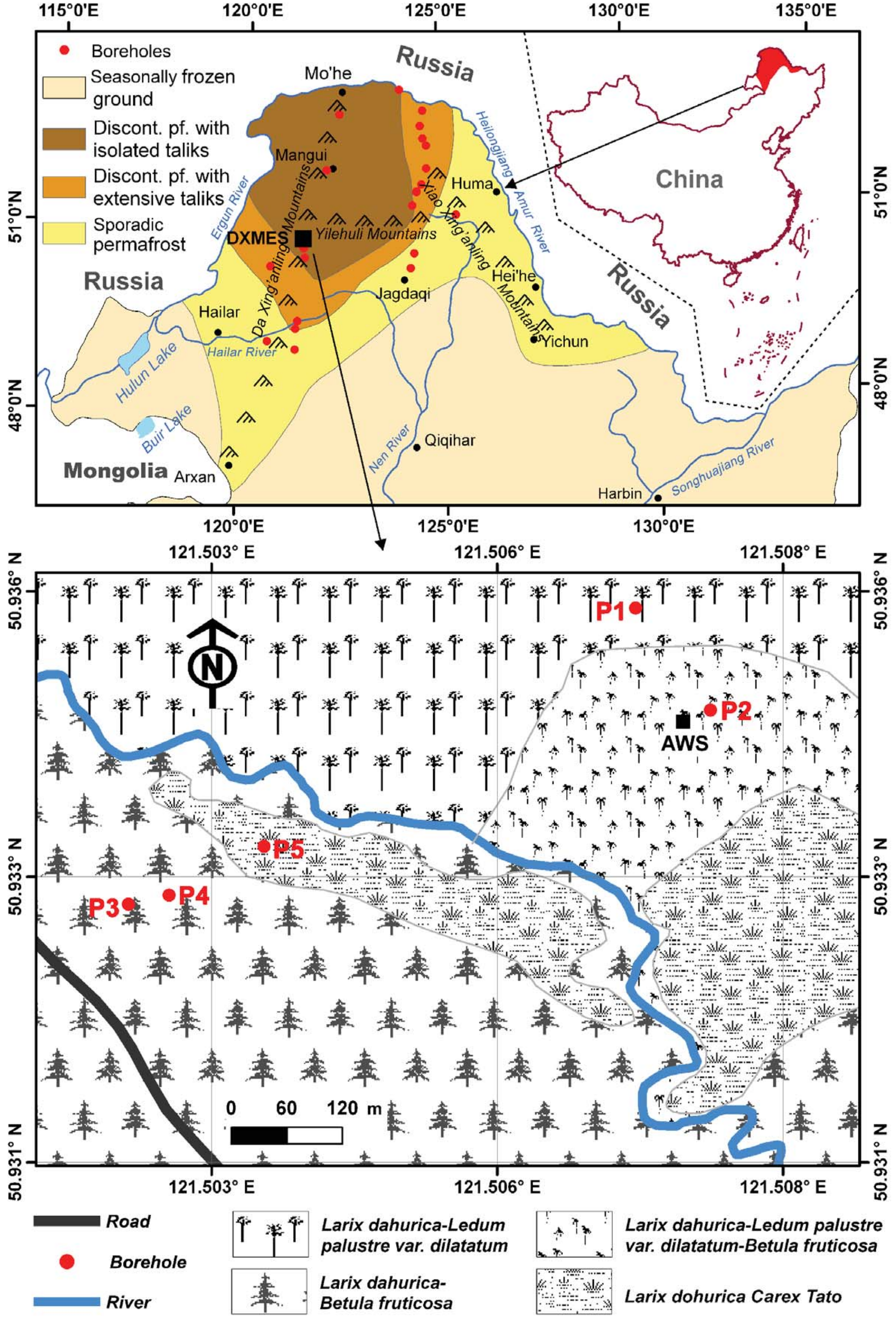

FIGURE 1. Study region, vegetation distribution, and locations of study plots and observation sites at the DXMES near Gen'he, Inner Mongolia Autonomous Region, northern Northeast China.

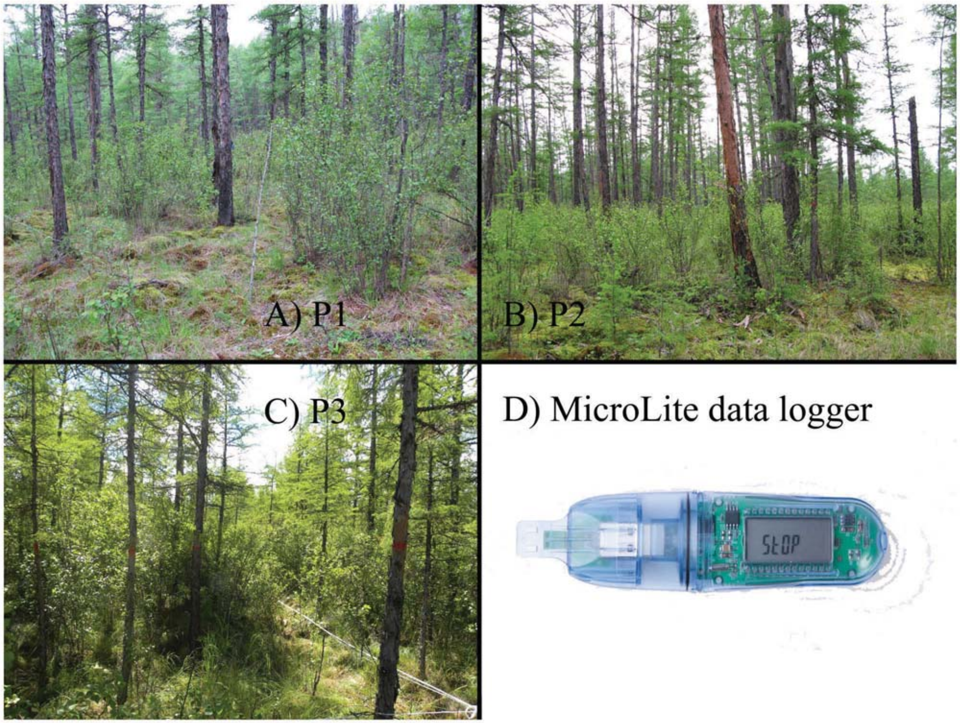

FIGURE 2. Views of borehole sites and MicroLite. (A) View of *Larix dahurica–Ledum palustre* var. *dilatatum*, P1; (B) view of *Larix dahurica–Ledum palustre* var. *dilatatum–Betula fruticosa*, P2; (C) view of *Larix dahurica–Betula fruticosa*, P3 and P4; and (D) view of MicroLite.

logical variables at height of 2 m from the ground surface, including solar radiation, air temperature, wind speed/direction, relative humidity (RH), and rainfall were observed from 7 June 2008 to 26 August 2010 in hourly step using a HoboPro automatic weather station (AWS) manufactured by Onset Computer Corporation. To better understand the detailed mechanisms for the influences of forest vegetation on permafrost, the vertical distribution of some key meteorological variables (including air temperature, relative humidity, and wind speed) in the forest were investigated intensively from mid-August to mid-October in 2009 at the DXMES. The sensors were installed at the height of 1.5, 4.0, 8.0, and 16 m, respectively.

In addition, snow depths and ground surface temperatures (at the snow-soil interface) at 20 plots (17 plots with valid data, including P1, P2, and P3) were also observed in the study region

TABLE 1
Characteristics of the four investigated plots.

Plot and elevation	Vegetation type	Tree layer: Based on one quadrat of 20 × 20m	Shrub layer: Based on four quadrats of 5 × 5m	Groundcover layer: Based on four quadrats of 1 × 1m	Soil Moisture: Measured at the depth of 20 cm in September 2011
P1 820 m	*Larix dahurica–Ledum palustre* var. *dilatatum*	Dominant species is larch. 64 mature trees with average height of 5.9 m	Dominant species is *Ledum* with average height of 1.02 m and vegetative cover of 19.5%	Dominant species are *Bryum* with *Deyeuxia angustifolia*. The ground cover thickness is about 10 cm and average coverage is about 28%	51%
P2 803 m	*Larix dahurica–Ledum palustre* var. *dilatatum–Betula fruticosa*	Dominant species is larch. 66 mature trees with average height of 6.1 m.	Dominant species are *Ledum* and *Betula* with average height of 0.97 m and vegetative cover of 39%.	Dominant species is *Bryum*. The ground cover thickness is about 10 cm and average vegetative cover is about 31%.	63%
P3 805 m P4 791 m	*Larix dahurica–Betula fruticosa*	Dominant species is larch. 76 mature trees with average height of 5.5 m.	Dominant species is *Betula* with average height of 1.75 m and vegetative cover of 51%.	Dominant species is *Deyeuxia angustifolia* with average height of 30–40 cm. The vegetative cover is greater than 70%.	67%

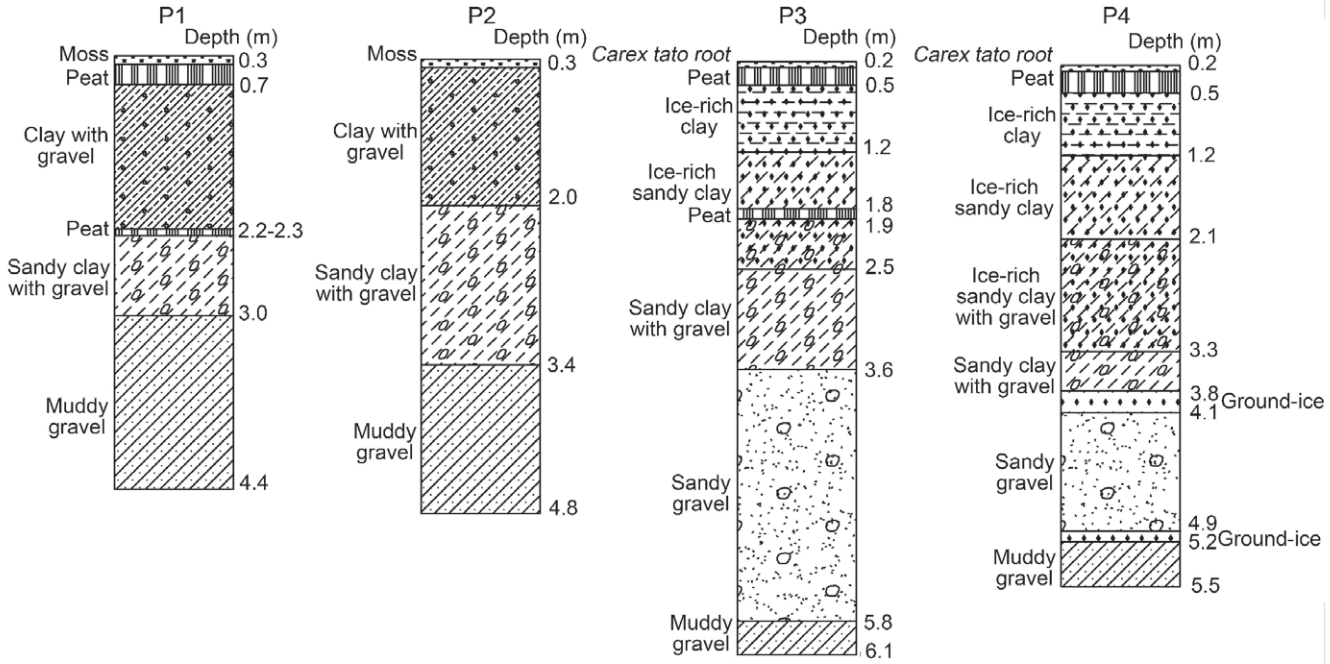

FIGURE 3. Profiles of soil texture at different plots.

from 2 October 2012 to 30 April 2013. Ground surface temperatures were observed by MicroLite data loggers with an accuracy of 0.3 °C in the temperature range from –40 to +80 °C. Similar to the ground temperature measurement, the snow depths were also measured manually once a week on Saturday.

CONTROL EXPERIMENT OF VEGETATION REMOVAL

For the purpose of control experiment for understanding the effects of vegetation removal and distinguishing the repercussions of vegetation removal on ground temperatures, another borehole was installed (plot P4) in the larch forest with a birch understory in the vicinity of plot P3. To ensure the two boreholes with the similar possible conditions in weather, soil, micro-reliefs and vegetation, plot P4 was set only 20 m away from P3. One half year later after the observation beginning, on 15 July 2009, the first vegetation removal was conducted at plot P4. In a circular area with a center at plot P4 and a radius of 4 m, all trees, shrubs, and herbs were cleared to the ground surface. However, the litter layer and root systems were left intact. Although the harsh climate in the study region may be adverse to tree growth after the removal, the vegetation recovery still will take place slowly in the shrub and herb layers. To maintain the unvegetated state at P4, the vegetation was removed again on 15 July 2010. After these two removal events, the vegetation recovery in shrub and herb layer was left undisturbed in order to investigate how the ground temperature responds to the vegetation recovery.

Results and Discussions

INFLUENCES OF FOREST CANOPY ON METEOROLOGICAL CONDITIONS

Solar radiation is the main energy source to drive the thermal processes near the land surface. It also shapes the surface meteorological conditions. The three-dimensional distribution of canopy elements (e.g., foliage area, canopy gaps, stems, and branches) regulates the patterns of direct and diffuse radiation incidents on the ground surface (Pomeroy et al., 2008). The absorption and reflection of radiation by the forest canopy often effectively reduces the solar radiation incident on the land surface. Wright (2009) reported that on average the net all-wave radiation below the tree canopy was 17% less than that on the adjacent treeless surfaces. In the forest at the DXMES, the shadowing effect of vegetation canopy becomes even more apparent according to the studies on the average diurnal oscillations of solar radiation in June 2003 (shown as in Fig. 4) (Zhou, 2003). The net all-wave radiation observed under the canopy was only 60% of that above the canopy. In the period between 10:00 and 16:00, the net radiation under the canopy

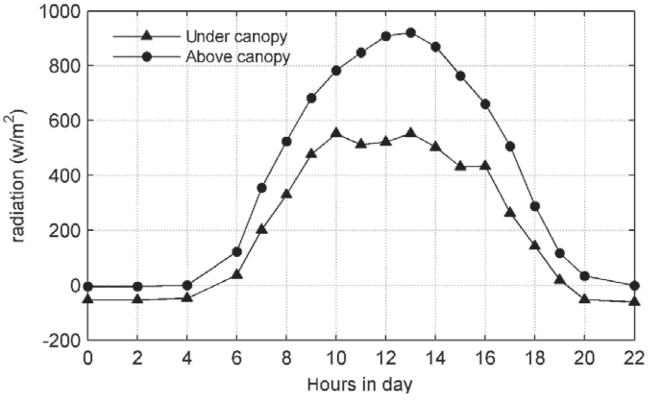

FIGURE 4. Average diurnal oscillations of all-wave radiation observed in June 2003 above and under the canopy in the larch forest at the CFERN DXMES Station at Gen'he, northeastern Inner Mongolia Autonomous Region, China (after Zhou et al., 2003).

is reduced most severely. The shadowing effect on solar radiation by the forest canopy not only decreases the net energy income on the land surface, it also has significant impacts on the vertical distribution of meteorological conditions in the forest. They have both direct and indirect influences on the thermal processes in the active layer and permafrost.

The results of intensively observed vertical distribution of key meteorological variables are shown in Figure 5. Air temperatures at different heights in the forest display an evident warming with rising height (as shown in Fig. 5, part A). The reason for such an inversion of temperature may lie on the inversion of net radiation below the canopy surface. The canopy surface acquires more net radiation and the canopy temperature increases more significantly than down below, leading to the air temperature inversion. The difference of daily mean air temperature between 16.0 and 1.5 m and the daily total downward shortwave radiation are shown in Figure 5, part B. In order to better compare, they are normalized for values during the observing period as follows:

$$normalVal_i = \frac{Val_i - Val_{\min}}{Val_{\max} - Val_{\min}} \tag{1}$$

where the *normalVali* is the *i*th normalized value, Val_i the *i*th observed value, *Valmin* the minimum, and Val_{max} the maximum. As shown in the figure, there is obvious correlation between the normalized downward shortwave radiation and the normalized temperature difference. On the whole, the difference of air temperature between two selected heights is greater when the radiation is stronger, and vice versa.

In contrast, the relative humidity has an opposite trend in vertical distribution to that of air temperature in the forest canopy. It decreases with rising height. In addition, the canopy effectively reduces the wind speed (as shown in Fig. 5, part D) and suppresses the formation of air turbulences in the forest. Both air temperature inversion and wind speed reduction may impede the heat exchange between the soil and atmosphere. According to Chasmer et al. (2011), diminished within- and below-canopy shadowing effects will result in increased radiation incident on the ground surface and in augmented thawing of permafrost.

GROUND TEMPERATURE REGIMES IN DIFFERENT VEGETATION SUB-TYPES

Ground temperatures at some selected soil depths of plots P1, P2, and P3 are compared and shown in Figure 6. The differences in ground temperatures at three selected plots are notable, which have obvious connections with vegetation types. To some extent, these differences and patterns could be attributed to the influences of vegetation structure and density.

In summer, shortwave radiation is the main part of soil energy influx. In theory, the denser the vegetation, the more interception of downward shortwave radiation by vegetation canopy and the less energy onto the ground surfaces. Less shortwave radiation influx is adverse to ground warming. Among these three plots, the vegetation density is smallest at P1 and largest at P3. Therefore, soil temperatures at P1

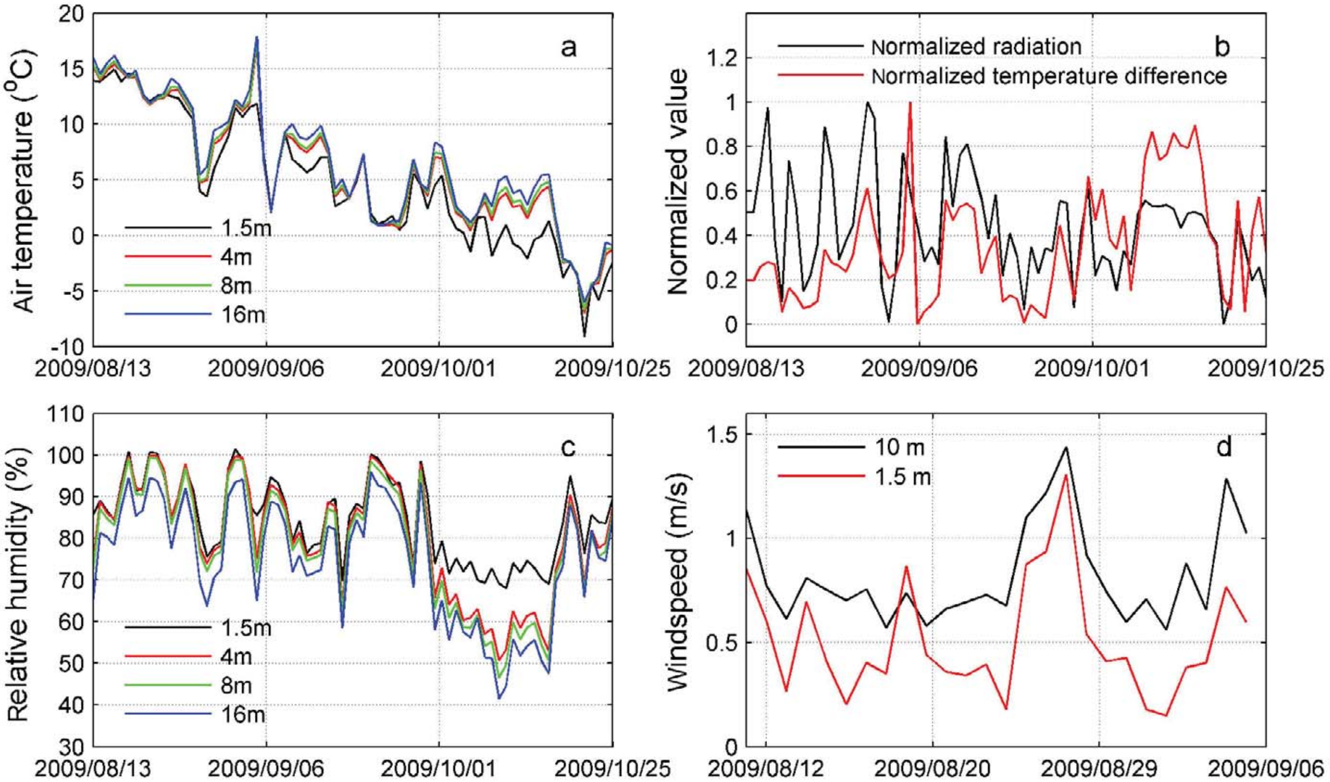

FIGURE 5. Meteorological variables in the forest canopy at the CFERN DXMES Station, Gen'he, northeastern Inner Mongolia, China, during the intensive observation period from August to October 2009. (A) Vertical distribution of air temperature in the canopy; (B) comparison of the normalized downward shortwave radiation and normalized air temperature difference between the heights of 1.5 and 16.0 m in the canopy; (C) vertical distribution of relative humidity; and (D) wind speeds at the heights of 1.5 and10.0 m. Dates are shown as yyyy/mm/dd.

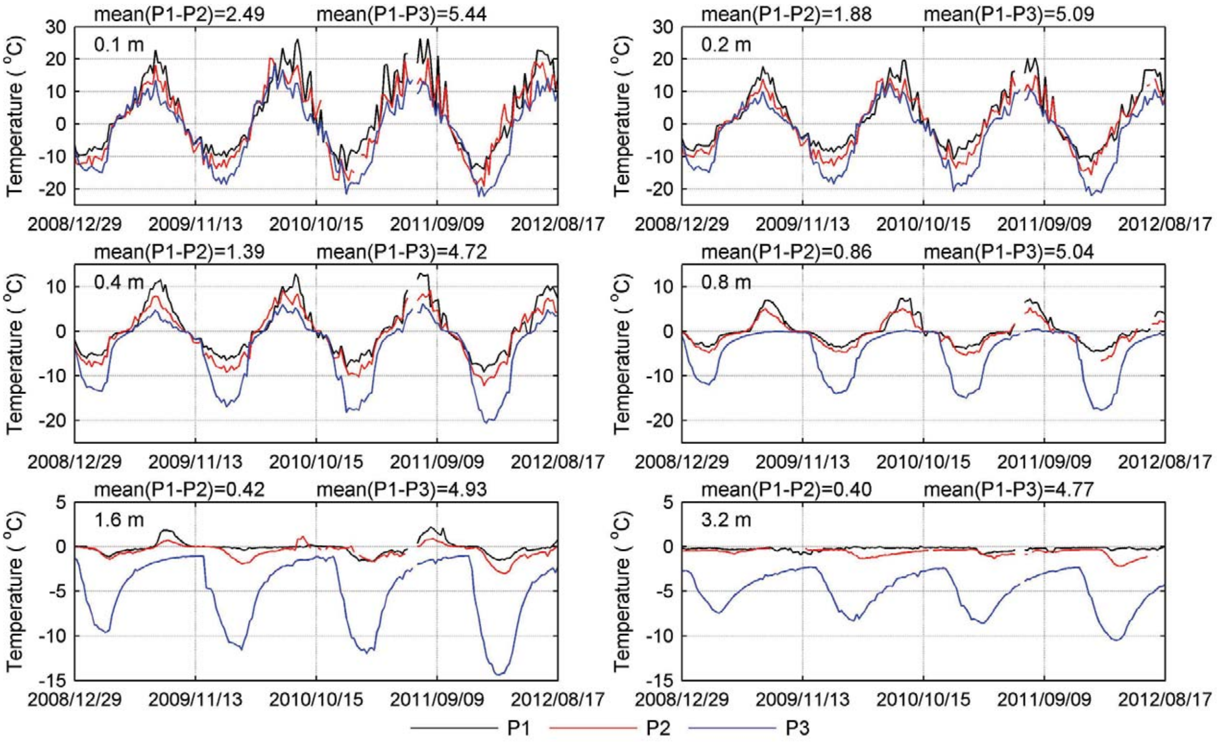

FIGURE 6. Comparisons of ground temperatures at various depths among the monitored boreholes.

are relatively higher, and those at P3 are lower (Fig. 6). The means of ground temperature difference between plots P1 and P2 and that between P1 and P3 at various depths were listed above the corresponding panel in Figure 6. As shown, the shallower the depth, the stronger the influences on soil temperatures from vegetation. The temperature differences among plots P1, P2, and P3 are larger at the ground surfaces, but they decrease downward with depth.

In winter, the situation is a little more complicated because snowpack has important impacts on the ground energy balance. As reported by other research, seasonal snowpack is well known to reduce and retard ground freezing by effectively insulating the soil surface and greatly limiting the thermal interactions between the ground and atmosphere. A lack of snow cover will result in deeper and longer ground freezing in comparison with a situation when snowpack is established in early winter (Shanley and Chalmers, 1999; Hardy et al., 2001). However, the problem becomes much more complex when the effect of forest vegetation is included (Hardy et al., 2001).

In the study region, both trees and shrubs are deciduous. Contrary to evergreen forests, the snow interception by leafless trees and shrubs is insignificant, which will not lead to significantly less snow accumulation in a denser vegetation stand. However, the shadows of tree and shrub stems could reduce the shortwave radiation incidence onto the snow surface under the vegetation, which may protect the snow from sublimating and melting to some extent (Price, 1988). Therefore, it is reasonable that the more severe shadowing effects of denser vegetation will lead to thicker snow depth. The bottom panel of Figure 7 shows observed snow depths at three selected plots over the period from winter 2012 to spring 2013. It is obvious that snow depth is much deeper under denser vegetation (P3). The averaged difference of snow depth between P1 and P3 is about 4.5 cm.

The comparison results of observed snow depths and ground surface temperatures (ground-snow interface) at plots P1, P2, and P3 are very interesting (as shown in Fig. 7). When its thickess is small (<15 cm), snow cover has little influence on the ground temperature. As shown in Figure 7, ground surface temperatures at three selected plots are almost the same before 8 December 2012. It also reads that the ground surface temperature is lower when snowpack is thicker during the snow accumulation period. Apparently, this pattern seems inconsistent to the previous findings of other research, that is, that seasonal snowpack is to reduce and retard ground freezing. On the contrary to previously reported snow clearance experiments to obtain snow-free conditions, the main difference in snow-cover among plots P1, P2, and P3 is the thickness rather than the conditions with and without snowpack. Therefore, the reasons for the found ground surface temperature pattern may lie in the difference in snow thickness. When the snow cover is adequately thick (15–30 cm as shown in Fig. 7), the ground surface temperature may also be influenced by the amount of shortwave radiation reaching the snow-ground interface.

In general, more shortwave radiation will penetrate through a shallower snowpack and warm the ground surface. This can be somewhat proven by the fact that the ground surface temperatures at three selected plots became more consistent when there was significant snow event and differentiated again after. This is due to the fact that downward solar radiation would be diminished when it is rainy or snowy.

In short, the combined effects from vegetation stem shadows and extinction of solar radiation in snowpack may have been contributed to the deeper snow depth and lower ground temperature in denser vegetation stands. As also shown in Figure 6, the ground temperatures at the same depth are lower in denser vegetation stand in winter.

THERMAL IMPACT OF VEGETATION REMOVAL

Figure 8 shows the ground temperatures at various soil depths of plots P3 and P4. The corresponding temperature difference at

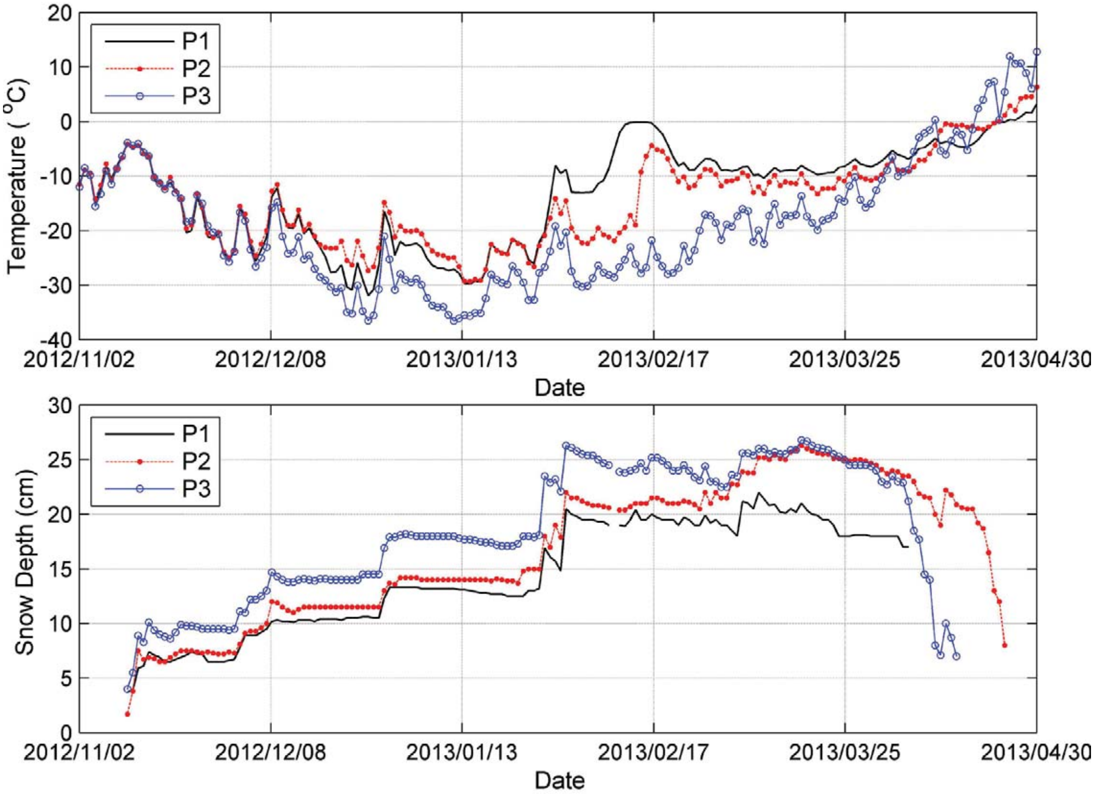

FIGURE 7. Ground surface temperatures (measured at the snow-ground interface in winter, shown in the top panel) and snow depths (shown in the bottom panel) at the borehole plots.

a given depth (abbreviated as DIF_I hereafter, with the subscript *I* standing for the depth or layer index) between plots P4 and P3 (P4 minus P3) was presented in Figure 9. The maximum and mean values of these differences at various depths (abbreviated as MAXDIF_I and $\mathrm{MEANDIF}_I$ hereafter, with the subscript *I* standing for the depth or layer index) over each year were listed in Table 2. Figure 10 is a visual summary by means of boxplot. Each box in Figure 10 represents the range, median, mean, quartiles, and interquartile range of the MAXDIF_I and $\mathrm{MEANDIF}_I$ at all selected ground depths over each period defined in Table 2.

As previously described, plots P3 and P4 have almost the same underlying surface, soil, and weather conditions, except for the twice removal of vegetation at plot P4 during the observation period. As shown in Figures 8 and 9, the difference in ground temperatures (DIF_I) between plots P3 and P4 before the first vegetation removal event (indicated as the upward arrows in Figs. 8 and 9) is much smaller than that after the removal, which can be inferred more obviously from Figure 10 and the values listed in Table 2. During the period from 29 December 2008 to 4 July 2009 (year 2008), the $\mathrm{MEANDIF}_I$ at almost all selected depths are smaller than 0.5 °C, except at depths of 0.8 and 1.6 m with the values of 0.58 and 0.51 °C, respectively. The means of $\mathrm{MEANDIF}_I$ and MAXDIF_I at all depths are 0.43 and 1.30 °C, respectively, which are notably smaller than those of other periods. These relatively small differences in ground temperatures reflect the similar conditions between plots P3 and P4 before the first vegetation removal. After the removal, ground temperatures at plots P3 and P4 began to differentiate and the difference declines downward. In general, ground temperatures at plot P4 are higher than those at P3 both in summer and winter after the vegetation removal. The specific reasons for these differences are similar to those stated previously. The vegetation removal at P4 increased the solar radiation incidence on ground surface in summer and that on snow surface, and in turn on ground surface, in winter.

It can be inferred from Figure 8 that the patterns of DIF_I are dissimilar between shallow (≤0.8 m) and deep (>0.8 m) soils. The values of DIF_I in shallow soils have two obvious spikes corresponding to summer and winter, respectively. While in deep soils with only one peak, the temperature difference is more obvious in winter than summer (Fig. 9). In summer, ground temperatures at depths less than 1.6 m are notably different between the plots P3 and P4. It is worth noting that, in summer, ground temperatures at the depth of 1.6 m are both subzero and almost the same at P3 and P4. However, in winter, the temperature difference could be easily seen between P3 and P4, even at the depths of 4.0 and 5.0 m.

It could be concluded that in summer the thermal effects from the vegetation removal could only reach the soil depth less than 1.6 m, while the temperature wave caused by vegetation disturbance would penetrate much deeper in winter. The reasons for this may lie in the zero curtain effect and the difference of thermal conductivity between frozen and thawed states of soils. In summer, huge latent heat is consumed in thawing the top soil layer and the thermal conductivity of thawed organic-rich soils is generally much lower than that of frozen organic soils, which have greatly limited energy flowing downward to deeper soils. On the other hand, when the entire frozen soil column has higher thermal conductivity and

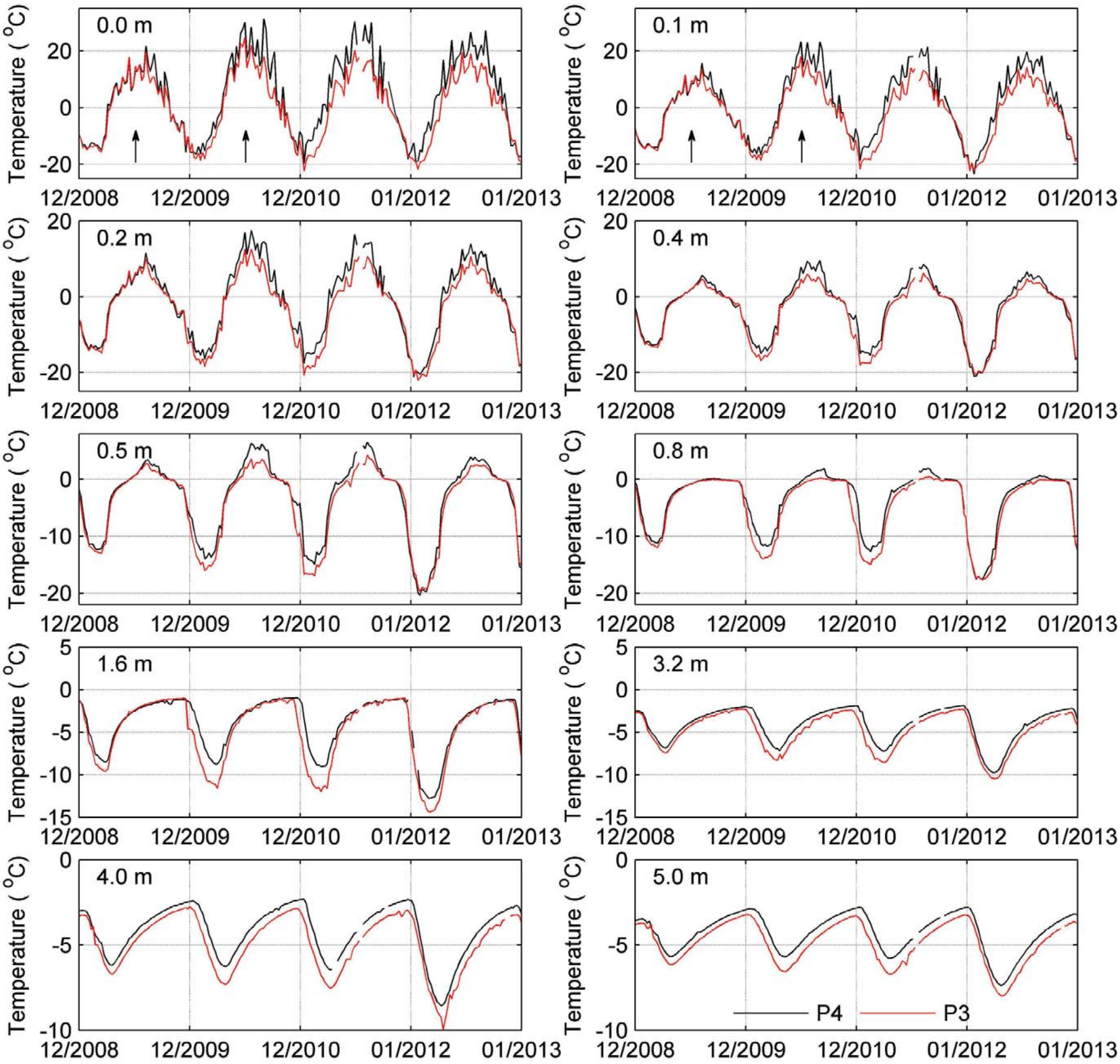

FIGURE 8. **Comparison of ground temperatures at various depths between plots P3 and P4. The timing of vegetation removal indicated by the upward arrows.**

there is no obvious latent heat released or absorbed by soil, it is beneficial for the absorbed solar energy to conduct downward.

It also can be inferred from Figures 9 and 10 that the disturbance of vegetation removal has accumulative effect. The temperature difference after the first removal event are smaller than those after the second one, both in winter and summer. The statistic values and variation ranges of MAXDIF_I and $\mathrm{MEANDIF}_I$ reach the maxima in the year after the second vegetation removal event, and then begin to decrease year by year. Although it will take years or decades for trees to restore after removal, the annual herbaceous plants and shrubs under trees can restore more rapidly, for example, in one year or two. Thus, the value of all DIF_I between P3 and P4 will diminish gradually. However, the vegetation cannot fully restore to the early state before the first removal event in a short time, which results in the persistence of DIF_I in years after the last removal event, especially for the top soils. As shown in Figure 9, the values in DIF_I in deep soils diminishes more rapidly than in shallow soil. One reason may be that the values of DIF_I in deep soils are small, and more sensitive to the heat exchange in soil. Another important reason may lie in the presence of strong lateral heat interaction between observed stand with surrounding soil. After all, the area subjected to vegetation removal is actually small compared with the surrounding forest and the effect of lateral heat exchange could not be ignored, especially in deep soils.

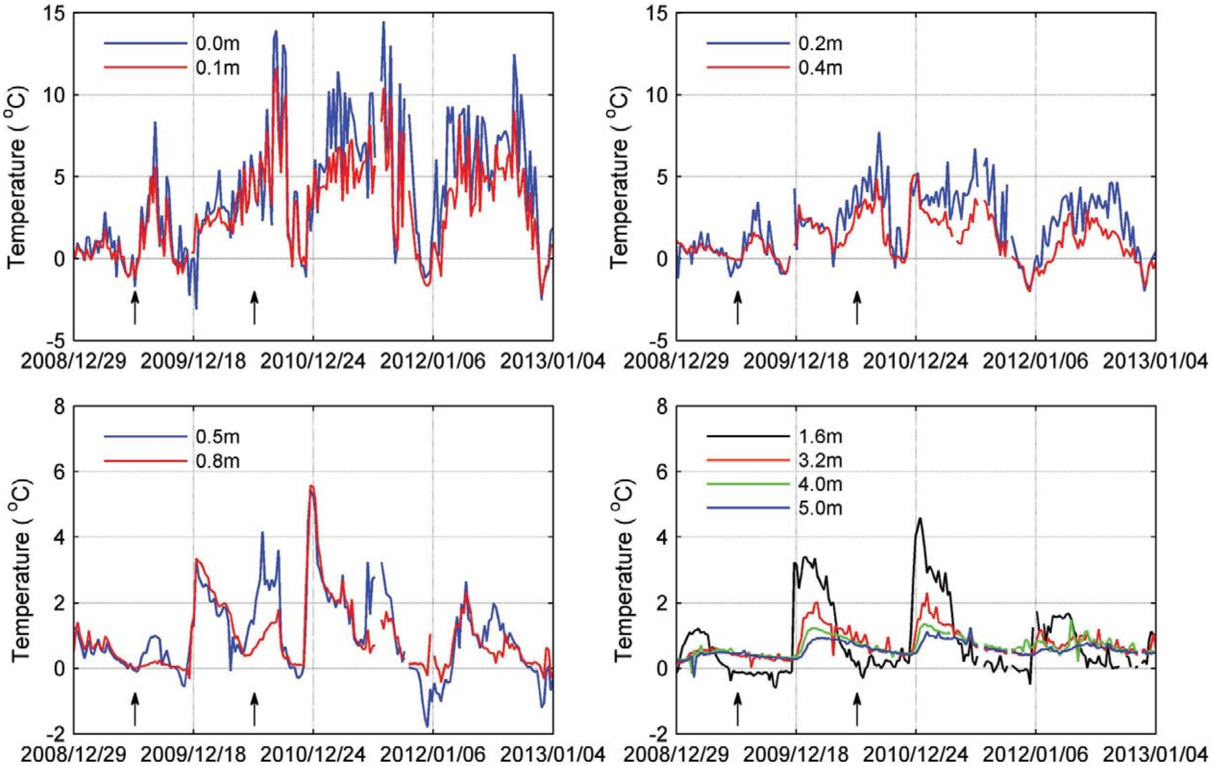

FIGURE 9. Difference in ground temperature at various depths between plots P3 and P4 (P4 minus P3). The timing of vegetation removal is indicated by the upward arrows.

DISCUSSIONS

Although the environmental conditions such as micro-reliefs, geology, soil type and texture, soil moisture, and meteorological conditions are similar among P1, P2, and P3, except vegetation, there are heterogeneities even between P3 and P4, which are adequately close (20 m) to each other and have the same vegetation conditions before the vegetation removal. The heterogeneities of various factors have impacts on energy transfer in the soil and bring uncertainties in the analysis as follows:

1. Soil moisture content is one of the factors with the most direct influence on ground temperatures. On one hand, soil

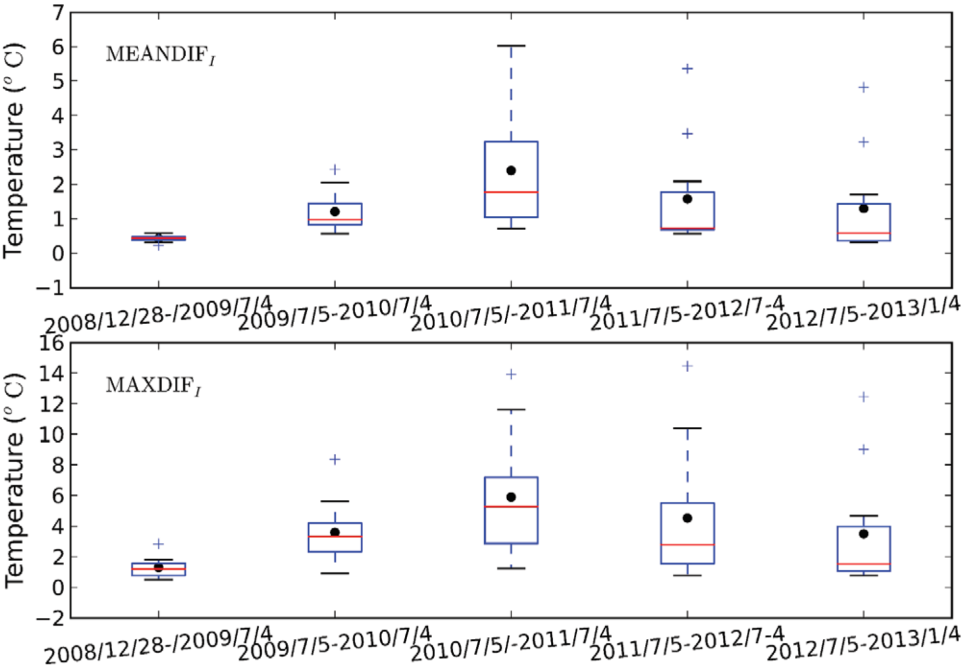

FIGURE 10. Box plots of the MAXDIF$_I$ and MEANDIF$_I$ at various depths over each period defined in Table 2.

TABLE 2

Values of $MAXDIF_I$ and $MEANDIF_I$ at various depths over each year.

I	Depth	29 Dec 2008 to 4 Jul 2009 (2008)		5 Jul 2009 to 4 Jul 2010 (2009)		5 Jul 2010 to 4 Jul 2011 (2010)		5 Jul 2011 to 4 Jul 2012 (2011)		5 Jul 2012 to 4 Jan 2013 (2012)	
		MAXDIF	MEANDIF	MAXDIF	MEANDIF	MAXDIF	MEANDIF	MAXDIF	MEANDIF	MAXDIF	MEANDIF
	(m)	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$	$^\circ C^{-1}$
1	0.0	2.84	0.43	8.34	2.42	13.92	6.02	14.46	5.36	12.45	4.82
2	0.1	1.83	0.23	5.62	2.06	11.60	4.84	10.41	3.47	9.00	3.22
3	0.2	1.63	0.32	4.48	1.57	7.71	3.57	6.15	2.09	4.67	1.71
4	0.4	1.09	0.47	3.28	1.11	5.12	2.23	3.55	0.86	2.00	0.47
5	0.5	1.22	0.49	3.31	0.97	5.42	1.96	3.23	0.67	1.85	0.32
6	0.8	1.41	0.58	3.34	0.94	5.59	1.60	2.35	0.75	1.06	0.33
7	1.6	1.21	0.51	3.40	0.98	4.59	1.25	1.74	0.62	1.12	0.32
8	3.2	0.62	0.44	2.03	0.80	2.31	0.97	1.18	0.69	1.20	0.62
9	4.0	0.69	0.44	1.23	0.68	1.36	0.81	1.49	0.71	0.92	0.63
10	5.0	0.50	0.38	0.92	0.57	1.25	0.71	0.79	0.57	0.76	0.54
Mean		1.30	0.43	3.59	1.21	5.89	2.40	4.54	1.57	3.50	1.30

thermal conductivity varies greatly with moisture content, especially when the soil is frozen in winter. On the other hand, the moisture-rich soils would release or absorb huge fusion heat in the freeze-thaw processes, which would have critical impacts both on the timing and range of variations in ground temperature. The soil water contents at P1, P2, and P3 were measured one time in September 2011 by means of drying and weighting, as listed in Table 1. Unfortunately, the comparison of soil water dynamics among the three plots was unavailable. Therefore, the specific impacts of soil water content on the ground temperature regimes at the selected plots were not analyzed in this paper, which will bring some uncertainties in the analysis presented previously.

2. With low bulk density and thermal conductivity, the soil organic layer effectively insulates the mineral soil from the atmosphere. Its depth usually varies greatly and influences the ground thermal dynamics in different vegetation type. However, it is hard to distinguish its thermal effects from vegetation without the help of a model because the measuring sample is too small, which is another important source of uncertainties.
3. Description on the vegetation density in this study is more qualitative than quantitative. The shrub and ground cover type may also differ in different tree type due to topography, hydrology, ecology, and micro-climate conditions. To understand their specific effects on the ground thermal dynamics, a physically based model with robust radiative transfer module and more observation and control experiments are necessary.

Although spatial heterogeneities of various controlling factors are inevitable and may have some influences, the impacts of vegetation on the ground temperature regime and permafrost have been identified successfully. The difference in ground temperature for the studied vegetation types (e.g., P1, P2, and P3) and that caused by vegetation disturbance (e.g., P3/P4) are consistent in both summer and winter. The insulating effect of vegetative cover on the soil thermal regime and its disturbance on permafrost degradation presented in this study are consistent with other literature (Balisky and Burton, 1993; Lewis, 1998; Bakalin and Vetrova, 2008). By comparing closely spaced sites, Lewis (1998) found that the ground surface temperature in forest was cooler than in cleared areas, and it will increase in the process of deforestation. If the forest did not grow up again, a permanent increase in ground surface temperature would be resulted at the time of deforestation. Few studies also discussed permafrost resilience and recovery from reforestation (Mackay, 1995; Viereck et al., 2008). As a new forest grows, the ground cools (Nitoiu and Beltrami, 2005), which is also consistent with the result introduced in this study. However, it will take decades for both the vegetative cover and ground surface temperature to restore, if at all possible, to the undisturbed state (Calmels et al., 2012).

It is worth noting that the area of vegetation removal is small compared to both the tree height and the vast forest. This is adverse to analogize the effects of extensive vegetation degradation on permafrost. First, the surrounding standing trees will cast shadows on the experiment spot receiving vegetation removal (plot P4). The received solar radiation may be much smaller than that in the extensive vegetation degradation case. Second, the extensive degradation of vegetation will increase the wind speed near surface in general. The wind field change in the vicinity of plot P4 caused by vegetation removal could almost be negligible because of the untouched thick forest surrounding. The experiment in this study could not reflect the effects of wind speed increase on turbulent flux near surface—for example, evaporation and snow sublimation. They have both direct and indirect effects on ground temperatures. At last, the lateral heat exchange in deep ground between the vegetation removed area and undisturbed forest could not be ignored. Some energy will be lost from plot P4 to the surrounding ground in terms of lateral heat flux. The increase in ground temperature at P4 will be offset somewhat, especially at deep soils with small temperature increment. This may be the underlying reason for the quickly decreased ground temperature difference between P3 and P4. For these reasons, the ground temperature increases and permafrost degradation will be more severe in case of extensive vegetation degradation, especially in deep soils. It also will take a longer time for the ground temperature and permafrost to restore after reforestation.

Heat and water fluxes in the soil-vegetation-atmosphere transfer (SVAT) system are overwhelmingly complicated, which involve many interactive factors. In such a system, a perfect control experiment in field is hardly possible. Therefore, it is difficult to truly distinguish the effects of vegetation on ground temperature only by virtue of observation, let alone to quantify these effects, although they are expected at the beginning of this study. Moreover, the analysis on the responses of snow depth and ground temperature to the shadows of vegetation stems in winter has large uncertainties. More direct evidences are planned to be collected in future study. In addition, model simulations based on comprehensive observational data is necessary to obtain thorough and quantitative assessment.

Conclusions

Based on comprehensive observations, comparative analysis, and control experiments of vegetation removal in a typical boreal forest region, this paper aims at studying the impacts of vegetation on the ground temperature regime. In boreal forest, vegetation is a main controlling factor on the energy and mass transfer near the ground surface. Firstly, through the influence on radiative transfer and wind field cast by canopy, vegetation could shape meteorological conditions of the atmosphere to some extent. Local temperature inversion may be caused and wind speed may be reduced by vegetation, which may impede the heat exchange between the soil and atmosphere. Secondly, the absorption and reflection of downward solar radiation by vegetation canopy and stem could reduce its incidence onto ground and snow surfaces under the forest. More downward solar radiation is intercepted by canopy and stem in a denser vegetation stand, which in general will lead to lower ground temperatures at the same soil depth when other conditions are held the same. In combination with wind speed reduction, the radiation interception by vegetation canopy will also lead to deeper snow depths and lower ground surface temperatures in denser vegetation in winter.

According to the control experiment, ground will warm up after vegetation removal. The disturbance of vegetation has accumulative effect on ground temperatures. The more severe vegetative degradation will lead to stronger ground warming. Temperature increase is larger at the ground surface layer and decreases downward with depths. Because of the zero curtain effect caused by the presence of latent heat released or absorbed in soil freezing or thawing processes and the difference in thermal conductivity between the frozen and thawed soils, the wave of temperature increase caused by the vegetation degradation could reach much deeper in winter than in summer. Although the ground cover and shrub under trees will restore rapidly, vegetation cannot restore to its earlier state before the degradation in a short time. The resultant temperature increase will last for a long time, especially in the top soil, resulting in a deepening active layer.

Because the area of vegetation removal is small compared to both the tree heights and the vast forest, the influence of surrounding trees on radiative transfer and wind field as well as the lateral heat exchange in deep soils could be significant, which will reduce the effect of vegetation removal in this study. In the case of extensive vegetation degradation, the ground temperature increases and permafrost degradation will be more severe. It also will take longer time for ground temperature and permafrost to restore.

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