

The Effect of Moisture Content on the Thermal Conductivity of Moss and Organic Soil Horizons From Black Spruce Ecosystems in Interior Alaska

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Abstract: Organic soil horizons function as important controls on the thermal state of near-surface soil and permafrost in high-latitude ecosystems. The thermal conductivity of organic horizons is typically lower than mineral soils and is closely linked to moisture content, bulk density, and water phase. In this study, we examined the relationship between thermal conductivity and soil moisture for different moss and organic horizon types in black spruce ecosystems of interior Alaska. We sampled organic horizons from feather moss-dominated and *Sphagnum*-dominated stands and divided horizons into live moss and fibrous and amorphous organic matter. Thermal conductivity measurements were made across a range of moisture contents using the transient line heat source method. Our findings indicate a strong positive and linear relationship between thawed thermal conductivity (K_t) and volumetric water content. We observed similar regression parameters (B or slope) across moss types and organic horizons types and small differences in B_0 (y intercept) across organic horizon types. Live *Sphagnum* spp. had a higher range of K_t than did live feather moss because of the field capacity (laboratory based) of live *Sphagnum* spp. In northern regions, the thermal properties of organic soil horizons play a critical role in mediating the effects of climate warming on permafrost conditions. Findings from this study could improve model parameterization of thermal properties in organic horizons and enhance our understanding of future permafrost and ecosystem dynamics.

Key words: Thermal conductivity, soil moisture, black spruce, moss, boreal forest.

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Moss and organic soil horizons function as important controls on soil temperature and the thermal state of permafrost in high-latitude ecosystems (Dyrness, 1982; Bonan and Shugart, 1989; Yoshikawa et al., 2003; Nicolsky et al., 2007a). In general, organic soil horizons have low thermal conductivity values relative to mineral soil (Farouki, 1981) and consequently reduce vertical heat fluxes through the soil column and insulate permafrost from warm summer air temperatures. Recent climate warming at high latitudes has resulted in warming and thawing of permafrost (Lachenbruch and Marshall, 1986; Jorgenson et al., 2006), particularly in the discontinuous permafrost zone (Osterkamp and Romanovsky, 1999; Jorgenson et al., 2001), where soil temperatures are near 0 °C. However, the thermal properties of organic soil horizons may function to minimize the effects of climate warming on the ground thermal

regime (Shur and Jorgenson, 2007; Yi et al., 2007), slowing rates of soil warming and permafrost degradation.

The thermal conductivity of unfrozen organic soil horizons is influenced by soil moisture, bulk density, and decomposition state of the organic matter (Farouki, 1981; Yoshikawa et al., 2003). Organic soil horizons have very high porosity (Yi et al., 2009a), and thus, the thermal conductivity of organic horizons can fluctuate widely with moisture content. Prior studies have illustrated that the thermal conductivity of peat increases with moisture content (Johansen, 1975; Andersland and Anderson, 1978; Farouki, 1981). Andersland and Anderson (1978) reported a nonlinear relationship between the thermal conductivity of unfrozen peat and gravimetric moisture content, whereas Johansen (1975) reported a linear relationship between the square root of thermal conductivity and the degree of saturation. Thermal conductivity of organic matter also increases with bulk density (Andersland and Anderson, 1978), and bulk density typically increases with decomposition of soil organic matter (Manies et al., 2004). As a result, thermal conductivity should increase with decomposition and humification of soil organic matter.

To accurately predict future changes in permafrost extent and thickness, climate models have begun to include explicit thermal and hydrologic properties of soil organic horizons in high-latitude regions (Euskirchen et al., 2006; Nicolsky et al., 2007a; Lawrence et al., 2008; Yi et al., 2009b). In earlier studies, soil thermal models and ecosystem process-based models prescribed a constant average thermal conductivity value for thawed and frozen peat (Zhuang et al., 2001; Romanovsky and Osterkamp, 2000), but did not account for the effect of interannual and seasonal variability in moisture content on thermal conductivity, even though it was recognized as a necessary next step (Romanovsky and Osterkamp, 1997). Indeed, variability in the thermal conductivity of surface organic horizons can have a profound effect on simulated soil temperatures at depth (Bonan, 1991). More recently, several studies have used Kersten numbers to calculate thermal conductivity as a function of moisture content (Lawrence and Slater, 2008; Yi et al., 2009b). The Kersten number is a normalized thermal conductivity value used to weigh the saturated and dry thermal conductivity values of a given substrate (Kersten, 1949; Farouki, 1981). The incorporation of thermal conductivity as a moisture-affected variable in climate and ecosystem models is an important step forward in understanding high-latitude permafrost dynamics. To further enhance the projections of high-latitude permafrost dynamics, it will be critical to include the parameterizations for multiple organic horizons, based on improved *in situ* soil-moisture measurements and more accurate thermal conductivity parameters (Nicolsky et al., 2007b).

The aim of this study was to examine the relationship between thermal conductivity and moisture content in different organic horizons from black spruce (*Picea mariana* [Mill.] B.S.P.) ecosystems of interior Alaska. Black spruce is the dominant forest type in interior Alaska, covering approximately 44% of the landscape (Van Cleve et al., 1983), and is typically underlain by permafrost. Mosses dominate forest floor cover in black spruce

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ecosystems (Barney and Van Cleve, 1973; Beringer et al., 2001). Moss species vary with soil drainage in black spruce ecosystems. Feather moss-dominated stands often occur in somewhat poorly drained conditions but are generally quite pervasive across drainage classes (Harden et al., 1997; Bisbee et al., 2001), whereas *Sphagnum*-dominated stands typically occur in poorly drained conditions. To evaluate the effect of moisture content on thermal conductivity, we collected samples from the organic horizons of both feather moss-dominated and *Sphagnum*-dominated black spruce ecosystems. Organic samples were divided into three horizons (live moss, fibrous, amorphous) that differ with respect to physical properties and extent of decomposition, and we measured thermal conductivity across a range of moisture contents. Relationships derived from these data, which will allow for the calculation of thermal conductivity directly from *in situ* measures of soil moisture in surface organic horizons, are useful for modeling how the soil temperature regime of black spruce forests will respond to climate variability and change.

MATERIALS AND METHODS

Soil samples were collected from three somewhat poorly drained and two poorly drained black spruce forests in interior Alaska. Somewhat poorly drained sites are typically located in areas with limited slope (<5%), silt-dominated mineral soil texture, and permafrost that is typically present in the top 1 m. We sampled somewhat poorly drained sites at the Bonanza Creek Experimental Forest (www.lter.uaf.edu), Delta Junction, Alaska (DFCC site; see Harden et al., 2006), and in the uplands of the Washington Creek watershed (25 km north of Fairbanks, AK). Poorly drained sites are typically underlain by permafrost, with a shallow active layer depth (30–50 cm), and a water table is typically within 20 to 30 cm of the moss surface. We sampled poorly drained sites that included a *Sphagnum*-dominated site at the Bonanza Creek Experimental Forest and a site in the valley bottom of the Washington Creek watershed. Feather mosses (*Hylocomium splendens* and *Pleurozium schreberi*) were the dominant moss species in the somewhat poorly drained stands, whereas *Sphagnum* spp. (most commonly *Sphagnum fuscum*) dominated the forest floor cover in the poorly drained stands. Field measurements of moisture content in the fibrous organic horizons of black spruce ecosystems indicate that typical moisture values are greater in *Sphagnum*-dominated than in feather moss-dominated forest floors (Fig. 1; O'Donnell et al., 2009).

Organic soils were sampled by hand to ensure accurate volume and bulk density measurements. Using a variety of soil knives, saws, and scissors, samples were cut into small blocks and measured for volume. Samples were divided into live moss, fibrous organic matter (slightly decomposed), and amorphous organic matter (moderate to highly decomposed) for both moss types, following the stratified approach of Yi et al. (2009a). Samples were then transferred into small Tupperware containers and stored in a cooler until returned to the laboratory for further analysis. In the laboratory, all samples ($n = 5$ per site per horizon, total = 75 samples) were saturated with deionized water and allowed to drain for 24 h. After 24 h, we removed any excess water from the Tupperware containers that had drained from the samples. Herein, we refer to this initial moisture content as "field capacity (laboratory based)," based on the definition of field capacity as "the amount of water held in the soil after the excess gravitational water has drained away and the downward movement of water has materially decreased" (Veihmeyer and Hendrickson, 1931; Cassel and Nielsen, 1986).

We began measuring thawed thermal conductivity (K_t) using the KD2 Pro Thermal Properties Analyzer (Decagon

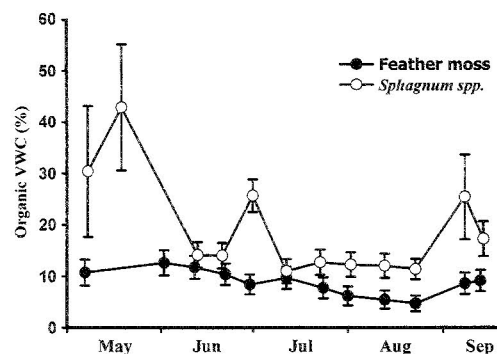


FIG. 1. Seasonal variation in VWC of shallow organic soils (10 cm below the ground surface) near Erickson Creek, Alaska (replotted from O'Donnell et al., 2009).

Devices, Inc., Pullman, WA). The KD2 Pro takes measurements using the transient line heat source method (Bristow et al., 1994). Briefly, the measurement cycles consist of a 30-sec equilibrium time, a 30-sec heating time, and a 30-sec cooling time. Temperature measurements are made every second during heating and cooling, and then temperature measurements are fit with an exponential integral function using nonlinear least-squares procedure. On average, samples were relatively thin (3–4 cm thick), ensuring uniform distribution of water throughout each sample. Measurements were made by inserting the KD2 Pro probe horizontally into the middle of each soil sample. Samples were allowed to air dry at room temperature (23°C) from the soil surface. We took daily measurements to generate a K_t moisture content relationship for each sample from each horizon type. Repeated measurements of thermal conductivity at similar moisture contents varied by approximately 6%. Unreasonably high or low values for thermal conductivity were omitted from our data collection and analysis.

To determine moisture content, we weighed each sample at the time of each thermal conductivity measurement. After the samples were air dried, we oven dried each sample at 65°C for 48 h and weighed each sample again after drying. Bulk density was calculated by dividing the oven-dry sample weight by sample volume. Gravimetric moisture content was calculated for each sample and then converted to volumetric moisture content by multiplying gravimetric moisture content by the oven-dry bulk density.

Analysis of variance (ANOVA) techniques were used to evaluate the effects of moss type and organic horizon type on bulk density, field capacity, and porosity. Analysis of variance was also used to evaluate the effects of moss type, organic horizon type, and water phase on average thermal conductivity values. Tukey post hoc comparisons were used to evaluate statistical differences among treatments. Linear regression techniques were used to assess the relationship between thermal conductivity and moisture content for different organic matter types. All data are reported as means $\pm$ 1 SD. All statistical analyses were conducted in either Sigma Plot version 10.0 (Systat Software, Inc., San Jose, CA) or Statistica version 7.0 (StarSoft, Inc., Tulsa, OK).

RESULTS

Physical Characteristics of Soil Organic Matter

The bulk density and field capacity (laboratory based) of organic horizons differ between feather moss- and *Sphagnum*-dominated black spruce ecosystems (Table 1). Bulk density

TABLE 1. Bulk Density, Field Capacity (Laboratory Based), and Porosity of Different Organic Horizon Types in Somewhat Poorly and Poorly Drained Black Spruce Ecosystems

	Live	Fibrous	Amorphous
Feather moss (somewhat poorly drained)			
Bulk density (g cm ⁻³)	0.02 ± 0.01 (15)	0.06 ± 0.02 (15)	0.12 ± 0.06 (15)
Field capacity (laboratory based; %)	27.5 ± 8.0 (15)	39.0 ± 10.5 (15)	65.0 ± 13.6 (15)
Porosity (%)*	98.9 ± 1.1 (32)	96.5 ± 2.6 (94)	88.3 ± 8.0 (45)
<i>Sphagnum</i> spp. (poorly drained)			
Bulk density (g cm ⁻³)	0.04 ± 0.03 (10)	0.06 ± 0.02 (8)	0.17 ± 0.10 (9)
Field capacity (laboratory based; %)	60.6 ± 19.0 (9)	62.7 ± 10.0 (9)	70.6 ± 10.5 (9)
Porosity (%)*	98.2 ± 0.9 (8)	97.4 ± 1.3 (30)	88.1 ± 7.4 (26)

Values in parentheses indicate sample size.

*Porosity values were calculated from Yi et al. (2009a).

varied as a function of moss type (ANOVA: $df=1$, $F=4.28$; $P=0.04$) and organic horizon type ($df=2$, $F=35.48$; $P<0.0001$). In general, bulk density increased with the extent of organic matter decomposition. For instance, live feather moss had significantly lower bulk density than feather moss-derived amorphous horizons, averaging 0.02 ± 0.01 and 0.12 ± 0.06 g cm⁻³, respectively (Tukey post hoc, $P=0.0001$). Similarly, live *Sphagnum* averaged 0.04 ± 0.03 g cm⁻³, and amorphous organic matter derived from *Sphagnum* averaged 0.17 ± 0.10 g cm⁻³ ($P=0.0001$).

Field capacity (laboratory based) values were governed by the interaction of moss type and organic horizon type ($df=2$, $F=5.16$; $P=0.008$; Table 1). Among feather moss horizons, field capacity (laboratory based) increased from $27.5 \pm 8.0\%$ in live samples to $65.0 \pm 13.6\%$ in amorphous samples ($P=0.008$). Among *Sphagnum* samples, field capacity (laboratory based) was not significantly different among organic horizon types ($P>0.05$), ranging from 60 to 70% among all horizons. Field capacity (laboratory based) values also varied between moss types, where values were more than double in live *Sphagnum* than live feather moss ($P=0.0002$). However, the field capacity (laboratory based) of fibrous ($P=0.44$) and amorphous ($P=0.99$) organic matter was not significantly different between feather moss and *Sphagnum* samples.

Soil porosity was governed by organic horizon type ($df=2$, $F=81.20$; $P<0.0001$) but was not significantly different between moss types ($P=0.98$; Table 1). For both feather moss and *Sphagnum* samples, porosity decreased with decomposition extent. For instance, the porosity of live feather moss was significantly greater than that of amorphous horizons derived from feather moss, averaging $98.9 \pm 1.1\%$ and $88.3 \pm 8.0\%$, respectively ($P<0.0001$).

The Effect of Moisture Content on Thermal Conductivity

We observed strong positive and linear relationships between K_t and VWC across moss types and organic horizon types (Table 2; Fig. 2). We did not observe significant differences among regression parameters (B) across moss types or organic horizons types, with B averaging 0.0051 ± 0.0005 , collectively (Table 2). However, we did observe small variations in B_0 across organic horizon types (Table 2), indicating that minimum K_t values under dry conditions are variable across organic horizon types. We also observed higher maximum K_t in live

Sphagnum than in live feather moss (Fig. 2), due to the higher field capacity in live *Sphagnum* moss relative to live feather moss (Table 1).

DISCUSSION

Controls on Thermal Conductivity of Organic Horizons

Soil thermal dynamics in organic horizons are strongly governed by soil-moisture content (Fig. 2). Dry organic horizons have considerably lower thermal conductivity than do wet organic horizons and thus function as good insulators against warm air temperatures. Wet organic horizons also dampen the amplitude of seasonal temperature variations through the absorption and release of latent heat during phase transitions (Romanovsky and Osterkamp, 2000). Both feather moss- and *Sphagnum*-derived organic horizons have high porosity (Table 1), and consequently, changes in soil-moisture content largely determine the variability in thermal conductivity values. Based on our findings, there is nearly a fivefold to eightfold difference in thermal conductivity of dry and wet feather moss-derived organic horizons, and a tenfold difference between dry and wet *Sphagnum*-derived organic horizons. Maximum K_t ranged from 0.5 and 0.6 W m⁻¹ K⁻¹ considerably lower than the values suggested by Brown and Williams (1972; 1.1 W m⁻¹ K⁻¹), but consistent with the measurements by Andersland and Anderson (1978). Our measurements are also consistent with the K_t values suggested by Bonan (1991), who used 0.023 W m⁻¹ K⁻¹ for dry moss and 0.291 W m⁻¹ K⁻¹ for saturated moss in Alaskan ecosystems. Sharratt (1997) measured *in situ* thermal conductivity in black spruce forests of interior Alaska and reported values for relatively dry moss ranging from 0.03 to 0.09 W m⁻¹ K⁻¹ over the growing season, which are consistent with our measurements at low moisture content (<20% by volume). Minimum K_t values measured in this study are also consistent with *in situ* thermal conductivity measurements of *Sphagnum* peat by Kettridge and Baird (2007). Our results are also in a good agreement with the estimates of Romanovsky and Osterkamp (2000; Table 1) based on interpretation of high-resolution and high-precision temperature measurements from a black spruce forest site in the Bonanza Creek LTER research area (0.1 W m⁻¹ K⁻¹ for the living moss, 0.3 W m⁻¹ K⁻¹ for the dead moss, and 0.5 W m⁻¹ K⁻¹ for the peat layer). Our measurements and calculations of organic horizon physical properties were also consistent with other

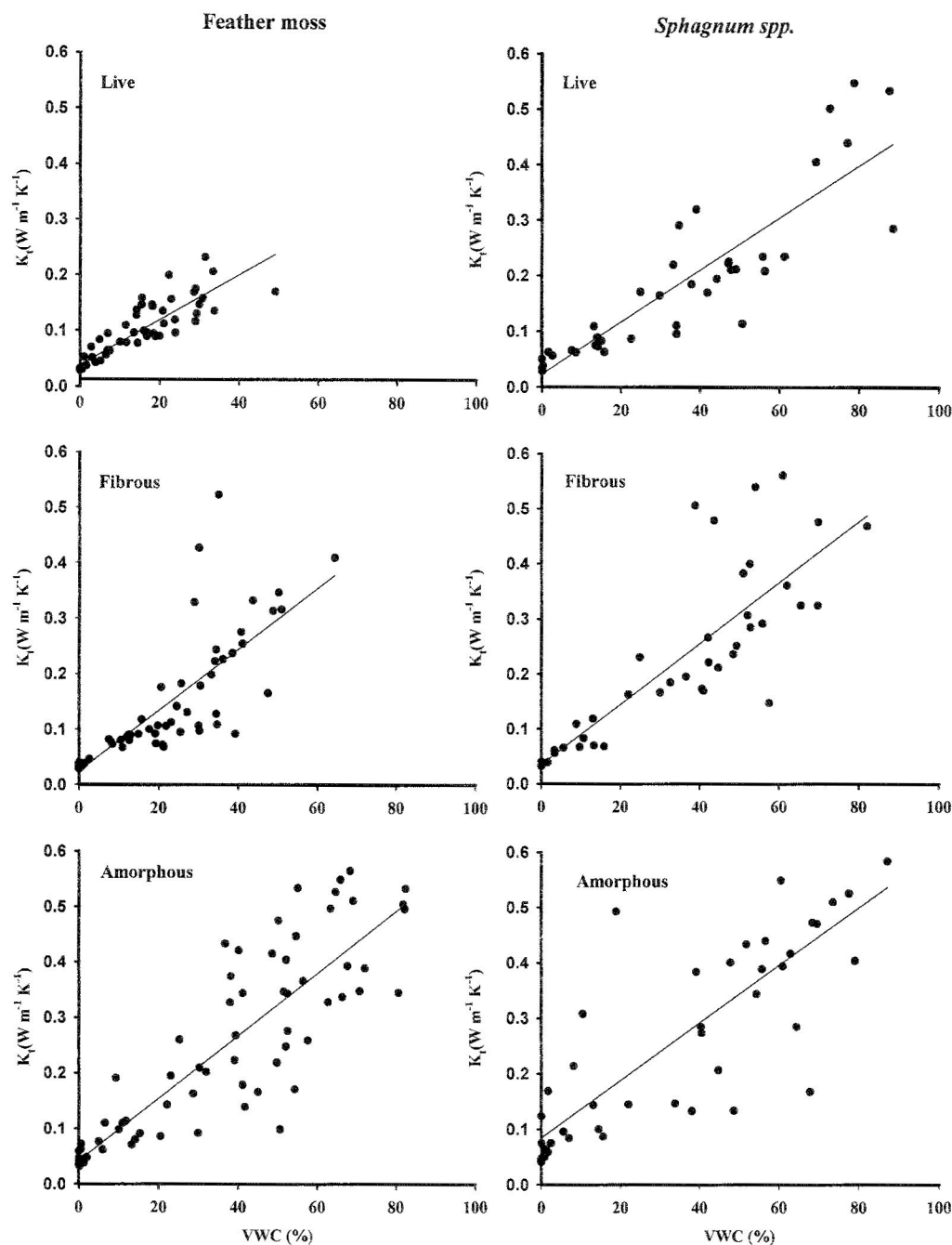


FIG. 2. The relationship between thawed thermal conductivity (K_t) and VWC within different moss and organic matter types. Regression techniques revealed a positive linear relationship between K_t and VWC for all samples types. Detailed regression statistics are reported in Table 2.

reported values for bulk density (O'Neill et al., 2003), porosity (Raaflaub and Valeo, 2009), and field capacity (Yoshikawa et al., 2003).

We observed substantive differences in K_t values between moss types, which can, in part, be explained by differences in physical and ecophysiological properties of each moss. *Sphagnum* spp. can absorb and retain more water than can feather mosses, as indicated by the higher field capacity (laboratory

based) values (Table 1; also see Yoshikawa et al., 2003). In the field, *Sphagnum* spp. can wick and obtain moisture from deep in the soil profile through capillary action (Bisbee et al., 2001), whereas feather mosses depend on precipitation inputs and dew formation for moisture. Despite this difference in maximum K_t minimum K_t values were similar between moss types, as both mosses are easily subject to desiccation on warm and sunny days (Skre et al., 1983; Bonan and Shugart, 1989).

TABLE 2. Results From Linear Regression Between Thawed Thermal Conductivity and Volumetric Water Content for All Six Organic Matter Types

	β	β_0	t	r^2	P
Feather moss					
Live	0.0041	0.0377	15.39	0.79	<0.0001
Fibrous	0.0055	0.0243	11.67	0.67	<0.0001
Amorphous	0.0056	0.0420	17.60	0.79	<0.0001
<i>Sphagnum</i> spp.					
Live	0.0047	0.0233	13.97	0.81	<0.0001
Fibrous	0.0055	0.0347	11.09	0.74	<0.0001
Amorphous	0.0052	0.0844	8.48	0.61	<0.0001

Soil Thermal Dynamics and Climate Change at High Latitudes

Improved parameterization of soil thermal dynamics in organic horizons is essential for modeling future permafrost and ecosystem dynamics in high-latitude ecosystems (Yi et al., 2009b). The thermal properties of organic horizons help to mediate and slow the effects of future climate warming on permafrost degradation (Shur and Jorgenson, 2007). Atmospheric warming may stimulate the release of carbon dioxide and methane from boreal ecosystems (Zhuang et al., 2006), which currently harbor large stores of organic carbon in near surface soils and permafrost (Schuur et al., 2008). Incorporation of organic horizon thermal properties into large-scale model simulations has improved our understanding of future permafrost dynamics (Euskirchen et al., 2006; Nicolsky et al., 2007a; Lawrence et al., 2008) and, as a result, will improve our ability to predict the fate of organic carbon in northern soils.

Incorporation of organic horizon thermal properties, as measured in this study, could improve model simulations of future climate change and ecosystem dynamics in the boreal region. In particular, the inclusion of specific thermal conductivity-soil-moisture relationships for different organic horizon and moss types will improve the current predictions of permafrost vulnerability to climate warming. Future studies could use these relationships to calculate thermal conductivity directly from *in situ* moisture measurements in organic soil horizons or from the soil-moisture content values calculated in coupled permafrost-hydrological models. The redistribution of surface and soil water in response to permafrost thaw (Jorgenson et al., 2001) or regional drying (Smith et al., 2005; Goetz et al., 2005) will clearly influence thermal conductivity of organic horizons and can be easily represented in models based on our measurements. In our related study (Jorgenson et al., submitted for publication), we showed that changes in the organic horizon moisture content and related changes in thermal conductivity not only may result in changes in permafrost temperature but also can lead to a long-term permafrost thawing and disappearance. Future vegetation and moss dynamics in black spruce ecosystems may also alter soil thermal properties (Potter 2004) either through changes in or loss of moss types. Our findings suggest that a shift toward *Sphagnum*-dominated from feather moss-dominated ecosystems could enhance heat conduction through organic horizons via wetter soil conditions, causing a thickening of the active layer and even thawing of permafrost. Alternatively, moss species abundance may decline in response to changing vascular plant composition or resource availability (Hart and Chen, 2006), which would likely reduce organic horizon thickness and protective insulation for permafrost.

CONCLUSIONS

Considerable uncertainties still exist regarding the fate of permafrost at high latitudes in response to climate warming (Lawrence and Slater, 2005, 2006; Burn and Nelson, 2006), largely due to the complex interactions among climatic, ecosystem, and disturbance controls on permafrost stability (Shur and Jorgenson, 2007). Thermal properties of soil organic matter play a critical role in mediating the effects of climate change, particularly in the discontinuous permafrost zone. Here, we illustrate the importance of moisture content on the thermal conductivity of soil organic horizons. Our findings suggest that this thermal conductivity-moisture relationship is consistent across moss type and decomposition state of soil organic horizons.

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