PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **16**: 217–222 (2005)
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/ppp.502

Short Communication

Thermal Conductivity of Soils in the Active Layer of Eastern Siberia

Anatoli Brouchkov,[1] Masami Fukuda,[2] Go Iwahana,[2] Yoshikazu Kobayashi[1] and Pavel Konstantinov[3]*

[1] Research Center for North Eurasia and North Pacific Regions, Hokkaido University, Sapporo, Hokkaido, Japan
[2] Institute of Low Temperature Science, Hokkaido University, Sapporo, Hokkaido, Japan
[3] Permafrost Institute, Russian Academy of Sciences Siberian Branch, Yakutsk-10, Sakha (Yakutia) Republic, Russia

ABSTRACT

Landscape changes accompanied by changes in soil properties occur in Central Siberia as a result of forest fire, surface processes and human impact. A non-steady-state technique tested the thermal properties of Siberian soils. Thermal conductivity of thawed soil increases in the active layer at depths of 5 and 30 cm after fire, especially in the organic layer due to an increase in density. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: frozen soils; permafrost; thermal conductivity; Yakutia; Siberia

INTRODUCTION

Several authors have noted the influence of the thermal properties of organic soils upon the permafrost thermal regime (Kudryavtsev, 1959; Nakano and Brown, 1972; Brown and Péwé, 1973; Riseborough and Burn, 1988). It is known that forest fires are one of the triggers of thermal regime change and the formation of thermokarst. Forest fires modify ground surface conditions and cause deepening of the active layer. Subsequent disturbance of surface vegetation and organic layer changes the energy budget of soil significantly.

In the Yakutsk area of Central Siberia, the active layer includes several soil horizons. The O horizon, primarily composed of organic matter, is only 1–2 cm thick. The A horizon, typically a dark-coloured layer due to the presence of organic matter, reaches 5–15 cm in thickness. In spite of their small depths, these horizons affect the heat balance of the active layer due to their low thermal conductivity and diffusivity. In addition, soil thermal properties differ in the thawed and frozen states. As a result, the mean annual temperature at the surface and in the O and A horizons, and the active-layer depth vary (Figure 1); these so-called 'offsets' of the mean annual temperature are well known (Kudryavtsev *et al.*, 1974; Smith and Riseborough, 2002).

TECHNIQUES

The thermal conductivity of frozen soils can change significantly due to ice-water phase transfers. Non-steady-state techniques perform measurements during the process of temperature change; these can be made quickly and conveniently both for laboratory and field studies (Kay *et al.*, 1981). The equipment used includes a needle-shaped electrically-heated probe, suitable for insertion into the soil. A thermocouple is placed next to the heater. Analysis of the temperature change relative to the starting temperature is carried out. For a short distance from the heater, the rise in temperature is given by:

$$T - T_0 = \frac{q * (a + \ln(t))}{4\pi * K}$$

* Correspondence to: Anatoli Brouchkov, Research Center for North Eurasia and North Pacific Regions, Hokkaido University, W8 N9, Kita-ku, Sapporo, Hokkaido, 060-0809 Japan.
E-mail: anatoli@nenp.hokudai.ac.jp

Received 25 April 2003
Revised 19 May 2004
Accepted 24 June 2004

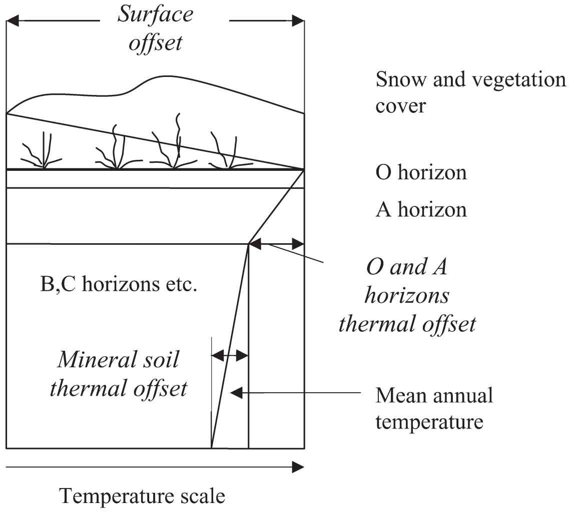

Figure 1 Mean annual temperature profile of the surface (snow and vegetation) cover and the active layer consisting of the O, A and other (B,C etc.) soil horizons.

where T is the measured temperature, T_0 is the initial temperature, q is the heat generated per unit time and unit length of the wire, K is the thermal conductivity, a is a constant, and t is time. A plot of temperature versus the log of time can be used to derive the thermal conductivity. Typically, the electrical voltage used is 3V, current is 100 mA for a 5-s period, and the time of measurements is 2 h.

Basic soil properties are determined according to standard protocols; organic soil content was determined by ignition.

FIELD STUDIES

A field study site is at Neleger (62°19′, 129°31′) located on the Tyungylyn Terrace of the Lena River, approximately 25 km northwest of the city of Yakutsk, Russia. The terrace is covered with boreal forest (taiga); elevation above sea level is about 200 m. The vegetation is dominated by larch forest. The greater part of the primary forest was cut or affected by fire and is now being recolonized by secondary birch forest. The forest plays a key role in keeping low temperatures of permafrost. At 15–20 m depths they are −2 to −4°C. The active layer in the forest area is about 1–2 m deep.

Typical values of thermal conductivity in the A horizon are in the range of 0.05–0.25 W/m*K depending on landscape (Table 1). Variation of thermal conductivity of the A horizon in 18 measurements is larger in disturbed forest than in undisturbed forest; values vary from the average by three times or more (Table 2).

Table 1 Average values of thermal conductivity of the A horizon, Neleger site, left bank of the Lena River, and Yukechi site, right bank of the Lena River.

Landscape	Thermal conductivity, W/m*K	
Neleger site		
Larch forest	0.05–0.15	
Disturbed forest	0.1–0.4	
Birch forest	0.05–0.22	
Alas	0.09–0.25	
	Depth: 5 cm	30 cm
Yukechi site		
Larch forest	0.08	0.57
Birch forest	0.07	0.37
Cut forest 7 years	0.2	0.88
Cut forest 12 years	0.1	0.46
Slope of alas	0.1	0.7
Alas	0.09	0.98

Table 2 Variation in thermal conductivity of the A horizon in disturbed and undisturbed forest.

Thermal conductivity, W/m*K	Forest	Disturbed (cutover) forest
Average value	0.05	0.14
Deviation	0.03	0.09

The thermal conductivity of sandy silt at a depth of 30 cm is several times higher; as a result, the thermal mode of soils and the active-layer depth are affected significantly by variations in the organic layer. Thermal conductivity of the A horizon at a depth of 5 cm and the mineral soil at a depth of 30 cm also depends on water content (Figure 2). Thermal conductivity values were calculated using soil temperatures and heat fluxes were similar to those measured by the non-steady-state technique (Table 3).

INFLUENCE OF FIRE

Forest fires in the boreal forest affect the surface energy balance and water budget; as well, soil properties alter the surface albedo, density and moisture, infiltration and evaporation rates, thermal conductivity and heat capacity (Hinzman *et al.*, 2001). The

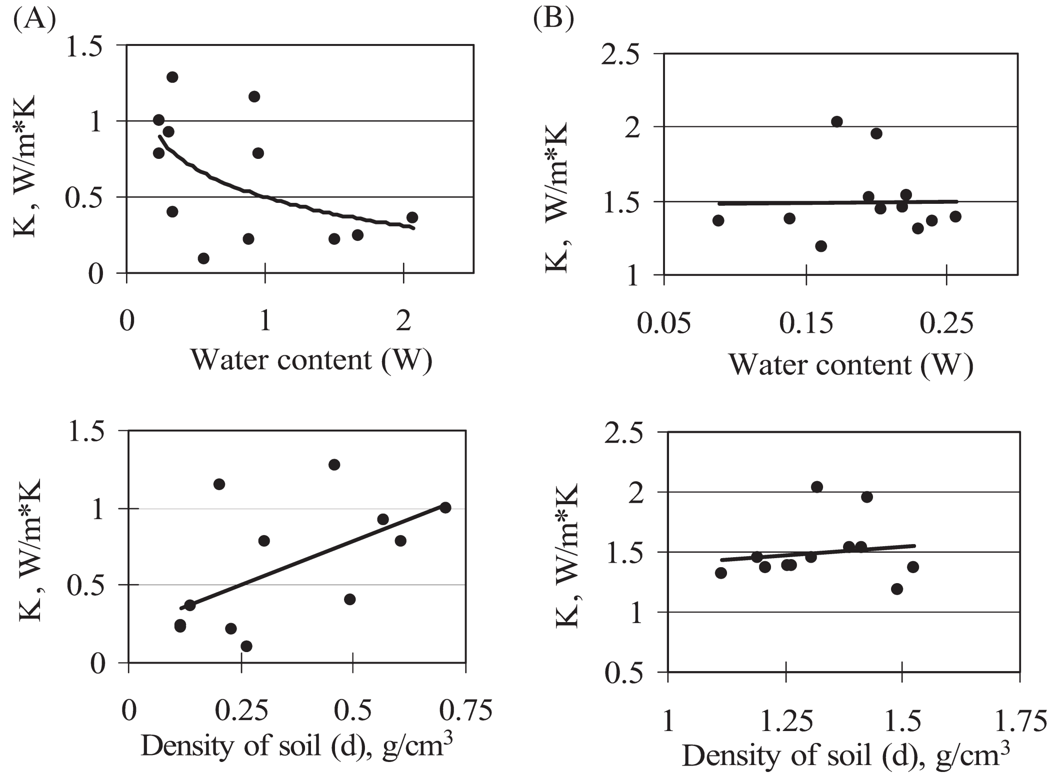

Figure 2 Thermal conductivity of Yakutsk soil vs. gravimetric water content and vs. density at depths of (A) 5 cm and (B) 30 cm.

changes in thermal conductivity within the active layer were studied at six sites in an experimental fire area; measurements were made at depths of 5 and 30 cm.

The differences between thermal conductivities at depths of 5 and 30 cm are larger before a fire than after a fire (Figure 3): the thermal conductivity of soil at a depth of 5 cm increased to almost double after a fire. This is probably because the density of the A horizon increased (Figure 4) due to drying of the soil and burning of organic material.

ACTIVE-LAYER DEPTHS

The thermal mode of the active layer is affected by a number of factors. For example, the surface vegetation cover reduces the amplitude of daily temperature changes by three times and more. Moss has a special cooling effect. It was established that every 5 cm increase in surface moss cover—consisting of *Tomenthypnum nitens* and *Aulacomnium palustre* mostly—leads to ≈1–2° C decrease in annual mean temperature of sandy silt in West Yakutia. The thermal insolation is less in disturbed forest.

Measured data were used for calculations of the thermal mode and the active-layer depth. A modified Kudryavtsev equation has advantages over other analytical models and accurately estimates active-layer thickness (Romanovsky and Osterkamp, 1997). Kudryavtsev's approach (Kudryavtsev *et al.*, 1974) allows calculation of the thermal offsets and the annual mean temperature at the base of the active layer (Table 4).

Field measurements of water content in the autumn and at the end of winter show that redistribution of water is connected to freezing of the active layer (Figure 5). The redistribution is especially significant in the A horizon, and differences in thermal conductivity values of frozen (in winter) and unfrozen (in summer) states can be more than those taken from calculations.

Therefore, the A horizon affects the active-layer thermal mode and significantly decreases the annual mean temperature of permafrost. Forest fires that destroy surface vegetation and change A horizon

Table 3 Temperature, heat flux and calculated values of thermal conductivity of the A horizon at a depth of 5 cm at Neleger site.

Site and date	Time	Ground heat flux W/m^2	Temperature, °C at the depth			Thermal conductivity, W/m*K
			1 cm	5 cm	10 cm	
Larch forest, thawed soil July 15, 2000	11:20	−9.87	26.2	18.2	13.7	0.07
	11:30	−10.12	26.4	18.2	13.8	0.07
	11:40	−10.32	28.7	18.8	14	0.06
	11:50	−10.53	30.9	19.2	14.2	0.05
	12:00	−10.71	29.4	19.5	14.5	0.06
	12:10	−10.84	26.2	19	14.6	0.08
	12:20	−10.91	25.4	18.4	14.7	0.09
	12:30	−10.99	24.9	18.2	14.7	0.09
	12:40	−11.14	23.8	17.8	14.7	0.11
	12:50	−11.36	23.4	17.5	14.6	0.11
Larch forest, partly frozen soil May 16, 2000	22:50	0.446	−0.1	0.2	0.2	0.12
	23:00	0.573	−0.2	0.2	0.2	0.11
	23:10	0.613	−0.2	0.1	0.1	0.16
	23:20	0.583	−0.2	0.1	0.1	0.16
	23:30	0.637	−0.2	0.1	0.1	0.17
	23:40	0.628	−0.2	0.1	0.1	0.17
	23:50	0.631	−0.2	0.1	0.1	0.17
Disturbed forest, thawed soil July 15, 2000	13:50	−18.98	27.3	17.9	12	0.11
	14:00	−19.46	27.3	18	12.1	0.11
	14:10	−19.91	27.5	18.1	12.2	0.11
	14:20	−20.32	27.4	18.2	12.2	0.12
	14:30	−20.72	27.4	18.2	12.3	0.12
	14:40	−21.07	26.7	18.2	12.4	0.13
	14:50	−21.39	26.6	18.2	12.4	0.13
	15:00	−21.79	25.9	18.2	12.5	0.14
	15:10	−22.26	25.6	18.2	12.5	0.15
	15:20	−22.71	25.5	18.2	12.6	0.15

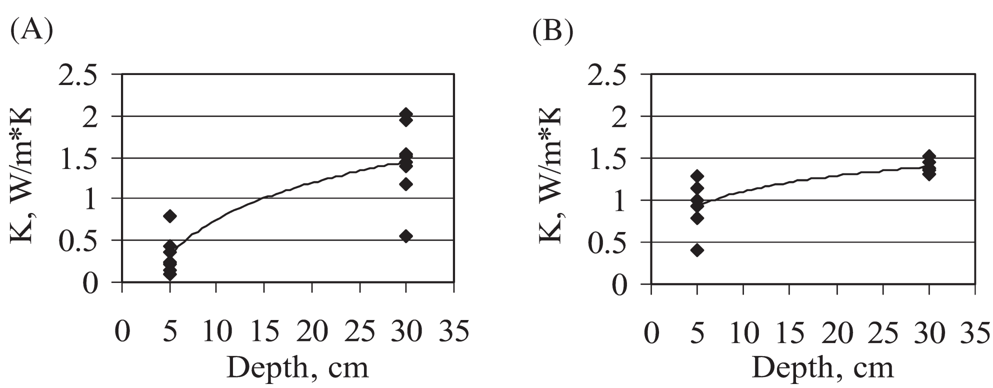

Figure 3 Thermal conductivity of soil at different depths before (A) and after (B) the experimental fire.

Figure 4 Average density of the A horizon at a depth of 5 cm before and after fire.

thermal properties can cause an increase in permafrost temperatures of up to 1.5–2°C or more.

DISCUSSION

Climate and terrain determine the heat exchange at the ground surface. The latter refers to surface conditions and includes the thermal properties of the organic layer and the ground itself. Changes expected with global climate change, human impact and forest fire are likely to increase the depth of the active layer. The increased active-layer depth has many effects at the surface. Permafrost is a source of greenhouse gases, thus thawing of the frozen soils affects the global carbon cycle. Organic material in thawing permafrost decays quickly, releasing carbon dioxide and methane.

An increase in thermal conductivity of the organic layer (A horizon) after fire as well as a higher water content in alas and swamp areas in summer results in greater thawing of the active layer and an increase in the temperature of permafrost. The process of thawing of permafrost, once started after fire, could be accelerated. Swamp and alas sites, formed due to an increase in frozen ground temperatures and thawing of permafrost, are characterized by water saturation of soil. Because soil is consolidated, values of thermal conductivity increase.

Soil density and possibly mineral content also increase after fire at depths of 5 cm. However, the reasons for this are not completely clear. Heat impact normally leads to drying of soil and consequent compacting of soil particles, but the observed changes need to be studied experimentally. The water regime of the active layer is a key to determination of the thermal properties of soil; however, it is still poorly known in cold regions, especially for disturbed landscapes (Hinzman *et al.*, 2001).

The redistribution of water during freezing of the active layer and the consequent change of thermal properties need further study.

CONCLUSION

A non-steady-state technique used to test soils gives the possibility to study thermal conductivity of soil horizons in the landscapes of Eastern Siberia. Calculations based on Kudryavtsev's model show a high sensitivity of the thermal mode of the active layer to surface disturbance. Enriched by organic material, the soil A horizon has a low thermal conductivity that differs in its frozen and thawed states; this creates a negative thermal offset that decreases the temperature of permafrost by up to 1.5 to 2°C.

Table 4 Data and results of calculations of thermal mode of soils at the Neleger site.

Landscapes	Larch forest	Birch forest	Disturbed forest
Snow depth, m	0.40	0.4	0.45
Snow density, g/cm^3	0.14	0.14	0.14
A horizon thickness, m	0.10	0.10	0.05
A horizon thermal conductivity, frozen/thawed, W/m*K	0.08/0.06	0.12/0.10	0.15/0.14
Calculated A horizon thermal offset, °C	−1.4	−1.0	−0.3
Soil gravimetric water content	0.3	0.35	0.35
Thermal conductivity of soil, frozen, W/m*K	1.0	1.1	1.2
Thermal conductivity of soil, thawed, W/m*K	0.8	0.9	1.0
Calculated soil thermal offset, °C	−0.9	−0.4	−0.5
Summer precipitation, mm	74	93	93
Radiation adjustment, °C	0.5	0.5	1
Calculated active layer depth, m	1.5	1.7	2
Measured active layer depth, m	1.1–1.3	1.3–1.6	1.3–1.6
Calculated annual mean temperature at active layer depth, °C	−4.0	−3.5	−1.8
Measured annual mean temperatures at active layer depth, °C	−3.0– −3.5	−2.2– −2.7	−1.8– −2.3

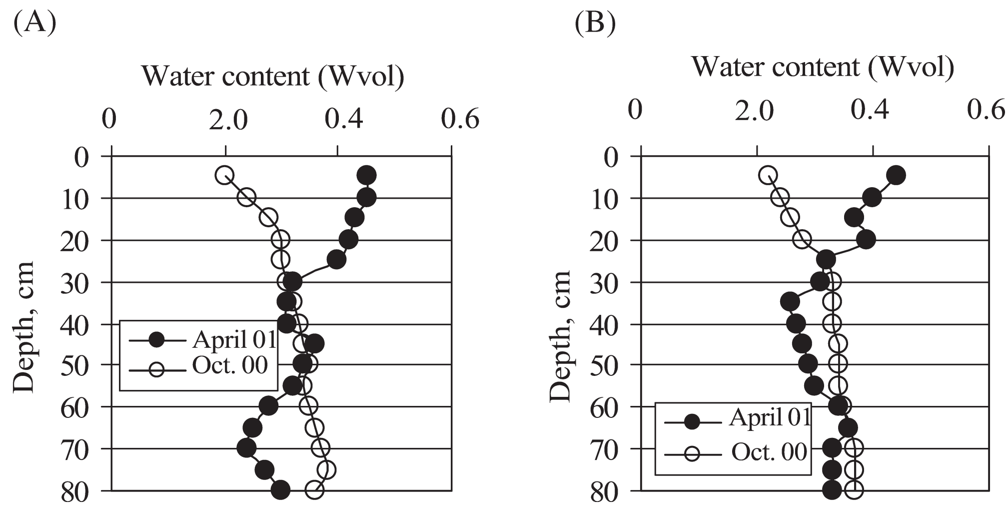

Figure 5 Soil volumetric water content distribution with depth in October, 2000 and April, 2001 in (A) the larch forest and (B) in the disturbed cutover forest site, Neleger site.

Thermal conductivity of the soil A horizon increases significantly after forest fire. In surface depressions such as swamp and alas sites, values of thermal conductivity of both organic (A horizon) and mineral soil increase; therefore, a process of warming of permafrost, once started, could accelerate as a result of the alteration of the thermal properties of soil.

ACKNOWLEDGEMENTS

This work has been supported by CREST of JST (Japan Science and Technology). We are grateful to Professor Hugh French for his assistance in editing this paper.

REFERENCES

Brown RJE, Péwé TL. 1973. Distribution of permafrost in North America and its relationship to the environment: a review, 1963–1973. In *Proceedings, Second International Conference on Permafrost, North American Contribution*. National Academy of Sciences: Washington DC; *(Science Reports, Tohoku University, Series 5)*, 71–100.

Hinzman L, Yoshikawa K, Fukuda M, Romanovsky V, Petrone K, Bolton W. 2001. Wildfire in the subarctic boreal forests, ecosystem impacts and response to a warming climate. *Tohoku Geophysical Journal, (Science Reports, Tohoku University, Series 5)* **36**(2): 230–232.

Kay DB, Fukuda M, Izuta H, Sheppard MI. 1981. The importance of water migration in the measurement of the thermal conductivity of unsaturated frozen soils. *Cold Regions Science and Technology* **5**: 95–106.

Kudryavtsev VA. 1959. About seasonal freezing and thawing of soil. *Materials of 7th Meeting on Geocryology.* Soviet Union Academy of Sciences Press: Moscow; 168–173 (in Russian).

Kudryavtsev VA, Garagula LS, Kondrat'yeva KA, Melamed VG. 1974. Osnovy merzlotnogo prognoza. MGU, 431 p. (in Russian). CRREL translation: Fundamentals of frost forecasting in geological engineering investigations, CRREL Draft Translation 606, 1977 (489 pp.).

Nakano Y, Brown J. 1972. Mathematical modeling and validation of the thermal regimes in tundra soils, Barrow, Alaska. *Arctic and Alpine Research* **4**: 19–38.

Riseborough DW, Burn CR. 1988. Influence of an organic mat on the active layer. In *Proceedings, Fifth International Conference on Permafrost*, Trondheim, Norway, Tapir publishers, Vol. 1; 633–638.

Romanovsky VE, Osterkamp TE. 1997. Thawing of the active layer on the Coastal Plain of the Alaskan Arctic. *Permafrost and Periglacial Processes* **8**: 1–22.

Smith MW, Riseborough DW. 2002. Climate and limits of permafrost: a zonal analysis. *Permafrost and Periglacial Processes* **13**: 1–15.