E R D K U N D E

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EFFECTS OF VEGETATION COVER ON SOIL HEAT FLUX IN THE SOUTHERN YUKON TERRITORY

With 7 figures, 6 photos and 9 tables

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Zusammenfassung: Auswirkungen der Vegetationsdecke auf den Bodenwärmestrom im südlichen Yukon Territory

Im südlichen Yukon Territory entspricht die Nettostrahlung an wolkenlosen Augusttagen 25% der potentiellen Strahlung. Im Schatten bleibt die Nettostrahlung allerdings sogar um 14.00 h negativ.

Der Bodenwärmestrom im Torf mit unterschiedlicher Vegetationsbedeckung wies Ende August im südlichen Yukon Territory erhebliche Unterschiede auf, je nach Pflanzenarten und Vegetationsstruktur. Einschichtige Vegetationsdecken oder -matten zeigten die geringsten negativen Werte und die größten Tagesamplituden. Mehrschichtige Vegetationsdecken führten zu größeren negativen Werten bei geringsten Tagesschwankungen des Wärmestroms. Im Juni unmittelbar nach der Schneeschmelze durchgeführte Messungen ergaben höhere Wärmeflüsse und Tagesschwankungen als solche im August, außer bei *Cladina stellaris* mit nur geringen Unterschieden. Das mag auf den relativ geringen Feuchtegehalt dieser Mattenvegetation oder auf ihre höheren Albedowerte zurückgehen. *Spagnum*-Torfmoose waren noch im August feucht und spielen darum keine größere Rolle bei der Isolation der Unterlage gegenüber der Sonnenwärme.

Hänge mit 5°-Neigung in verschiedenen Expositionen weisen erhebliche Unterschiede des Wärmestroms auf, wenn man sie mit horizontalen Oberflächen im schluffigen Lehm am Fox Lake vergleicht. Darum bedarf es bei Geländeformen mit flachen Oberflächen (z. B. Torf-Plateaus) weniger Feldmessungen als Modellierungs-Grundlage als im reliefierten Gelände. Von Buschwerk bedeckte Oberflächen zeigten wiederum größere Wärmeverluste als solche mit einschichtiger Mattenvegetation. Solche Faktoren müssen bei meso- oder mikroskaligen Studien des Wärmestroms untersucht werden. Diese Beobachtungen mögen auch erklären, warum die Hänge perennierender Frosthügel nicht kollabieren und degradieren, nämlich wegen des Insolationseffektes der mächtigeren Winterschneedecken.

Weiterhin versteht sich, daß mehrschichtige Vegetationsdecken und Flechten-Matten den unterlagernden Permafrost während kurzer Phasen mit positiven Lufttemperaturen isolieren können. Sicherlich sind mittlere Jahrestemperaturen, die auf Mittelbildung aus den Tagesextremen der Lufttemperatur in 2 m Höhe über einer horizontalen Grasdecke beruhen, als Indikator des tatsächlichen Wärmestroms an der Bodenoberfläche nur von recht begrenztem Wert.

Summary: Net radiation on bright sunny days during August in the southern Yukon represents 25% of the potential radiation. However, in the shade, net radiation is negative, even at 1400 hours. Heat flux into the substrate beneath different vegetation covers over peat in late August in the southern Yukon Territory showed marked differences, depending on the plant species and vegetation structure. Single vegetation canopies or mats showed the least negative values and the highest diurnal amplitudes. Multiple canopies of vegetation provided more negative values but lowest diurnal ranges of heat flux. June measurements made immediately after snowmelt showed higher heat fluxes and diurnal ranges than those in August, except for *Cladina stellaris*, which scarcely changed. This may be due to the relatively small amounts of moisture held by such mats, or to its higher albedo. *Sphagnum* was still moist in August, so it was not a major factor in insulating the ground from summer heat.

Five degree slopes with different aspects have profound differences in heat flow when compared to horizontal surfaces on silt loams at Fox Lake. Thus flat-topped landforms such as peat plateaus will require fewer field measurements for modelling than landforms with sloping surfaces. Once again, shrub-covered surfaces showed greater heat loss than those with a single mat. These factors must be examined when carrying out meso- or micro-scale studies of heat flow. These observations may also explain why the slopes on perennial mounds do not collapse and degrade due to the insulating effect of the thicker winter snow covers.

It is also clear that vegetation covers with multiple canopies and a mat of lichens can insulate the underlying permafrost during short periods with mean annual air temperatures above 0°C. Clearly, mean annual air temperature based on the average of the highest and lowest daily air temperature measured 2 m above a grassy horizontal surface is of relatively limited use as an indicator of the actual heat flow at the ground surface.

1 Introduction

When considering the effects of potential climatic warming in permafrost areas, it is assumed that if the mean annual air temperature rises above 0°C, the permafrost will disappear (WOO et al. 1992). There appears to be a sound basis for this in that the mean annual ground temperature at the top of the zone of zero annual amplitude is consistently warmer than the mean annual air temperature by 1 to 7°C (HARRIS 1981). This is well established in the literature, but the actual difference varies considerably both locally and

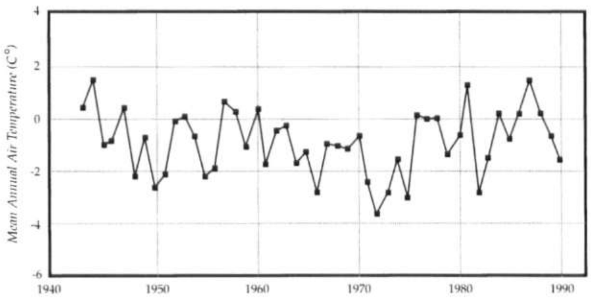


Fig. 1: Variation of mean annual air temperature at Whitehorse between 1944 and 1990 (data from A.E.S., Monthly Weather Records)

Mittelere Jahrestemperaturen der Luft in Whitehorse von 1944–1990

from continent to continent (BROWN a. PÉWÉ 1973). In continental western Canada, VITT et al. (1994) have provided evidence that the southern limit of peat plateaus is closely related to the −1°C mean annual air isotherm. Southwards, there is evidence of melting of former permafrost mounds.

However, there are also instances at the southern limit of permafrost where for a year or two, a mean annual air temperature above 0°C has occurred and the palsas and lithalsas have survived. A good example is near Whitehorse, Yukon Territory, Canada (Fig. 1) where in 1945 the mean annual air temperature was 1.5°C, yet trees on the surface of the mature lithalsas at Fox Lake, north of Whitehorse have up to 192 annual rings (HARRIS 1993). To maintain undisturbed tree growth, the mounds on which the trees grew must have endured these years of above-zero temperatures without melting. The same thing is found with trees on palsas around the north end of Marsh Lake, just east of Whitehorse. This indicates that the heat exchange between the soil and the air is modified in some way which offsets the effects of short-term fluctuations in air temperature. An obvious example of interference in the heat exchange would be the effects of different vegetation covers. For example, PAYETTE et al. (1986) regarded a loss of coniferous trees in subarctic Québec and their replacement by lichen cover as the cause of the development of ice wedges, implying ground cooling. On Plateau Mountain, HARRIS a. BROWN (1978) showed permafrost to be present under tundra, but absent under the adjacent forest. Similarly a north-facing slope on a mound should have a different thermal regime to that of a south-facing slope.

This paper attempts a quantitative description of how vegetation, slope and aspect may influence this process.

2 *Past work*

2.1 *Factors affecting permafrost distribution*

BROWN and PÉWÉ (1973) divided the factors affecting permafrost distribution into climatic and terrain factors. They presented qualitative evidence that these factors modify the heat exchange at the ground surface so that permafrost occurs in isolated masses in the ground in regions with mean annual air temperatures (MAAT) of up to 6°C (DIONNE a. SEGUIN 1992; VITT et al. 1994). Likewise, not all ground contains permafrost when the MAAT is below 0°C or even −3°C (HALSEY et al. 1995).

The climatic factors identified by BROWN and PÉWÉ included air temperature, snowfall, altitude and latitude, and cold air drainage. These factors are dominant in areas of continuous permafrost when the MAAT is below −7°C. Their postulated terrain factors included vegetation, topography (slope and aspect), substrate, hydrology, glaciers, and time. To these can be added the effects of Man and fire. These should be particularly important along the warmer margins of the permafrost areas where the permafrost is discontinuous or sporadic.

2.2 *Measurements used in studying the effects of these factors*

The methods used to demonstrate the effects of the factors usually involve comparing one factor with either permafrost distribution (e.g. VITT et al. 1994), or ground temperature (e.g. BROWN 1960, 1972; GRANBERG 1973; SEPPÄLÄ 1982), or active layer thickness (e.g. HARRIS 1987a, 1987b; PRICE 1971; MACKAY 1973, 1977, 1978, 1995), or heat flow into the ground (e.g. LACHENBRUCH a. MARSHALL 1969; HALLIWELL et al. 1990). Each method has its advantages and disadvantages. Ground temperatures vary at a given depth from year to year in marginal permafrost, which also usually lacks a level of zero amplitude. The thickness of the active layer is difficult to measure accurately and may vary considerably from year to year in marginal permafrost areas.

2.3 *Effects of vegetation cover*

There is a considerable body of literature showing that the vegetation cover alters the microclimate in the soil beneath it. One known effect is in reducing the depth of the active layer by shielding the ground from insolation (LINDSAY a. ODYNSKY 1965; BROWN a. JOHNSON 1965; JEFFREY 1967; PRICE 1971; HARRIS 1987a a. b; GREENE 1983). Most earlier works were

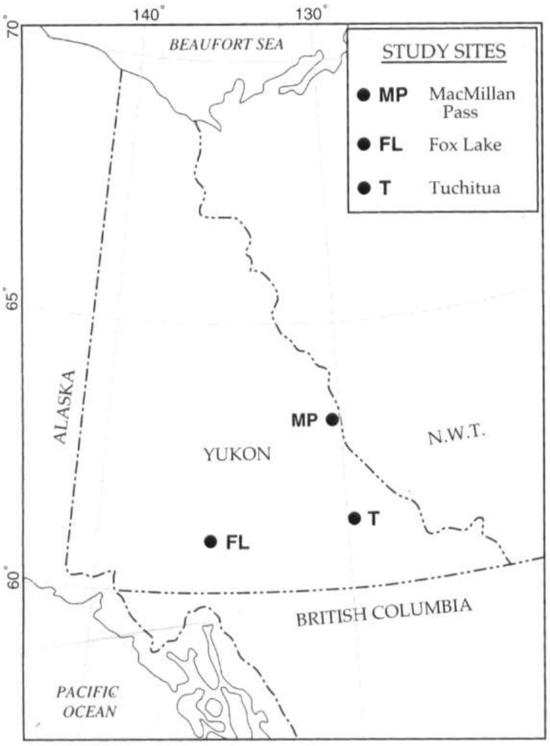


Fig. 2: Location of the study sites in the southern Yukon Territory

Lage der Untersuchungsgebiete im südlichen Yukon Territroy

based on differences in soil temperature beneath different vegetation covers, while later works focused on differences in mean annual ground temperatures under different plant associations.

More recently studies have indicated that heat flow into permafrost is greater than in areas lacking permafrost. ROUSE (1993) summarizes the literature on heat flow measurements in the Arctic and Subarctic, but the bulk of the studies are site-specific and the data is used to generalize on the situation for large regions where the vegetation is basically homogeneous. Thus there is a need for studies of microsites such as peat plateaus which are covered by a mosaic of different species of vegetation (see for example ZOLTAI 1972; SJORS 1961; NICHOLSON a. GIGNAC 1995). In this paper, results of soil heat flux below different species of plants and different plant associations on adjacent surfaces will be presented from the Subarctic.

2.4 Effects of topography

The amount of solar radiation received on the ground surface is modified wherever slopes occur. The differences in vegetation on north- and south-facing slopes have been documented many times in the Subarctic. For example, compare the vegetation on the south-facing slopes of Sheep Mountain (HOEFS et al. 1975) with that on the north-facing Outpost and Vulcan Mountains (HARRIS a. GUSTAFSON 1993). The slope and aspect are often used by botanists to study specific associations of plants in specialized situations (e.g. HOEFS et al. 1975; EDWARDS a. ARMBRUSTER 1989). Studies have also been carried out on lichen distribution relative to different slopes (PETZHOLD a. MUHERN 1987).

These studies of the effects of topography have rarely been carried out on a micro-scale, although similar effects are to be expected on smaller mounds such as palsas, lithalsas, peat plateaus and even earth hummocks. One exception is KERSHAW and ROUSE (1971) who concentrated on variations in species distribution over raised beach ridges and the effect of the microclimate on the metabolism of the plants. Since permafrost is directly affected by the microclimate, the latter should be different on slopes with opposing aspects and this should be reflected in the soil heat flux. This will be tested in this paper.

3 Study areas

Three different studies were undertaken on permafrost mounds in the southern Yukon Territory (Fig. 2). Table 1 summarizes the available climate data for each site. The mounds at the Fox Lake site consisted of the

Table 1: Comparative climatic data for the three study sites, together with latitude and elevation

Vergleich von Klimadaten für die drei Untersuchungsgebiete, mit Breiten- und Höhenlage

Site	Elevation (m)	Latitude	Mean Annual Air Temp. (°C)	Mean Annual Precipitation (mm)	Source of data
Fox Lake	800	61°06'N	c. −2.0	273	A.E.S., 1982
MacMillan Pass	1200	63°12'N	c. −7.0	>600	WAHL et. al., 1987
Tuchitua	915	61°18'N	−3.8	591	HARRIS a. SCHMIDT,1994; WAHL et al., 1987

tops and sloping sides of lithalsas where no peat was present. At the measurement site (lithalsa #4, HARRIS 1993), the dominant vegetation cover was *Arctostaphylos uva-ursi* (bearberry) up to 15 cm high, near thickets of *Salix brachycarpa* spp. *niphoclada* up to 1.5 m high, interspersed with grassy areas. The cover of bearberry was instrumented on a representative lithalsa, 2.4 m high, 22 m long and 15 m wide. The sites were well drained and the sediments consisted of calcareous silt loams, loams and sandy loams (see HARRIS 1993). During the study, the active layer was near maximum thickness (about 60 cm) and the weather was sunny and dry. Fox Lake has the lowest mean annual precipitation of the three sites.

The MacMillan Pass site was at tree line on the north side of the Canol Road, 2 km N of the MacMillan Pass airport, on the top of rolling peaty hills with permafrost present. The peaty deposits occur on the lower slopes of the valley sides, and the White River ash layer is present at about 15 cm below the surface in these sediments. This ash is dated to 1147 years B.P. (CAPPS 1915; HUGHES et al. 1972; CLAGUE et al. 1995), and since the peat is over 5 m thick in places, the peaty mound probably represents a middle to early Holocene peat deposit at seepage sites. The active layer was only about 40 cm thick, and the vegetation consists of *Ledum decumbens*, *Vaccinium* spp., and a mat of lichens. Table 2 lists the species present on and around the mounds. Locally, the surface of the vegetation cover has been disturbed by man. The climate is wettest and coldest at this site (Tab. 1), but the weather at the time of the measurements was dry and clear with frost at night.

The Tuchitua site was on the south side and top of an over-mature peat plateau at km 161.7 on the Robert Campbell Highway, which had been studied previously by HARRIS and SCHMIDT (1994). The peat plateau was frozen (anchored) to the mineral substrate (Fig. 3) and the peat was 2–5 m thick. Permafrost has been present for over 1200 years since the White River Ash was present in the woody peat deposit forming the top of the mound. The general vegetation cover is described by HARRIS and SCHMIDT (1994) but the specific study site had a 10–25% cover of *Picea mariana* with a 60% cover of an ericaceous understorey including *Vaccinium uliginosum*, *V. vitis-idaea*, and *Ledum decumbens*. The continuous ground cover included the sequence of mosses from *Polytrichum juniperinum*, through *Aulacomnium palustre*, to *Sphagnum fuscum* from the slopes of the peat plateaus down to the poorly drained sites. This is in contrast to the lichen cover dominated by *Cladina stellaris* on the well-drained top.

The lichens and mosses present are listed in Table 3. *Cladina stellaris* is the dominant lichen on the main surface of the peat plateau with lesser amounts of *Cladina arbuscula* spp. *arbuscula*, *C. mitis* and *C. rangifera*. These are the more cosmopolitan lichens that can tolerate canopies (PETZOLD a. MULHERN 1987). Clumps of mosses including *Polytrichum juniperinum* and *Aulacomnium palustre* also occur, but become more abundant towards the more open and poorly drained margins of the peat plateau, especially on the south side. *Sphagnum fuscum* is the most common species on the margins of the peat plateau.

Active layer thickness was between 60 and 120 cm at the time of the measurements. It had recently snowed and the snow had just melted. Mean annual temperature and precipitation at this site are intermediate between Fox Lake and MacMillan Pass (Tab. 1).

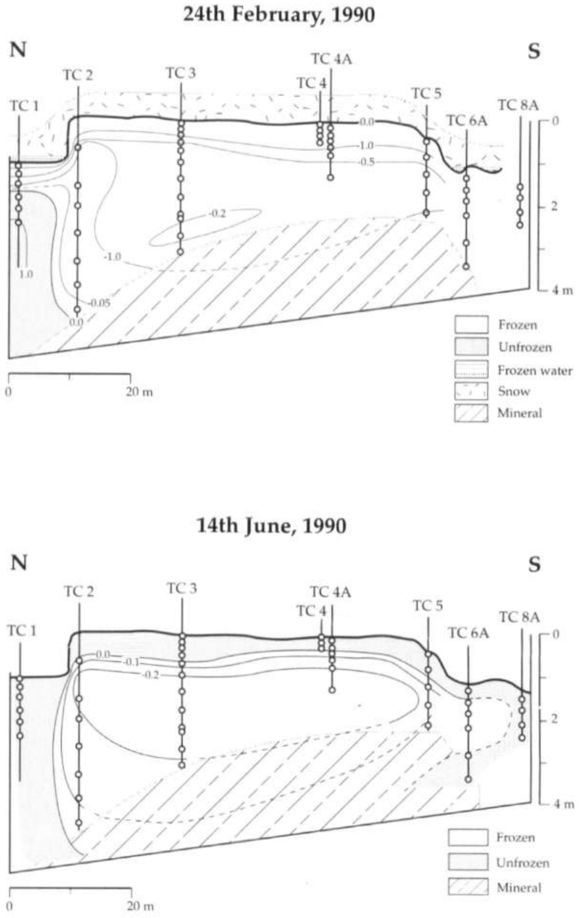


Fig. 3: Ground temperatures in the peat plateau at km 161.7, Robert Campbell Highway, Tuchitua (modified from HARRIS and SCHMIDT, 1994)

Bodentemperaturen im Torf-Plateau bei km 161,7, Robert Campbell Highway, Tuchitua

Table 2: Distribution of species of vascular plants and bryophytes on the fens, peaty hills and mineral soils in the tundra at MacMillan Pass

Verteilung von Gefäßpflanzen- und Moos-Arten auf den Mooren, Torfhügeln und Mineralböden der Tundra am MacMillan Paß

	Fens	Peaty mounds	Mineral soils
Abies lasiocarpa	×		×
Achillea nigrescens			×
Agropyron novae-angliae			××
Anemone parviflora	×	×	×××
Anemone richardsonii	×		×
Antennaria monocephala			×
Antennaria pallida			×
Antennaria pedunculata			×
Arabis holboellii var. *retrofracta*			×
Arctostaphylos alpina		××	×××
Arnica lessingii			××
Artemisia norvegica ssp. *saxatilis*			××
Astragalus alpinus			××
Astragalus canadensis			×
Barbarea orthoceras			×
Betula glandulosa	××	××	×××
Carex aquatilis	××		
Carex atrofusca	××		
Carex canescens	×		
Carex pachystachya	×		
Carex preslii	×		
Carex pyrenaica	×	×	×
Cassiope tetragona spp. *saximontana*		×	×
Cassiope tetragona spp. *tetragona*		×	×
Cerastium arvense		×	×
Cerastium beeringianum			×
Claytonia lanceolata			×
Cornus canadensis			×
Crepis nana			×
Delphinium glaucum			×
Deschampsia caespitosa			××
Draba alpina			×
Dryas punctata		×	×
Empetrum nigrum		××	××
Epilobium angustifolium			×
Epilobium latifolium			××
Equisetum sylvaticum var. *pauciramosum*	×	×	×
Eriophorum angustifolium var. *angustifolium*	×		
Eriophorum angustifolium var. *majus*	××		
Eriophorum scheuchzeri	×		
Erigeron acris spp. *delibis*			×
Erigeron acris spp. *politus*			×
Erysimum pallasii			×
Festuca altaica			×××
Fragaria vesca var. *americana*			×
Gentianella propinqua			×
Hedysarum alpinum ssp. *americanum*			××
Hieracium gracile			×
Hieracium triste			×
Juncus castaneus ssp. *castaneus*	××		×
Juncus drummondii	××		×
Kalmia microphylla		××	
Ledum decumbens		××	××
Lloydia serotina			×
Luzula arcuata var. *unalaschensis*	×		×
Luzula confusa	×		
Luzula parviflora	×		×
Lycopodium alpinum			×
Lycopodium annotinum var. *acrifolium*			×
Lycopodium annotinum var. *pungens*			×
Lycopodium clavatum var. *monostachyon*			×
Minuartia rubella			×
Oxyria digyna			×
Parnassia kotzbuei	×		×
Pedicularis labradorica		×	×
Petasites frigidus	×		
Petasites palmatus	×		
Poa alpina			××
Poa arctica			×
Poa glauca			×
Polemonium acutiflorum			×
Polemonium boreale			×
Polemonium pulcherrimum			×
Polygonium alaskanum			×
Polygonium viviparum		×	×
Populus tremuloides			×
Potentilla fruticosa		×	××
Potentilla norvegica			×
Ranunculus eshchscholteii		×	××
Rubus acaulis	×	×	
Rubus chamaemorus		×	
Rumex arcticus			×
Salix alaxensis			×
Saxifraga tricuspidata			×
Selaginella selaginoides			×
Senecio lugens			×
Senecio triangularis			×
Sibbaldia procumbens			×
Smilacina stellata			×
Spiraea beauverdiana			×
Stellaria longipes			×
Taraxacum hyparcticum			×
Tolmachevia rosea			×
Trisetum spicatum var. *maidenii*			×
Triglochin maritima	×		
Triglochin palustris	×		
Vaccinium uliginosum var. *alpinum*		×	×
Vaccinium vitis-idaea var. *minus*		×	×
Veronica wormskoldii var. *wormskoldii*			×
Viburnum edule			×
Viola rugulosa			×
Zygadenus elegans			×
Aulacomnium palustre	×		
Calliergon giganteum	×		
Calliergon richardsonii	×		
Campylum sp.	×		
Ceratodon purpureus	×		
Dicranum acutifolium	×		
Dicranum fuscensens	×		
Dicranum groenlandicum	×		
Dicranum undulatum	×		
Drepnocladus aduncus	×		
Helodium blandowii	×		
Hylocomnium splendens	×		
Meesia uliginosa	×		
Mnium sp.	×		
Oncophorus virens	×		
Pleurozium schreberi	×		
Pohlia nutans	×		
Sphagnum angustifolium	×		
Sphagnum fuscum	×		
Sphagnum lindbergia	×		
Sphagnum warnstorfii	×		
Sphagnum wulfianum	×		
Timmia austriaca	×		
Tomenthypnum nitens	×		
Alectoria ochroleuca		××	
Aspicilia cinerea			×
Bryoria lanestris			×
Bryoria nitidula			×
Bryoria simplicior			×
Cetraria ericetorum		××	
Cetraria nigrescens		×	
Cladina arbuscula spp. *arbuscula*		××	
Cladina mitis		××	
Cladina rangiferina		××	
Cladina stellaris		×	
Cladonia amaurocraea		×	
Cladonia coccifera		×	
Cladonia pleurota		×	
Dactylina beringica		×	
Flavocetraria cucullata		××	
Flavocetraria nivalis		××	
Hypogymnia bitteri		×	×
Lecidea plana		×	
Nephroma arcticum		×	×
Parmelia sulcata		×	×
Pseudophebe pubescens			×
Rhizocarpon distictum			×
Rhizocarpon obscuratum			×
Solorina crocea			×
Stereocaulon paschale		×	××
Tremolecia atrata		×	
Umbilicaria hypoborea		×	
Umbilicaria proboscidea			×
Umbilicaria rigida			×
Umbilicaria torrefacta			×
Vulpicida pinastri		×	×

4 *Methods used*

4.1 *Theory*

The daily energy balance can be expressed as:

$$Q^* = Q_H + Q_E + Q_S \qquad (1)$$

Where Q^* is net radiation exchange between the ground surface and the atmosphere; Q_H is sensible heat flux from the surface to the atmosphere; Q_E is latent heat of evapotranspiration; Q_S is heat flow through the soil.

By convention, heat flow into the ground surface from the atmosphere is regarded as positive (energy input) and heat flow upwards away from the ground surface into the atmosphere (energy loss) is regarded as negative. In the present study only Q^* and Q_S are measured. Provided the soil does not either freeze or thaw during the period of study, and there is no precipitation:

$$Q^* - Q_S = Q_H + Q_E \qquad (2)$$

In this study, the measurements are made beneath the surface of the unfrozen active layer during periods when the soil remains thawed, so interference by the latent heat of fusion of ice is avoided.

Figure 4 shows the characteristic shape of net radiation (Q^*) and heat flow data for the soil under conditions of clear sky and a single air mass during a 42-hour period (see also SELLERS 1965). Key parameters for each measurement are the amplitude of the energy flux, the time of the peak (T_P), the mean daily heat flux, and any obvious fluctuations such as clouds that indicate modification of the heat flux. In general, the amplitude should be proportional to the effective thermal conductivity of the soil above the heat flux plate. Higher effective thermal conductivities should give greater thermal amplitudes. The thermal conductivities of air and water at 0°C are 0.025 ($Wm^{-1}K^{-1}$) and 0.56 ($Wm^{-1}K^{-1}$) respectively (JOHNSTON 1981), so wet soils in midsummer should have higher thermal conductivities and amplitudes than similar wet soils in late summer because the reduction in net solar radiation (K^*) in late summer should correspond with a reduction in amplitude.

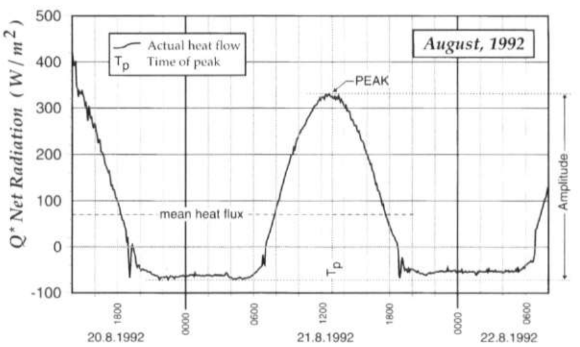


Fig. 4: Characteristic shape of the net radiation (Q^*) and heat flow data in the soil under conditions of a clear day and a single air mass (partly after SELLERS, 1965)

Charakteristischer Gang der Netto-Strahlung (Q^*) und der Wärmefluß-Daten im Boden an einem wolkenfreien Tag mit einheitlicher Luftmasse

The lag between the T_P for Q^* and the T_P for a given Q_S will indicate the relative volumetric heat capacity of the soil (C_S) above the heat flux plate. The lower the lag, the lower the value of the volumetric heat capacity and the greater the heat flux. In unfrozen soils:

$$C_S = X_m C_m + X_o C_o + X_w C_w + X_a C_a \qquad (3)$$

Where C_m is volumetric heat capacity of the mineral component in the soil; X_m is percentage volume of mineral matter in the soil; C_o is volumetric heat capacity of the organic component in the soil; X_o is percentage volume of organic matter in the soil; C_w is volumetric heat capacity of the water; X_o is percentage volume of water in the soil; C_a is volumetric heat capacity of air; X_a is percentage volume of air in the soil.

Since the mineral content does not change and the organic content varies only with the overlying vegetation, the main differences between soils are due to the water/air content of the vegetation and water/air content in the soils. Thus the lag will be different between wet soils with low air space immediately after snow melt, and drier soils of late summer.

The soil heat flux will be affected by at least three other factors, viz., the slope and aspect of the ground-air interface, the type and structure of any vegetation cover, and the nature of the substrate. If the surface is not perfectly horizontal, the timing of T_P will alter, as will the magnitude of the incoming radiation at T_P with slope. The angle of incidence of the short-wave radiation will vary so that both amplitude and the mean diurnal heat-flux will be affected.

The vegetation cover is also very important. It is known from mesoscale studies that the structure of the vegetation alters the surface energy balance (see Tab. 3.6 in ROUSE 1993; BLANKEN a. ROUSE 1994). BROWN and PÉWÉ (1973) summarized the literature which suggests that a surface cover of *Sphagnum* moss can reduce the energy balance in favour of increased permafrost. HARRIS (1987a) has shown a quantitative relationship between the thickness of the active layer and thickness of *Hypnum* moss at Kluane Lake, Yukon

Table 3: Distribution of species of vascular plants and bryophytes on the fens, on the sides and tops of hummocks and peat plateaus at km 161.7, Robert Campbell Highway, Tuchitua

Verteilung von Gefäßpflanzen- und Moos-Arten auf den Mooren, an den Flanken und auf den Kuppen von Erdhügeln und Torf-Plateaus bei km 161,7, Robert Campbell Highway, Tuchitua

Species	Floating fen	Fen	Slope of hummock	Top of hummock	Slope of peat plateau	Peat plateau
Drosera anglica	—					
Carex sp.	—	—				
Spiranthes romanzoffiana	—	—				
Potentilla palustris	—	—				
Tofieldia pusilla	—	—	—			
Carex aquatilis		—				
Scirpus caespitosus spp. *austriacus*		—				
Tofieldia glutinosa		—				
Menyanthes trifoliata		—				
Pinguicula villosa		—				
Petasites palmatus		—				
Triglochin maritimum		—	—			
Eriophorum brachyantherum		—	—			
E. chamissonis		—	—			
Parnassia palustris var. *neogaea*		—	—			
Smilacina trifolia		—	—	—		
Betula glandulosa		—	—	—		
Pedicularis labradorica		—	—	—		
Larix laricina		—	—	—	—	
Scirpus hudsonianus		—	—	—	—	
Salix macCalliana		—	—	—	—	
Empetrum nigrum		—	—	—	—	
Sphagnum fuscum		—	—	—	—	
Myrica gale		—	—	—	—	—
Rubus arcticus		—	—	—	—	—
R. chamaemorus		—	—	—	—	—
Oxycoccus microcarpus		—	—	—	—	—
Vaccinium uliginosum var. *uliginosum*		—	—	—	—	—
V. vitis-idaea var. *minus*		—	—	—	—	—
Mylia anomala		—	—		—	
Andromeda polifolia			—	—	—	—
Chamaedaphne calyculata			—	—	—	—
Ledum decumbens			—	—	—	—
L. groenlandicum			—	—	—	—
Cladina arbuscula spp. *arbuscula*			—	—	—	—
C. mitis			—	—	—	—
Flavocetraria nivalis			—	—	—	—
Cladonia cornuta spp. *cornuta*			—	—	—	—
C. cyanipes			—	—	—	—
Polytrichum juniperinum			—	—	—	—
Sphagnum obtusum			—	—	—	—
S. warnstorfii			—	—	—	—
Aulocomnium palustre			—		—	
Arctostaphylos rubra				—	—	—
Picea mariana				—	—	—
Cladonia pleurota				—	—	—
Cladina rangiferina				—		—
C. stellaris				—		—
Cladonia chlorophaea				—		—
C. fimbriata				—		—
C. gracilis var. *dilatata*				—		—
Kalmia microphylla					—	
Dicranum acutifolium					—	
D. elongatum					—	
Maianthemum canadense var. *interius*					—	—
Drosera rotundifolia						—
Alectoria ochroleuca						—
Arctoparmelia centrifuga						—
Cetraria islandica						—
C. laevigata						—
Cladonia coniocraea						—
C. deformis						—
C. pyxidata						—
Dactylina madreporiformis						—
Flavocetraria cucullata						—
Stereocaulon paschale						—
Umbilicaria proboscidea						—
Vulpicida pinastri						—
V. tilesii						—

Territory, as well as a similar relationship for the organic layer of the soil at Inuvik (HARRIS 1987b). Thus it is essential to only compare data for energy budgets for different species of cover, or different plant layers on the same substrate if the results are to demonstrate the effects of differences due to the species present.

4.2 Vegetation Studies

Collections of plants, mosses and lichens were made in 1984, and the species present were identified. An examination was then made of their distribution over the landforms and the specific habitats for each species (e.g. HARRIS 1993; HARRIS a. SCHMIDT 1994) were carefully documented. This distribution was similar to that in other peatlands in western Canada (e.g. ZOLTAI a. JOHNSON 1985).

For this study, attention was paid to the stratification of the vegetation into distinct canopies in some areas and not in others. Another factor was the homogeneity of the species forming the vegetation cover. On lithalsas, the vegetation cover was uniform in composition and canopy structure over the surface of a given landform, whereas the surface of the peat plateaus and peat mounds at Tuchitua and MacMillan Pass were covered by a complex mosaic of plant associations.

An example of a triple canopy would be *Larix laricina* (about 20% cover up to 8 m high), with *Ledum decumbens* (about 60% cover, up to 60 cm high) over a ground cover of *Cladina stellaris* (100% cover, up to 10 cm high). *Salix* spp. (10% cover, up to 3 m high) and *Picea mariana* (10% cover, up to 8 m high) were the other species in the upper storey at Tuchitua, while *Picea glauca* (2% cover, up to 16 m high) was the dominant species of the upper canopy at Fox Lake. Trees were almost entirely absent at the study sites at MacMillan Pass.

The shrub canopy at MacMillan Pass included *Kalmia polifolia* (40 cm high), *Ledum decumbens* (to 60 cm high), and *Vaccinium* spp. (to 40 cm high). At Tuchitua, *Chamaedaphne calyculata* (to 50 cm) also occurred, while at Fox Lake, *Arctostaphylos uva-ursi* (to 30 cm) and *Betula* spp. (to 1 m) were the most common species in the shrub canopy. The species growing that form the ground cover at each site were given in the site description. However, on the peatlands, the species that formed the ground cover were a mosaic of small patches with plant associations closely related to the microtopography. Pure stands of given species were unusual, and limited to *Cladina stellaris* and *Empetrum nigrum*. *Arctostaphylos uva-ursi* formed pure stands on the surface of lithalsa #4, Fox Lake in the area under study. At MacMillan Pass, disturbance had resulted in

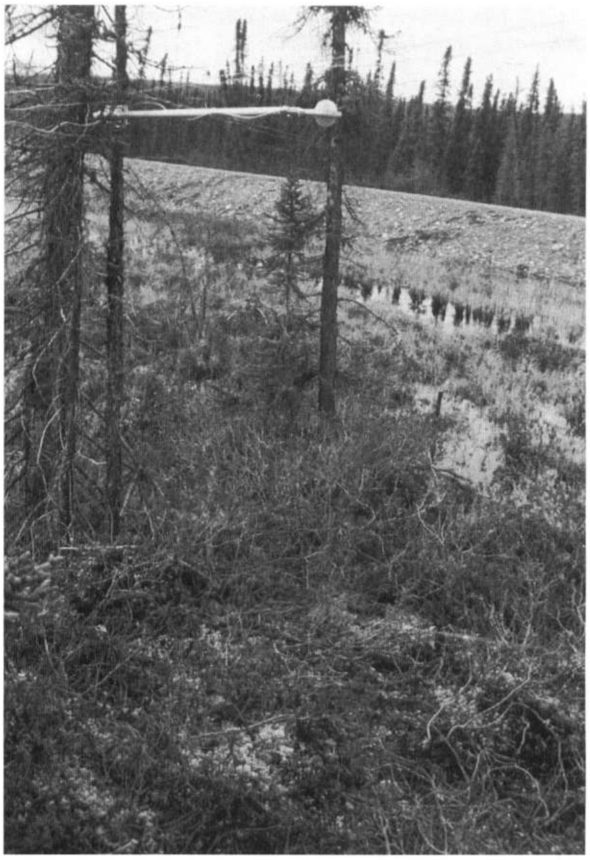


Photo 1: The Q-6 Net Radiometer mounted 1.5 m above a typical example of the dominant vegetation cover on the peat plateau at km 161.7, Robert Campbell Highway, Tuchitua

Das Q-6 Netto-Radiometer in 1,5 m Höhe über dem Torfplateau mit typischer dominierender Vegetationsdecke bei km 161,7, Robert Campbell Highway, Tuchitua

the occurrence of bare peat at a few isolated localities, and these were included in the study for comparative purposes.

Accordingly, the sites chosen were those characteristic for a given landform and they varied from covers with three canopies to those with a single canopy. Details of the exact plant cover above each heat flux plate were noted and are presented in Tables 4–7.

4.3 Energy Budget Instrumentation

The same equipment was used at each study site, and consisted of a Q-6 Net Radiometer, a Y.S.I. 44036 thermistor shielded from direct sunlight, and one Middleton CN3 and four Rimco HP3 heat flux plates connected to a Lakewood UL-16C data logger equipped with a circuit board which amplified the outputs from the heat flux plates so that they could be recorded. Data was collected at 5 minute intervals, i.e. 288 observations in 24 hours.

The net radiometer was new and had been calibrated in the factory. It was mounted at 1.5 m above a horizontal surface over the dominant vegetation cover (Photo 1). The signal was found to go off-scale on the data logger at mid-day in the June study, and this was corrected in the later studies by placing a 33K resistor in series with the radiometer to halve the output. The results subsequent were corrected during data processing by doubling the results. The sensitivity of the data logger in this mode was ± 0.07 W/m^2.

The thermistor was mounted alongside the radiometer at 1.5 m height above the same horizontal surface, protected from rain and moisture in a tygon tube under a white-painted, inverted can. The sensitivity of the output of the data logger was ± 0.01 °C.

The five heat flux plates were calibrated before and after the field work, using a new heat flux plate that had been calibrated in the factory. The heat flux plates were installed at 5 cm below the surface of the peat or soil where the data was obtained. The depth of emplacement was accurate to ± 10%. Changing over the heat flux plates did not alter the data, and it was found that a heat flux plate achieved equilibrium in 10–15 minutes after emplacement. The heat flux plates were always put in place at least 2 hours before each 24-hour test period, and the measurements were normally made for 30–36 hours.

The 5 cm depth reduces the errors of depth of placement to a reasonable level, while ensuring that the heat flux signal is dominated by the effects of the vegetation cover rather than by the effects of the soil. ROUSE (1984) suggested that heat flux plates can strongly underestimate the ground heat exchange and it is essential to ensure that the diurnal amplitude of the heat flux is substantially greater than the sensitivity of the equipment. The equipment noise varied from ± 0.06 W/m^2 to ± 0.13 W/m^2 according to the calibration of the heat flux plate. This is small compared with the observed diurnal amplitude (14.1–46.7 W/m^2). If the heat flux plates underestimate the heat flow, the errors should be consistent for all the vegetation covers.

5 Results

5.1 Immediately After Snow-Melt

The first study was carried out on the surface of the peat plateau at km 161.7, Robert Campbell Highway on June 3, 1992. The distribution of vascular plants at the site (Tab. 3) shows a marked relationship to topographic position. The vegetation of the floating fen consists of a single surface layer, whereas a few ericaceous shrubs and tree seedlings appear on hummocks in the floating fen. It is from these hummocks that a peat plateau appears to develop (HARRIS a. SCHMIDT 1994). Associated with the development of permafrost is the development of a three-tiered vegetational structure with an open woodland of *Larix laricina* (deciduous) and *Picea mariana* (evergreen), a shrub layer dominantly of ericaceous species, and a ground cover, as noted by RITCHIE (1957) and ZOLTAI and TARNOCAI (1971). On the margins of the mounds, the woodland is more open and the shrub layer is abundant, but further into the peat plateau, the trees are more closely spaced and lichens carpet the surface beneath scattered shrubs.

Table 4 shows the results of the heat flux measurements taken on June 3, 1992, just after the snow had melted, while Figure 6 shows the ground covers above the heat flux plates. Net radiation was greater than the scaled range, so the average for that day could not be calculated. The actual mean heat fluxes and amplitudes show substantial variations according to the vegetation cover, with extreme heat flux occurring under *Polytrichum juniperinum* and lower values under a three-canopy vegetation cover including *Sphagnum fuscum*. Lags in peaks were between 30 and 75 minutes. Only the single layer continuous vegetation covers of *Cladina stellaris* and *Aulocomnium palustre*, *Vaccinium uliginosum* and *V. vitis-idaea* had negative mean heat flows.

5.2 Late Summer Under Relatively Dry Conditions

The heat flux was measured again at the same peat plateau (km 161.7, Robert Campbell Highway) on 23 August, 1992. The weather was clear and sunny, with a frost at night. The soil nightly freezing occurred within 5 cm depth, but there may well have been some soil water movement to the freezing plane overnight, even though the peat was fairly dry. Table 5 shows the results of the measurements. Mean net radiation was 81 W/m^2, so that the ground surface was actually absorbing radiation, even though there was a mean daily heat flux of -5.5 W/m^2 at 5 cm depth in the soil under the same vegetation cover. Mean air temperature was 8.6 °C. All the different plant associations showed a negative mean daily heat flux in the underlying soil. A cover of *Cladina stellaris* produced the least mean heat loss (-2.1 W/m^2) and three-tiered vegetation cover the greatest (-6.1 W/m^2 at 5 cm depth). There was usually a lower range of amplitudes than immediately after snow-melt, with only the heat flux plate below the

Table 4: Soil heat flux (Q_S) at 5 cm depth, net radiation (Q^*) and air temperature measurements on 3rd June, 1992, on the peat plateau at km 161.7, Robert Campbell Highway

Messungen des Bodenwärmestroms (Q_S) in 5 cm Tiefe, der Netto-Strahlung (Q^*) und der Lufttemperatur am 3. Juni 1992 auf dem Torf-Plateau bei km 161,7, Robert Campbell Highway

Parameter	Vegetation cover Ground cover	Vegetation cover Canopy	Time of Max. peak (T_P)	Maximum	Minimum	Amplitude	Lag in T_P relative to radiometer	Mean
Net Radiometer Radiation at 1.5 m	*Vaccinium* spp.	*Ledum decumbens Picea mariana*	13.00 hrs. (14.15) hrs. (17.30) hrs.	>245.1 W/m²	–47.9 W/m²	>293.0 W/m²	0.00	n.d.
Air Temperature			17.45 hrs.	19.5°C	3.0°C	16.5°C	0.15 hrs.	8.6°C
Heat Flux Plate #1	*Aulocomnium palustre*	*Vaccinium uliginosum Vaccinium vitis-ideae*	15.30 hrs. (14.30) hrs. (18.30) hrs.	7.0 ± 0.09 W/m²	–5.7 ± 0.09 W/m²	12.7 W/m²	1.15 hrs.	0.2 W/m²
Heat Flux Plate #2	*Sphagnum fuscum*	*Ledum decumbens Vaccinium* spp. *Picea mariana*	13.55 hrs. (18.00) hrs.	7.9 ± 0.10 W/m²	–3.7 ± 0.18 W/m²	11.6 W/m²	0.40 hrs.	n.d.
Heat Flux Plate #3	*Aulocomnium palustre*	*Ledum decumbens Picea mariana*	15.30 hrs. (13.15) hrs. (18.30) hrs.	15.0 ± 0.08 W/m²	–8.4 ± 0.11 W/m²	23.4 W/m²	1.15 hrs.	8.4 W/m²
Heat Flux Plate #4	*Polytrichum juniperinum*	*Ledum decumbens Vaccinium* spp. *Picea mariana Larix laricina*	13.30 hrs. (15.20) hrs. (18.00) hrs.	61.5 ± 0.04 W/m²	–5.7 ± 0.06 W/m²	67.2 W/m²	0.30 hrs.	24.6 W/m²
Heat Flux Plate #5	*Cladina stellaris*		15.10 hrs. (18.00) hrs.	7.8 ± 0.08 W/m²	–7.7 ± 0.09 W/m²	15.5 W/m²	0.30 – 0.55 hrs.	–2.0 W/m²

Polytrichum juniperinum having higher amplitudes. Lag time varied from 30 to 75 minutes.

The net radiation (Q^*) minus the soil heat flux (Q_S) in equation (2) varied from 83.1 W/m² to 87.1 W/m² at the five test sites. Thus vegetation cover appears to have minimal effect on the sum of Q_H and Q_E (Tab. 5). One feature of the net radiation not seen in June is that when a shadow from a tree trunk developed on the net radiometer, the reading changed to a negative value, e.g., –86 W/m² at 14.05 hrs. This indicates that the heat gain at the surface will only be found where there is direct sunlight on that surface. Where there is shade, there was a net heat loss, even in the middle of the day.

A second site was examined at MacMillan Pass on August 21, 1992. Once again conditions were dry, bright and sunny, and there was a frost overnight. The substrate was peat, and again the measurements were made below horizontal surfaces. Since the site was at tree-line, there were only two-tiered and one-tiered vegetation structures, and a bare peat surface was included for comparison with vegetated surfaces. The species present are shown in Table 2. The main shrubs consisted of *Kalmia microphylla, Ledum decumbens* and *Vaccinium* spp. The surface of the ground is covered in a soft carpet of intertwined lichens with occasional herbs such as *Dryas punctata*, and mosses in the wet depressions.

Table 6 shows the results of the measurements. Once again, the mean net radiation was positive (71.1 W/m²), this low value probably reflecting the more northerly location relative to Tuchitua. All mean soil fluxes were negative and the diurnal amplitudes were quite high. Since there were no trees for shade, this may reflect higher soil thermal conductivities at this time of year. The area beneath the two layers of vegetation cover again exhibited greater negative heat flows, while the bare peat produced a heat flow intermediate between the one- and two-tiered vegetation covers. Q_H plus Q_E showed a range from 72–79 W/m².

A third study was carried out at lithalsa #4 at Fox Lake (HARRIS 1993) on August 17, 1992. This is a growing mound in mineral soils, unlike the previous sites. The study was aimed primarily at determining the effect of slope and aspect on the heat flux under

Table 5: Soil heat flux (Q_S) at 5 cm depth, net radiation (Q^*), $Q^* - Q_S$, and air temperature measurements on 23rd August, 1992, on the peat plateau at km 161.7, Robert Campbell Highway

Messungen des Bodenwärmestroms (Q_S) in 5 cm Tiefe, von Netto-Strahlung (Q^*), $Q^* - Q_S$ und Lufttemperatur am 23. August 1992 auf dem Torf-Plateau bei km 161,7, Robert Campbell Highway

Parameter	Ground Cover	Canopy	Time of Max. peak (T_P)	Maximum	Minimum	Amplitude	Lag in T_P relative to radiometer	Mean	$Q^* - Q_S = Q_H - Q_E$
Radiation at 1.5 m	*Cladina stellaris*	*Picea mariana Ledum decumbens*	13.00 hrs.	438.3 W/m²	−86.4 W/m²	524.7 W/m²	0.00 hrs.	81.0 W/m²	
Air Temperature			14.05 hrs.	25.1°C	−7.6°C	32.7°C	1.05 hrs.	8.6°C	
Heat Flux Plate #1	*Aulacomnium palustre*	*Ledum decumbens Picea mariana*	14.50 hrs.	16.9 ± 0.07 W/m²	−15.4 ± 0.06W/m²	32.3 W/m²	1.50 hrs.	−6.1 W/m²	87.1 W/m²
Heat Flux Plate #2	*Sphagnum fuscum*	*Ledum decumbens Picea mariana*	17.00 hrs.	20.2 ± 0.10 W/m²	−16.5 ± 0.11 W/m²	36.7W/m²	4.00 hrs.	−5.2 W/m²	86.2 W/m²
Heat Flux Plate #3	*Cladina stellaris*		15.20 hrs.	26.4 ± 0.13 W/m²	−14.4 ± 0.12 W/m²	40.8 W/m²	2.20 hrs.	−2.1 W/m²	83.1 W/m²
Heat Flux Plate #4	*Polytrichum juniperinum*	*Larix laricina Picea mariana Ledum decumbens Vaccinium* spp.	13.05 hrs.	9.6 ± 0.10 W/m²	−12.4 ± 0.09 W/m²	22.0 W/m²	0.05 hrs.	−2.3 W/m²	83.3 W/m²
Heat Flux Plate #5	*Cladina stellaris*	*Picea mariana Ledum decumbens*	13.30 hrs.	11.2 ± 0.06W/m²	−14.8 ± 0.07W/m²	26.0 W/m²	0.30 hrs.	−5.5 W/m²	86.5 W/m²

Table 6: Soil heat flux (Q_S) at 5 cm depth, net radiation (Q^*), $Q^* - Q_S$, and air temperature measurements on 21st August, 1992, on the surface of the peaty mounds at MacMillan Pass

Messungen des Bodenwärmestroms (Q_S) in 5 cm Tiefe, von Netto-Strahlung (Q^*), $Q^* - Q_S$ und Lufttemperatur am 21. August 1992 an der Oberfläche von Torfhügeln am MacMillan Paß

Parameter	Ground Cover	Canopy	Time of Max. peak (T_P)	Maximum	Minimum	Amplitude	Lag in T_P relative to radiometer	Mean	$Q^* - Q_S = Q_H - Q_E$
Radiation at 1.5 m	*Cladina mitis Cetraria* spp.	*Ledum decumbens*	12.55 hrs.	330.9 W/m²	−85.7 W/m²	416.6 W/m²	0.00 hrs.	71.1 W/m²	
Air Temperature			11.20 hrs.	20.3°C	−5.0°C	25.4°C	−1.35 hrs.	6.5°C	
Heat Flux Plate #1	*Cladina mitis Cetraria* spp.	*Ledum decumbens Vaccinium* spp.	13.35 hrs.	8.5 ± 0.07 W/m²	−17.3 ± 0.06 W/m²	20.3 W/m²	0.40 hrs.	−7.9 W/m²	79.0 W/m²
Heat Flux Plate #2	Bare peat		15.35 hrs.	20.4 ± 0.08 W/m²	−14.7 ± 0.12 W/m²	35.1 W/m²	2.40 hrs.	−3.6 W/m²	74.7 W/m²
Heat Flux Plate #3	*Cladina arbuscula* spp. *arbuscula*		13.45 hrs.	23.5 ± 0.12 W/m²	−14.9 ± 0.10 W/m²	38.4 W/m²	0.50 hrs.	−2.4 W/m²	73.4 W/m²
Heat Flux Plate #4	*Empetrum nigrum*		4.50 hrs.	27.6 ± 0.06 W/m²	−17.6 ± 0.05 W/m²	45.2 W/m²	1.55 hrs.	−1.0 W/m²	72.1 W/m²
Heat Flux Plate #5	*Cladina mitis Cetraria* spp.	*Betula glandulosa Vaccinium* spp.	16.25 hrs.	18.5 ± 0.08 W/m²	−17.7 ± 0.08 W/m²	36.2 W/m²	3.30 hrs.	−5.2 W/m²	76.3 W/m²

Table 7: Soil heat flux (Q_S) at 5 cm depth, net radiation (Q^*), $Q^* - Q_S$, and air temperature measurements on 17th August, 1992, on the surface of Lithalsa #4, Fox Lake

Messungen des Bodenwärmestroms (Q_S) in 5 cm Tiefe, von Netto-Strahlung (Q^*), $Q^* - Q_S$ und Lufttemperatur am 17. August 1992 an der Oberfläche von Lithalsa #4, Fox Lake

Parameter	Vegetation Cover	Time of Max. peak (T_P)	Maximum	Minimum	Amplitude	Lag in T_P relative to radiometer	Mean	$Q^* - Q_S = Q_H - Q_E$
Radiation at 1.5 m	*Arctostaphylos uva-ursi* on the flat top	(13.35) (14.30) (15.25) (16.00) (16.50) hrs.	456.6 Q/m²	–71.9 W/m²	528.0 W/m²	0.00 hrs.	79.0 W/m²	
Air Temperature		17.10 hrs.	18.9°C	4.3°C	14.6°C	0.20 hrs.	11.3°C	
Heat Flux Plate #1	*Salix brachycarpa* spp. *niphoclada Salix* sp. on the flat top	18.05 hrs.	4.0 ± 0.07 W/m²	–10.1 ± 0.07 W/m²	14.1 W/m²	1.15 hrs.	–5.0 W/m²	84.0 W/m²
Heat Flux Plate #2	*Arctostaphylos uva-ursi* on a 5° slope to the S.W.	15.00 hrs.	15.3 ± 0.08 W/m²	–17.2 ± 0.10 W/m²	32.5 W/m²	–1.50 hrs.	–3.5 W/m²	82.5 W/m²
Heat Flux Plate #3	Bare flat silt loam	17.20 hrs.	29.0 ± 0.10 W/m²	–17.2 ± 0.10 W/m²	48.4 W/m²	0.30 hrs.	–1.8 W/m²	80.8 W/m²
Heat Flux Plate #4	*Arctostaphylos uva-ursi* on the flat top	18.15 hrs.	11.7 ± 0.06 W/m²	–14.2 ± 0.07 W/m²	25.9 W/m²	1.25 hrs.	–1.9 W/m²	80.9 W/m²
Heat Flux Plate #5	*Arctostaphylos uva-ursi* on a 5° slope to the N.E.	12.40 hrs.	25.6 ± 0.09 W/m²	–21.1 ± 0.08 W/m²	46.7 W/m²	–4.10 hrs.	–5.6W/m²	84.6 W/m²

Arctostaphylos uva-ursi. The day was bright and sunny but periodically thin clouds crossed the sky. There was no overnight frost.

The results of the measurements are given in Table 7. Mean net radiation was 79 W/m². Although the net radiation was reduced substantially during periods of cloud cover, the net radiation always remained positive during the day. The most striking feature of the results is the difference in the heat flux data from southwest-facing, flat and northeast-facing slopes under the *Arctostaphylos*. Amplitude, actual range and time of the maximum positive heat flux in the soil were markedly different. The most negative mean heat fluxes occurred under the *Salix* on a horizontal surface, and under *Arctostaphylos* on a northeast-facing slope, while the least negative mean heat flux occurred under the bare soil surface. Q_H plus Q_E ranged from 80–84 W/m², again showing minimal effect of vegetation cover but considerable control by slope and aspect.

6 *Discussion*

6.1 *Net Radiation (Q^*)*

Complete data was only collected during the late August 1992 studies on bright sunny days. The actual values (71–81 W/m²) represent 23–28% of the potential radiation (I_o) at these sites for this time of year, corrected for latitude (Tab. 8). In spite of the high incoming levels of radiation (300–400 W/m²) in the middle of the day, the net radiation was negative in the shade of trees or shrubs in late August, even at 1400 hours.

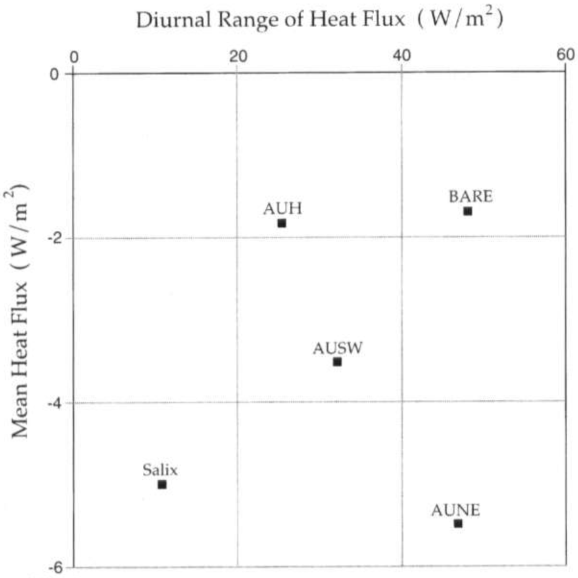
6.2 *Heat Flow Into the Substrate (Q_S)*

Values for the heat flow into the substrate at 5 cm depth appear to be dependent on the slope and aspect and on the vegetation on that substrate. The Fox Lake study shows the effect of small changes in topography on the heat flow under *Arctostaphylos uva-ursi* on a mineral substrate (Fig. 5). The horizontal surface shows the lowest diurnal range of heat flux and also the least negative mean daily heat flux. The results for the 5° southwest-facing slope show over twice the diurnal

Table 8: Comparison of potential insolation (I_o) with mean daily net radiation on bright sunny days in late August in the southern Yukon Territory

Vergleich der potentiellen Insolation (I_o) mit der mittleren täglichen Netto-Strahlung an August-Tagen mit voller Sonnenstrahlung im südlichen Yukon Territory

Location	Latitude	I_o (W/m²)	Q^* (W/m²)	100 Q^*/I_o (%)
Tuchitua	61° 18'	325	81.0	28
MacMillan Pass	63° 12'	c. 300	71.1	23
Fox Lake	61° 06'	350	79.0	23



Legend

Salix *Salix brachycarpa* ssp. *niphoclada* on a horizontal surface
AUH *Arctostaphylos uva-ursi* on a horizontal surface
AUSW *Arctostaphylos uva-ursi* on a 5 S.W. facing slope
AUNE *Arctostaphylos uva-ursi* on a 5 N.E. facing slope
BARE Bare silt loam on a horizontal surface

Fig. 5: Variation in mean soil heat flux (Q_S) and diurnal range of heat flux (W/m^2) at 5 cm depth in silt loam soils under various slopes/aspects and vegetation covers on lithalsa #4, Fox Lake, on August 17, 1992

Unterschiede im mittleren Bodenwärmestrom (Q_S) und im Tagesgang des Wärmeflusses (W/m^2) bei 5 cm Tiefe in schluffigen Lehmböden mit verschiedener Hangneigung, Exposition und Vegetationsbedeckung auf Lithalsa #4, Fox Lake, am 17. August 1992

Photo 2a: Vegetation above the heat flux plates on the peat plateau at km 161.7, Robert Campbell Highway, on June 3rd, 1992 in order of dominance: *Aulocomnium palustre, Vaccinium uligonosum* and *V. vitis-idaea*

Die Vegetation über den Wärmefluß-Sensoren auf dem Torfplateau bei km 161,7, Robert Campbell Highway, am 3. Juni 1992, in Reihenfolge der Dominanz

range and exhibit about 4 W/m^2 more negative mean heat flow. The times of the peaks of heat flow into the ground are markedly different, so the peak for a southwest-facing slope occurs during the hottest part of the day. This partly offsets the reduced insolation at 1500 hours, whereas the air temperature is still low when the northeast-facing slope records its peak earlier in the day. The presence of periodic light cloud complicates the interpretation of the data, but the effects are clear.

Slope and aspect measurement will only be applicable to similar slopes and aspects. Thus it will be much easier to study the heat flow on a landform with a large flat surface such as a peat plateau than on a palsa or lithalsa where the landform has only a small flat area on top. SEPPÄLÄ (1994) has demonstrated that the ground temperatures in winter at the foot of the margins of palsas are much warmer than those at equivalent depths on the top of the palsa, reflecting differences in winter snow cover. He concluded that this may limit lateral growth on palsas. Similar differences were demonstrated on lithalsas by HARRIS (1993), and probably occur at the margins of all mounds, e.g. peat plateaus (see HARRIS a. SCHMIDT 1994 and Photo 2 a–e). The heat-flux measurements from the lithalsas at Fox Lake demonstrate that there is greater heat loss in August from the sides of the mound. This will counteract the potential thawing that should otherwise result from the warmer winter ground temperatures. Without such a process, degradation of the slopes of the mounds would be inevitable. This probably affects all perennial mounds including pingos.

Also shown in Figure 5 is the negative mean heat flux under the *Salix*, which has much greater height

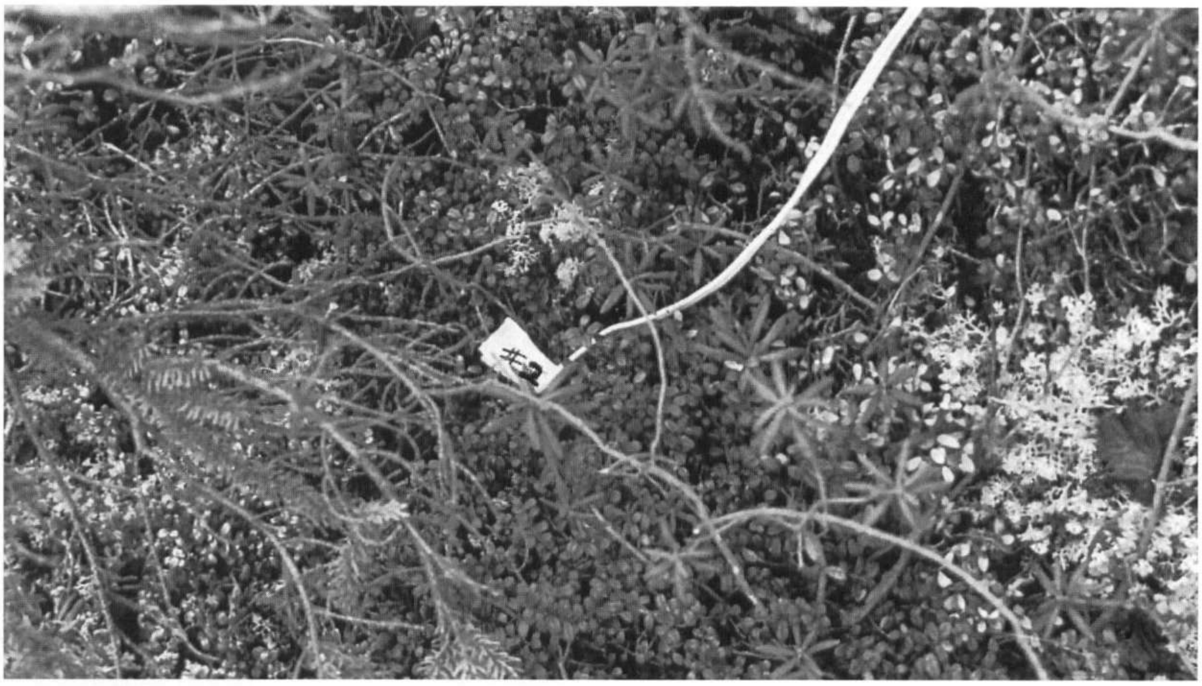


Photo 2b: Vegetation above the heat flux plates on the peat plateau at km 161.7, Robert Campbell Highway, on June 3rd, 1992 in order of dominance: *Ledum decumbens, Vaccinium* spp., *Picea mariana, Sphagnum fuscum*

Die Vegetation über den Wärmefluß-Sensoren auf dem Torfplateau bei km 161,7, Robert Campbell Highway, am 3. Juni 1992, in Reihenfolge der Dominanz

Photo 2c: Vegetation above the heat flux plates on the peat plateau at km 161.7, Robert Campbell Highway, on June 3rd, 1992 in order of dominance: *Aulocomnium palustre, Ledum decumbens, Picea mariana*

Die Vegetation über den Wärmefluß-Sensoren auf dem Torfplateau bei km 161,7, Robert Campbell Highway, am 3. Juni 1992, in Reihenfolge der Dominanz

Photo 2d: Vegetation above the heat flux plates on the peat plateau at km 161.7, Robert Campbell Highway, on June 3rd, 1992 in order of dominance: *Polytrichum juniperinum, Ledum decumbens, Vaccinium* spp., *Picea mariana, Larix laricina*

Die Vegetation über den Wärmefluß-Sensoren auf dem Torfplateau bei km 161,7, Robert Campbell Highway, am 3. Juni 1992, in Reihenfolge der Dominanz

(1.5 m) than the *Arctostaphylos* (15 cm). Areas of *Salix* also have a lower diurnal range of heat flux. The bare silt loam has the highest diurnal range of heat flux, but a similar mean heat flux to soils under *Arctostaphylos* on a horizontal surface. Clearly vegetation cover has a profound effect on the heat flow regime.

This is seen again in Figure 6 where the data from Tuchitua and MacMillan Pass on peat substrates are compared. The data for two and three-tiered covers plot in an entirely different field to those for single-tiered vegetation mats, while the results for the bare peat are found in between. Single-tiered covers show a higher diurnal range in heat flux and less negative mean heat fluxes than the three-tiered covers. This is probably due to the negative net radiation recorded in the canopy. The deciduous trees and shrubs are in full leaf at this time of year, and so the greater the distance between the outer surface of the vegetation cover intercepting incoming radiation and the ground surface, the more negative the values of heat flux into the ground. At this time of year, the resulting heat flux is usually negative.

Tables 4 and 5 provide a comparison between the data for immediately after snow melt and in late August at Tuchitua, which is summarized in Table 9. In general, the mean Q_S becomes more negative from June to August, but the diurnal amplitude varies. Beneath a three-tier vegetation cover including *Sphagnum fuscum* or *Aulacomnium palustre*, and beneath *Cladina stellaris*, it increases substantially, possibly reflecting the markedly different radiation values between sun and shade. However, beneath a multi-tier cover including *Polytrichum juniperinum*, the diurnal amplitude decreased in August.

The *Cladina stellaris* was unique in that the mean Q_S was virtually -2 W/m_2 in both June and August. This may be related to the fact that the lichens form thick, mats on the ground surface with enormous air space and can intercept and absorb tremendous quantities of water (PÉCH 1989). They can also exchange water with the air as the vapour pressure changes, so that diurnal fluctuations of up to 15% are normal (PÉCH 1991). BELLO and ARAMA (1989) report that the maximum storage capacity of such lichens can be double that found in moss and lichen mats under forest. The water absorbed by the lichens gradually evaporates back into the atmosphere. Thus a lichen cover in tundra may intercept 61% of the summer precipitation and since

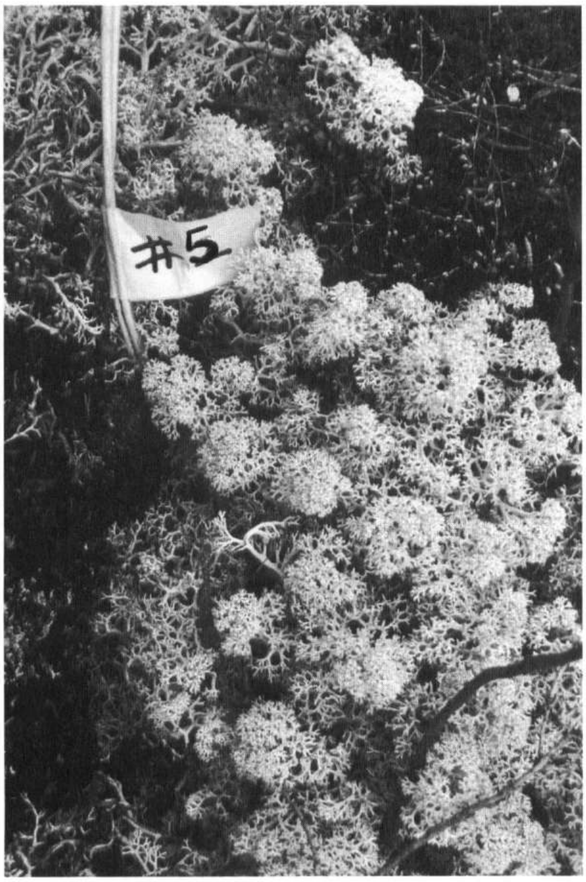


Photo 2e: Vegetation above the heat flux plates on the peat plateau at km 161.7, Robert Campbell Highway, on June 3rd, 1992 in order of dominance: *Cladina stellaris*

Die Vegetation über den Wärmefluß-Sensoren auf dem Torfplateau bei km 161,7, Robert Campbell Highway, am 3. Juni 1992, in Reihenfolge der Dominanz

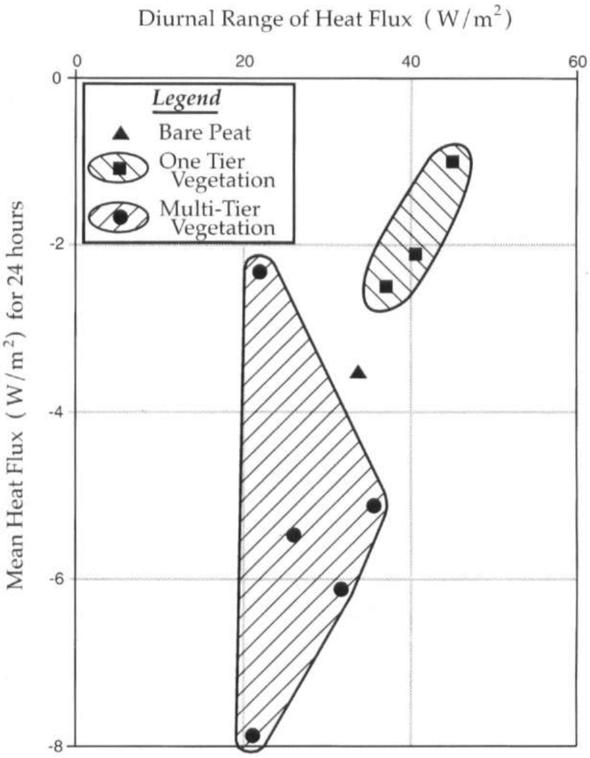


Fig. 6: Variation in mean soil heat flux (Q_S) and diurnal range of heat flux (W/m^2) at 5 cm depth in peat on horizontal surfaces under different vegetation covers at km 161.7, Robert Campbell Highway and at MacMillan Pass in late August, 1992

Unterschiede im mittleren Bodenwärmestrom (Q_S) und im Tagesgang des Wärmeflusses (W/m^2) bei 5 cm Tiefe in Torf mit horizontaler Oberfläche unter verschiedener Vegetationsbedeckung bei km 161,7, Robert Campbell Highway und am MacMillan Paß gegen Ende August 1992

lichens do not transpire and do not have water-conductive tissues, the moisture release may take much longer than from bryophytes. In the case of lichens beneath an open forest canopy such as at Tuchitua, the canopy/vegetation cover interception storage will be even greater. This, together with the regular summer rains could help explain the slight continual heat loss under the *Cladina stellaris* cover and the obvious short-term stability of the permafrost landforms with such a cover to above 0°C mean annual temperatures for periods of 1-3 years. The more canopies of vegetation cover and the greater their density, the greater will be this stability. If this is correct, then the other mat-forming lichens may be expected to act in a similar way, but this has not yet been tested.

The other factor affecting the heat loss under *Cladina stellaris* may be its higher albedo. PETZOLD and RENCZ (1975) found the albedo of dry *Cladonia stellaris* to be 0.223 to 0.264 at Schefferville, Quebec, whereas the albedo of black spruce was 0.158, *Dicranum fuscescens* was 0.147, and sedges 0.071 (wet) or 0.109 (dry). Thus this light coloured lichen will reflect more of the incoming solar radiation than the other plants.

What is surprising in the data is the fact that *Sphagnum fuscum* does not appear to show heat flow properties which are different from those of the other lichens and mosses. Since there are numerous species of *Sphagnum*, this will need more study. In the literature, it is stated that the thermal conductivity of the *Sphagnum* moss decreases as it dries out in summer (BROWN 1969; BROWN a. PÉWÉ 1973), but this is not consistent with the results obtained in the present study. Instead, it is producing similar results to those for *Aulacomnium palustre*. This could be due to frequent summer rains

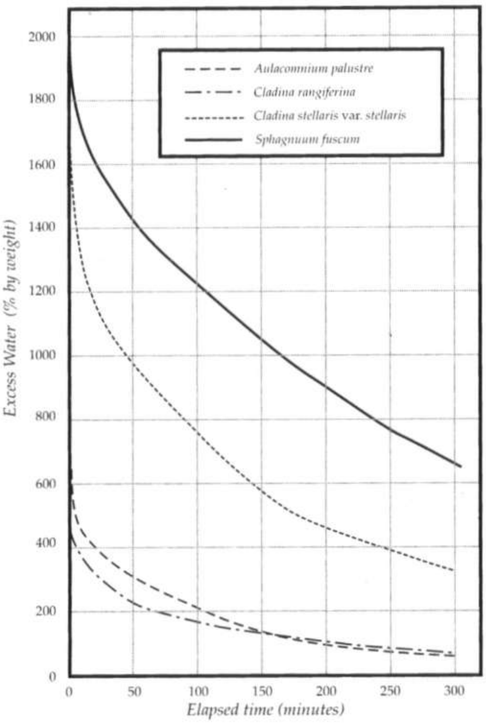


Fig. 7: Results of drying selected mosses and lichens at 21°C and 27% relative humidity, after they had been submersed in de-ionized water for 24 hours

Ergebnisse der Austrocknung von ausgewählten Moosen und Flechten bei 21°C und 27% relativer Luftfeuchte, nachdem sie 24 Stunden lang in entionisiertes Wasser eingetaucht waren

Table 9: Comparison of amplitudes and mean soil heat flux rates for 3 June and 23 August, 1992 under similar vegetation covers at km 161.7, Robert Campbell Highway, Yukon Territory

Vergleich der Amplituden und der Raten des mittleren Wärmestroms am 3. Juni und 23. August 1992 unter ähnlicher Vegetationsbedeckung bei km 161,7, Robert Campbell Highway, Yukon Territory

Vegetation Cover	Mean Q_S (W/m^2)		Diurnal Amplitude of Q_S (W/m^2)	
	3 June 1992	23 Aug. 1992	3 June 1992	23 Aug. 1992
Aulocomnium palustre *Vaccinium* spp.	−0.2	–	12.7	–
Sphagnum fuscum *Ledum decumbens* *Picea mariana*	–	−5.2	11.6	36.7
Aulocomnium palustre *Ledum decumbens* *Picea mariana*	8.4	−6.1	23.4	32.3
Polytrichum juniperinum *Larix laricina*	24.6	2.3	67.2	22.0
Cladina stellaris	−2.0	−2.1	7.8	40.8
Cladina stellaris *Ledum decumbens* *Picea mariana*	–	−5.5	–	26.0

and heavy dews preventing the *Sphagnum* from drying out. Thus without actual measurements, it is imprudent to use the presence of *Sphagnum* as a reason for colder ground temperatures (c.f. HALSEY et al. 1995).

Another species that appears to have unusual thermal properties is *Polytrichum juniperinum* (see Tab. 4 a. 5). The heat flux beneath it appears to be much greater than for the other species, resulting in abnormal amplitudes and mean heat fluxes.

This increase in heat loss under multiple canopies of vegetation means that once this vegetation cover has become established on a new permafrost landform, that landform will be able to withstand higher mean annual air temperatures than when it was forming. In most cases, the original vegetation is primarily a single-canopy cover, e.g. grass, lichens or sedges. A good example is the sequence of vegetation and landform development of the lithalsas at Fox Lake (HARRIS 1993). Once a two-canopy vegetation has developed on the surface of the mound, the mean annual ground temperatures in the permafrost drops 3–4°C and the active layer decreases from 3m to 60–80 cm. How much protection from elevated air temperatures this multiple canopy provides remains to be established.

6.3 Water Retention Properties of Some Lichens and Mosses at the Study Sites

There is an abundant literature on the water retention properties of lichens and mosses and their effects on the moisture status in the underlying soils. However, there are also discrepancies in the literature, which may partly be explained by different responses of strains of *Cladina stellaris* from different locations (KERSHAW a. ROUSE 1971, Figs. 7 a. 8). Accordingly two species of lichen and two of mosses from the Tuchitua peat plateau were collected, dried and tested in Calgary.

The water retention test consisted of weighing the air-dry material at 27% relative humidity and 21°C. The material was then submersed in deionized water for 24 hours at 21°C. Finally, the sample was removed from the water, the excess water being drained out on an absorbent sheet of paper. The sample was then weighed every five minutes for at least five hours, while it dried in air at 21°C and 27% relative humidity without any air currents. This was meant to simulate soaking by precipitation or dew, followed by drying under conditions of lower relative humidity than are found in the field for a period of time similar to the diurnal drying period.

Figure 7 shows the results. As expected, *Sphagnum fuscum* had the highest moisture absorption, followed closely by *Aulacomnium palustre*. These should show the greatest cooling by evaporation. All the materials showed similar drying curves, but the lichens, *Cladina stellaris* and *Cladina rangiferina*, had less than one third of the water absorption by weight of *Sphagnum fuscum*. At the end of five hours, their moisture content was far lower than that of the mosses, but the actual moisture loss was lower, and the material was fairly dry. Clearly, it would take several days without precipitation or dew to dry out the *Sphagnum fuscum* to the same degree, and two days for the *Aulacomnium palustre*. Since the peat plateaus are surrounded by fen, this can never normally happen, and so the insulating properties of a dry *Sphagnum* cover cannot operate.

The rapid drying of the reindeer mosses (*Cladina* spp.) explains the observations of KERSHAW and LARSON (1973) from wetter sites on north-facing slopes at Pen Island, Churchill, that the distribution of *Cladina stellaris* correlates with lower wind speeds, lower rates of evaporation, and higher temperatures. At Hawley Lake, Northern Ontario, KERSHAW and ROUSE (1971) showed that the lichen mat of this species had a very high stratified resistance to water loss and effectively mulched the underlying soil, producing very high moisture availability under the lichen mat. HUSTICH (1951) noted that it occurs in sandy areas and suggested that it is xerophytic, but it would seem more likely that the better draining sandy soils would produce better conditions for transport of air to the base of the thalli. This preference for better drained soils would also mean less competition from other plants and more light, which they prefer (FRASER 1956). Since the thalli of the lichens must be moist for metabolism to occur (AHTI 1967), the *Cladina* spp. tend to be the last species in the succession after fire (AHTI 1959).

For Tuchitua, these results indicate that the water retention by *Cladina* spp. is far less than for the mosses, and they dry out more quickly (c.f. BELLO a. ARAMA 1989; PÉCH 1989). This undoubtedly helps to explain the relatively constant heat flux through the thallus of this lichen. Thus it is necessary to check on the water retention properties of lichens at typical sites rather than to rely on data from a completely different region to provide the sole basis of the interpretation of the results.

6.4 $Q_H + Q_E$

The magnitude of the sum of the sensible heat flux between the ground and the air (Q_H) and the latent heat used in evapotranspiration (Q_E) is much greater than Q_S, and shows relatively little variation over the period of study in summer. This would presumably change in winter when some of the vegetation lost its leaves. There are probably significant differences in the Bowen ratio (Q_H/Q_E) that occur with season, but these were not examined in this study.

6.5 Relationship of Ground Temperatures to Long-term Mean Annual Air Temperatures

The mean annual air temperature (MAAT) is merely an average of the highest and lowest temperatures measured 2 m above the ground surface each day on a horizontal grassy surface. It is less accurate than monitoring by data logger, where the data is collected at regular intervals and then averaged (HARRIS a. PEDERSEN 1995) and the latter provides a better idea of the ambient temperatures. Even so, it is not the temperature at the ground surface.

BROWN and PÉWÉ (1973) summarized the main factors influencing the ground temperature. The results in Tables 4 to 7 clearly indicate the enormous influence of microtopography and the vegetation cover in altering the ground temperature relative to a common ambient air temperature. In the case of vegetation, structure of the canopy and species present alter the heat exchange processes enormously in summer. This is the critical time of year since in winter, the snow cover tends to reduce any such variations. Where the surface vegetation consists of a mosaic of species under an open canopy forest, on alpine slopes or on tundra, there will be enormous variations in near-surface ground temperatures, although these differences will become lost with increasing depth. However, for plant germination and growth in a shallow active layer, it is these near-surface conditions that are critical.

Hummocks and mounds of varying size are widespread in permafrost regions, and the results in Table 7 and Figure 5 are extremely important. They indicate that there are enormous differences in heat flow with quite small changes in slope and aspect, and that the temperatures over a horizontal surface cannot reasonably be expected to be found in the ground surface on these slopes. Clearly careful site-specific work on the effects of slope, aspect and vegetation cover must be carried out before it will be possible to produce accurate models of near-surface ground temperatures for such conditions.

7 Conclusions

The net radiation (Q^*) during clear sunny days in late August represents about 25% of the total incoming radiation (I_0) at this latitude. Although mean daily air temperatures are above freezing point, net radiation is negative in the shade of trees or shrubs, even in the middle of the day. Heat flow into the substrate (Q_S) at 5 cm depth is profoundly affected by plant species on a horizontal surface, by the structure of the vegetation, and by the slope and aspect under a given vegetation cover. On peaty soil where the plants form a continuous ground cover, the mean diurnal amplitude of heat flux is greatest and mean daily heat flux out of the soil is least. Where more than one layer of vegetation is involved, the mean daily heat flux out of the soil is much greater compared with peaty soils. On silt loams there is a taller shrub layer and greater mean daily heat flow out of the soil and lower mean diurnal amplitude. On peat, bare ground shows lower heat flux out of the soil than soils under vegetation covers with multiple canopies, but higher heat flux into the air than single-tiered vegetation mats. However, on the silt loam, bare soil shows the lowest heat flows into the air and highest diurnal amplitudes.

When the data for late August are compared with data obtained immediately after snow melt in early June, the diurnal amplitudes are seen to be greater in June under the same vegetation cover, while mean daily averages for heat flux are usually positive. This is probably due to drier vegetation cover and soils. Soils beneath a cover of *Polytrichum juniperinum* show unusual thermal properties, exhibiting a much greater heat gain and higher diurnal amplitudes. Frequent summer rains may prevent *Sphagnum fuscum* from exhibiting the insulating properties described by BROWN (1969), and may also account for the consistent diurnal heat flows under *Cladina stellaris* during both study periods. Although mat-forming lichens can absorb immense quantities of moisture from rain and dew into their thalli (BELLO a. ARAMA 1989; PÉCH 1989), the *Cladina* spp. at the study sites have only one third of the moisture-absorbing capacity of the mosses. The dewfall has a diurnal effect (PÉCH 1991), resulting in reasonably uniform thermal conductivity throughout the summer period. The unusually high albedo of *Cladina stellaris* may also be involved.

There is strong evidence from Fox Lake that a small change in slope (5°) produces a spectacular change in soil heat flux (Q_S) under a given vegetation cover. On northeast-facing slopes, the maximum positive heat flux occurs early in the day under direct sunlight, but when air temperature is lower. On southwest-facing slopes, the maximum heat flux occurs in the mid afternoon under direct sunlight when the air temperature is also at a maximum. In August, the horizontal surfaces show less negative mean heat fluxes and lower diurnal amplitude than the slopes. This means that measuring and modelling heat flow on landforms with extensive flat surfaces, such as peat plateaus, will be far easier than measuring it on landforms with sloping surfaces, such as palsas and lithalsas.

The greater heat loss from the ground on the slopes of perennial mounds in August may explain why such slopes are stable on pingos, palsas, peat plateaus, and lithalsas. Without such a process, the insulation of the sides of the mounds by snow in winter (SEPPÄLÄ 1994) should make them collapse.

It is clear that the MAAT measured 2 m above horizontal grass-covered ground and based on averaging the highest and lowest temperatures measured during the day fails to take into account all the local factors altering heat exchange at the ground surface. In future, slope (angle and aspect) and vegetation cover (species and structure) must be described in micro-scale and meso-scale studies of heat flow in and out of the ground. The seasonal changes must also be determined. Unless this is done, the results cannot be used to study specific problems of landform evolution and stability. Once a multi-tiered cover becomes established, a given landform could likely withstand a limited period of higher mean annual air temperatures without thawing, though the degree of this protection needs further work.

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