Effects of fire and firelines on active layer thickness and soil temperatures in interior Alaska

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Thaw depths and soil temperatures are compared for three adjacent sites in interior Alaska: an unburned stand of black spruce/feathermoss-*Cladonia* type; an adjacent stand, originally of the same type, burned in 1971; and a fireline between the two in which all of the vegetation and most of the organic layer was removed in 1971. Maximum thawing of the active layer in the unburned stand has ranged from 40 to 50 cm in the ten summers of the study. In the burned stand, the depth of thaw increased each year following the fire and reached a maximum thaw depth of 187 cm in 1980, about four times that of the original thaw depth. Thawing was deepest in the fireline and a maximum of 227 cm was reached in 1979. In 1980, the thaw depth was only 200 cm. This decrease has most likely resulted from the insulating effect of the re-establishment of the vegetation, especially a nearly continuous moss mat. Soil temperatures at 10 cm are given for each site for 1979 and show that during the summer months at that depth the temperatures were warmest in the fireline and coldest in the burned stand. Maximum, minimum, and average soil temperatures are compared for the three sites at depths to 200 cm and show that, at all depths, the yearly average temperatures are warmest in the fireline, intermediate in the burned stand, and coldest in the unburned stand.

Les profondeurs de dégel et les températures du sol de trois sites contigus en Alaska sont comparées: un peuplement d'épinettes noires et de cladonies non brûlé; un peuplement adjacent, du même type à l'origine, brûlé en 1971; une ligne coupe-feu entre les deux peuplements, dépouillée en 1971 de toute sa végétation et de la plupart de son humus. La profondeur maximale de dégel de la couche active dans le peuplement non brûlé a varié entre 40 et 50 cm au cours des dix étés qu'a duré l'étude. Dans le peuplement brûlé, la profondeur de dégel a augmenté chaque année après l'incendie et a atteint un maximum de 187 cm en 1980, ce qui équivaut à environ quatre fois la profondeur de dégel initiale. Le dégel a été le plus profond dans la ligne coupe-feu, atteignant un maximum de 227 cm en 1979. En 1980, la profondeur de dégel n'a été que de 200 cm. La cause la plus probable de cette diminution a été la reprise de la végétation, notamment sous la forme d'une couche de mousse presque continue. Si on considère la température du sol à 10 cm pour 1979, à chaque site, on constate qu'au cours des mois d'été, les températures à cette profondeur sont les plus élevées dans la ligne coupe-feu et les plus basses dans les peuplements brûlés. On compare les températures de sol maximales, minimales et moyennes des trois sites, à des profondeurs allant jusqu'à 200 cm, et on constate que, quelle que soit la profondeur, la moyenne annuelle des températures est la plus élevée dans la ligne coupe-feu, intermédiaire dans le peuplement brûlé et la plus basse dans le peuplement non brûlé.

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Introduction

When wildfire burns through a northern black spruce forest underlain by permafrost there is usually a subsequent increase in the active layer thickness. This results, not from the heat of the fire, but rather from the removal of some of the insulating organic layer, the change in surface albedo, and the removal of the shading effects of the tree and shrub canopy. The effects of fire on permafrost have been reviewed by a number of authors (Brown and Grave 1978; Kelsall *et al.* 1977; Viereck 1973; and Viereck and Schandelmeier 1980). Most of the studies of the effect of wildfire on permafrost have demonstrated changes in the active layer but few (for example Rouse 1976, and Viereck and Dyrness 1979) have actually made measurements of the soil temperatures following fire. In general, in the first few years following fire summer soil temperatures are increased by 3 to 6°C at depths of 10 to 20 cm and the thaw depth increases by two to four times the original thickness, depending on the severity of the fire and the local climate (Rouse 1976; Viereck and Dyrness 1979).

A special problem related to fire occurs when firelines are constructed by heavy equipment. In areas underlain by ice-rich permafrost, the complete removal of the organic layer results in a deeper thaw than occurs under the burn itself. The thawing and subsequent erosion can often create scars on the landscape that are conspicuous many years after the effects of the fire have become unnoticeable. The erosion, siltation, subsidence, and gulleying may continue for ten years or more following fireline construction. Although this erosion problem is recognized by fire suppression agencies and attempts are made to limit the use of heavy equipment in permafrost areas, in Alaska, firelines are still being constructed each year on ice-rich permafrost sites using large construction equipment.

In this study, the changes in thaw depth in a burned black spruce stand and an adjacent fireline have been monitored in an attempt to obtain information that will help to explain this process of permafrost thawing following fire and fireline construction. Although the study is established as a continuing long-term study, results of the first ten summers of investigation provide the basis for this paper.

Study Area

The Washington Creek Fire Ecology Research Area is located about 50 km north-west of Fairbanks, in interior Alaska. In June of 1971, the Wickersham fire, which burned 6313 ha, created a variety of conditions conducive to studies of fire effects. A number of studies have been carried out in the area (Viereck and Dyrness 1979; Viereck *et al.* 1979) and several studies are continuing.

The Wickersham fire was caused by lightning and it burned primarily in upland black spruce forest, much of which was underlain by permafrost. Because of the fire's proximity to Fairbanks an all-out effort was made to control the fire, and 29 bulldozers constructed nearly 113 km of fireline which averaged 13 m in width; much of the fireline network was constructed on permafrost soils. Thus an excellent opportunity to study the effects of both fire and fireline construction on the soil temperatures and active layer thickness was provided. More details of the fire and related studies were presented by Viereck and Dyrness (1979).

The site for this study was near the foot of a long west-facing slope and at an elevation of 335 m. The original vegetation was an open stand of black spruce with a 25 to 30 cm forest floor layer. The soil was in the Saulich series with an active layer of 40 to 50 cm in depth. On the basis of experience with the Wickersham fire, the burn intensity was classified as heavy, i.e. with all of the overstory shrubs killed by the fire, with most of the above-ground portion of the herbs and some of the shrubs completely burned and with the removal of about 1/3 (10 cm) of the organic layer (Viereck and Dyrness 1979). Using a scale developed as a result of some experimental burns (Viereck *et al.* 1979), the fire would have been classified as moderate in severity, i.e. with the organic layer partially consumed but with parts of the woody twigs remaining.

The fireline on which the study was conducted is about 25 m in width and was constructed by pushing all of the vegetation and much of the organic layer to either side. Because the fire occurred between the 24th and 30th of June, the organic layer would have been thawed to a depth of between 25 and 30 cm. Most, but not all, of the organic layer was removed by the bulldozer (Figure 1).

In order to compare the fireline and burned area with undisturbed conditions, a control was established in an adjacent unburned stand. This unburned site was on the same aspect and position on the slope and was considered to be essentially similar to the original condition of the fireline and burned area.

FIGURE 1. Fireline condition immediately following the fire.

Climate

Some climatic features of the site are given in Table 1 and compared with the nearest weather bureau station with a long-term record at Fairbanks, Alaska. Fairbanks has a mean annual temperature of −3.5°C, with January the coldest month with a mean temperature of −24.3°C and July the warmest month with a mean of 16°C. Annual precipitation in Fairbanks averages 285 mm, about one-half of which falls as snow.

By comparing the air temperatures for the short period that the site has been instrumented (Oct. 1978 to the present) with the Fairbanks airport for the same period, it appears that the Wickersham site is slightly colder than the Fairbanks airport. Extreme winter temperatures are usually not as low at the Wickersham site as they are at the Fairbanks airport because a strong temperature inversion that persists in interior Alaska in the winter results in colder extreme temperatures at lower elevations. Summer and winter temperatures, however, average 1 to 2° colder at the Wickersham site than at Fairbanks. A comparison of the 1979 data shows that at the Wickersham site the yearly mean temperature was 1.7°C colder than at Fairbanks. This would give the Wickersham site a long-term mean of −5.2°C.

The period from October 1978 to April 1979 was considerably colder than the same period in 1979-80. Freezing degree days at the Wickersham site totalled 3059 for the 1978-79 winter and only 2189 for the 1979-80 record. The thawing period however fol-

TABLE 1. Monthly mean, maximum, and minimum air temperatures for the Wickersham fire site and for the Fairbanks airport from October 1978 and September 1980

	Wickersham Fire				Fairbanks Airport					
	Max. °C	Min. °C	Ave. °C	Max. snow on ground in fireline cm	Max. °C	Min. °C	Ave. °C	Departure from mean °C	30-yr. mean °C	Max. snow on ground cm
1978										
Oct	4	−20	−6	15	7.2	−18.4	−5.0	−1.1	−3.5	0
Nov	−1	−26	−11	39	+0.6	−28.0	−13.0	+3.2	−16.3	25
Dec	−2	−34	−18	70	+1.1	−31.3	−16.0	+7.6	−23.0	41
1979										
Jan	−6	−34	−22	60	−3.9	−36.9	−22.1	+2.3	−24.3	48
Feb	−9	−42	−30	63	−11.7	−46.4	−32.0	−12.7	−19.8	64
Mar	+6	−31	−13	76	+5.0	−32.4	−11.7	+1.4	−13.1	58
Apr	20	−23	−2	80	+22.9	−21.8	−.5	1.1	−1.3	46
May	22	−4	+8	0	22.9	−2.8	+10.0	+1.4	+8.6	0
June	24	0	13		25.2	+5.0	14.2	.9	15.0	
July	28	+2	15		28.0	+7.2	16.4	.3	16.0	
Aug	29	0	13		27.4	+5.6	15.8	2.8	13.0	
Sept	22	−8	6	0	22.9	−4.4	8.1	1.2	6.9	0
Oct	10	−19	−2	5	17.9	−14.0	+0.2	4.0	−3.5	2
Nov	2	−22	−8	19	5.6	−18.4	−6.8	9.7	−16.3	10
Dec	−7	−36	−21	28	−1.1	−39.2	−23.6	−1	−23.0	23
1979 Year			−3.6				−1.87			
1980										
Jan	2	−34	−17	40	5.0	−48.1	−25.5	−2.6	−24.4	28
Feb	5	−27	−11	42	7.2	−23.5	−8.9	+10.3	−19.8	36
Mar	5	−34	−11	38	8.9	−3.9	−8.2	4.3	−13.1	33
Apr	13	−15	−2	30	15.6	−10.0	4.3	3.9	−1.3	20
May	20	−6	+6	0	22.9	−1.6	−10.5	1.9	+8.6	0
June	26	−3	10		25.7	+3.3	13.7	−1.4	15.0	
July	24	0	12		27.4	−0.6	16.0	+.1	16.0	
Aug	26	−4	8		30	+0.5	12	−1.0	13.0	
Sept	10	−13	0		19.0	−4.4	6.1	.8	6.9	
30-year average			(−5.2)[1]						−3.5	

[1] Estimated from two years of record.

lowed a different pattern with the 1980 summer being considerably cooler than that of 1979. The 1979 thawing period had 1686 thawing degree days compared with 1106 for 1980. The average daily temperature for the period of 1 May through 30 September was +11.0°C for 1979 and 7.2°C for 1980.

Snow accumulation at Wickersham is usually greater than in Fairbanks with maximum accumulations of about 1 metre compared to 75 cm at Fairbanks. During the two winters that snow depths have been recorded at the site, the snowfall maximum was 80 and 42 cm. Snowfall was below average in Fairbanks for those two winters.

Annual precipitation follows the general pattern of that of the Fairbanks airport with a minimum in April of 7 mm, an increase to a maximum in August of 57 mm, followed by a general decrease during the winter months. Annual precipitation at the Fairbanks airport is 285 mm and our short-term records at the Washington Creek site indicate that precipitation there is 50 to 75 mm more per year than at Fairbanks.

Methods

Because of the long-term nature of the study, the methods have been modified over the years. Initially in 1971 and 1972, a probe line of 10 points was established in each of the three sites (Figure 2, 3, and 4). For the first four years, depth to the frozen layer was determined every two weeks during summer with a steel probe. In 1975, soil temperatures were taken at depths of 5, 10, 20, and 50 cm with a steel probe with a thermistor at the tip. These temperatures were taken at five of the ten probe points at each of the three sites and only in the thawed soil in the summer months. Starting in 1978, a set of permanent thermistors was installed at each of the three sites at depths of 5, 10, 20, 50, 100, 150, and 200 cm in the fireline; 5, 10, 20, 50, 100, and 190 cm in the burned stand, and 5, 10, 20, 50, and 90 cm in the unburned stand. These temperatures were recorded weekly or bi-weekly during

FIGURE 3. Probe line in the burned stand in 1980.

FIGURE 2. Probe line across the fireline with burned stand in the background (1980).

FIGURE 4. Probe line in the unburned stand showing the characteristics of the open black spruce/feathermoss community type.

TABLE 2. Comparison of plant cover on three study sites at the 1971 Wickersham fire site: an unburned black spruce stand, a burned black spruce stand, and an adjacent fireline

Cover type	Percentage cover at each site						
	Unburned	Burned			Fireline		
		1972	1975	1980	1972	1975	1980
Tree canopy	45	0	0	1	0	P[1]	P
Tall shrub	6	P	1	8	2	4	33
Low shrub	36	3	6	26	—	—	9
Herb	7	7	11	48	6	50	46
Lichen	15	0	P	7	—	—	—
Moss	80	3	13	24	50	40	76
Mineral soil	—	2	—	—	60	30	1
Litter	20	2	42	52	—	—	21
Charred organic	—	92	87	57	—	—	—
Tall shrub							
Salix planifolia	2	1	1	3	2	4	24
Betula glandulosa	1	1	1	2	—	—	P
Salix bebbiana	—	—	—	1	—	—	4
Rosa acicularis	P	P	1	1	—	—	—
Salix glauca	—	—	—	1	—	—	—
Salix scouleriana	—	—	—	P	—	—	P
Salix arbusculoides	—	—	—	P	—	—	P
Low shrub							
Vaccinium vitis-idaea	18	1	1	7	—	—	—
Ledum groenlandicum	11	2	3	21	—	—	P
Vaccinium uliginosum	4	1	1	3	—	—	4
Ledum decumbens	1	—	P	—	—	—	—
Oxycoccus microcarpus	P	P	P	P	—	—	P
Spiraea beauverdiana	1	P	—	—	—	—	—
Empetrum nigrum	P	—	—	—	—	—	—
Chamadaphne calyculata	—	—	—	—	—	—	P
Herb							
Rubus chamaemorus	4	2	3	5	—	—	2
Equisetum sylvaticum	2	4	7	43	4	40	12
Calamagrostis canadensis	1	1	1	3	1	5	5
Petasites frigidus	P	P	P	P	—	—	—
Polygonum alaskanum	P	—	—	—	—	—	—
Eriophorum vaginatum	P	P	P	P	—	—	—
Epilobium angustifolium	—	P	P	2	1	—	—
Cornus canadensis	—	—	—	P	—	—	—
Eriophorum spissum	—	—	—	—	—	—	10
Festuca rubra	—	—	—	—	—	P	5
Carex aquatilis	—	—	—	—	—	10	10
Eriophorum angustifolium	—	—	—	—	—	—	10
Agrostis scabra	—	—	—	—	—	5	1
Moss							
Pleurozium schreberi	40	—	—	—	—	—	—
Sphagnum spp.	24	P	P	P	—	1	37
Polytrichum commune	—	2	7	19	20	33	19
Aulacomnium palustre	7	—	—	P	—	—	—
Hylocomium splendens	3	—	—	—	—	—	—
Dicranum undulatum	P	—	—	—	—	—	—
Ceratodon purpureus	P	—	7	6	—	—	—
Marchantia polymorpha	—	P	P	—	—	—	—
Calliergon stramineum	—	—	—	—	—	5	23
Lichens							
Cladonia rangiferina	8	—	—	—	—	—	—
Peltigera aphthosa	2	—	—	P	—	—	—
Cladonia amaurocraea	1	—	—	—	—	—	—
Peltigera canina	2	—	P	1	—	—	—
Nephroma arcticum	P	—	—	—	—	—	—
Cetraria islandica	P	—	—	—	—	—	—
Cladonia spp.	1	—	—	P	—	—	—
TREE DATA							
Picea mariana							
Live trees/ha	1,241	—	—	—	—	—	—
Live saplings/ha	741	—	—	—	—	—	—
Seedlings/ha	27,875[2]	14,125	10,750	28,500	0	—	11,000
Dead trees	141	4,025	4,279	3,875	—	—	—
Betula papyrifera							
Live trees/ha	—	—	—	—	—	—	—
Live saplings/ha	10	—	—	12	—	—	—

[1] P indicates present but with less than 1 per cent cover.
[2] Mostly layered branches (layerings).

the summer months and bi-weekly during the winter months. In addition, in October of 1978, a thermograph and weather shelter were installed at the site to record air temperatures. Snow depths were measured at two stakes at each of the three sites.

Vegetation in the burned and unburned stand was determined through a 20-plot system originally described by Ohmann and Ream (1971) and modified by Foote (1976). On the fireline ten vegetation plots were located, one at each of the probe sites. Vegetation cover was recorded for all species at each of the sites. Depth of the moss layer, 01, and 02 layers were determined at each of the probe sites.

Results

Vegetation

The vegetation that existed previous to the 1971 fire and fireline construction can be characterized by the present vegetation of the unburned stand (Table 2). The vegetation type is an open conifer forest, and the community type most closely fits that of the *Picea mariana*/feathermoss-*Cladonia* community type (Viereck and Dyrness 1980), although some small patches within the study area are of the *Picea mariana/Sphagnum-Cladonia* type as described by Neiland and Viereck (1977).

The vegetation of the unburned stand consists of open black spruce with an average diameter of 5.2 cm, a density of 1240 trees/ha and 45 per cent canopy cover (*see* Figure 4). The age of most of the trees is about 70 years but there are small patches and stringers of older trees, about 135 to 140 years in age, which survived the fire that burned the area in the early 1900's. There is an open shrub layer with 6 per cent cover of *Salix planifolia* and *Betula glandulosa* and a low shrub layer with 36 per cent cover, primarily of *Ledum groenlandicum* and *Vaccinium vitis-idaea*. Mosses, especially *Pleurozium schreberi* and *Sphagnum* spp., primarily *S. fuscum, S. girgensohnii*, and *S. warnstorfii*, are the most important element of the forest floor, with a combined cover of 80 per cent. Lichens, primarily species of *Cladonia* and *Peltigera*, have a combined cover of 15 per cent. An herbaceous layer of *Rubus chamaemorus*, *Equisetum sylvaticum*, and *Calamagrostis canadensis* is poorly developed and has a cover of only 7 per cent (Figure 5).

Following the fire, revegetation has been slow in the burned area, probably because of the remaining partially burned organic layer which averaged 15 to 20 cm in thickness. This layer, which becomes extremely dry during periods of low rainfall, is a poor seedbed for invading species. Consequently, most of the post-fire vegetation has been re-established by vegetative reproduction. In the summer following the fire, the live vegetation cover was sparse and consisted primarily of low ericaceous shrubs and *Equisetum sylvaticum*, which had developed from unburned below-ground parts. *Polytrichum commune* was the dominant moss. By 1980, the live plant cover had in-

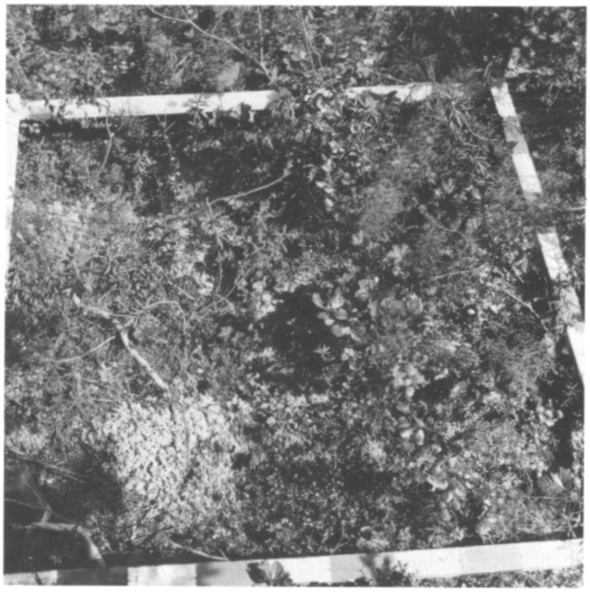

FIGURE 5. Forest floor of unburned stand with nearly continuous moss layer, a conspicuous clump of *Cladonia* and several herb and low shrub species.

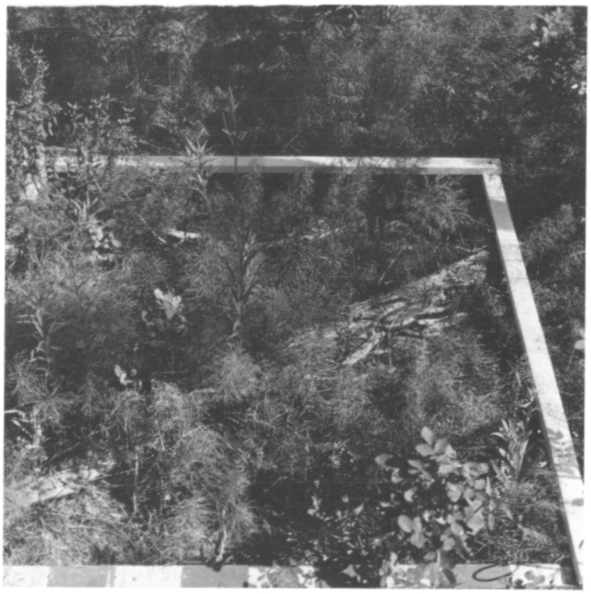

FIGURE 6. Typical vegetation in the burned stand in 1980. Conspicuous herbaceous species are *Equisetum sylvaticum* and *Epilobium angustifolium*. Shrubs are *Ledum groenlandicum* and *Vaccinum uliginosum*.

creased to nearly 100 per cent (Figure 6) primarily because of a 43 per cent cover of *Equisetum sylvaticum*. Although covering only three per cent of the area, clumps of *Calamagrostis canadensis* were a conspicuous component of the herbaceous layer. The tall shrub layer of willows and shrub birch had increased slowly during the post-fire period to a cover value of eight per cent, slightly above that found in the unburned stands. The dead spruce killed by the fire have remained standing until 1980 but offer little shade to the soil surface because they have lost all of their needles and some of their branches. The mosses have also been slow to develop and, after nine years, only *Polytrichum commune* and *Ceratodon purpureus* cover 24 per cent of the surface. A small amount of *Sphagnum* spp. that survived the fire persists but there has been no reinvasion of the feathermosses.

In contrast to the burned area, the fireline has revegetated rapidly (Figure 7). This is undoubtedly due to the exposed mineral soil and the abundance of moisture on the surface. The increased wetness of the fireline, compared with that of the burned area can be shown by the differences in the invading and recovering vegetation. On the fireline a number of herbaceous species of wet habitats, such as *Eriophorum spissum*, *Carex aquatilis*, and *Eriophorum angustifolium* have become abundant. Willows that were established from seed have also developed rapidly so that the tall shrub layer covered 33 per cent in 1980. Spruce seedlings have invaded in recent years but their growth has been slow and, in 1980, they covered less than one per cent.

There has been a rapid invasion of the fireline by mosses; in the dryer part, *Polytrichum commune* forms a nearly 100 per cent cover, whereas in the wetter sites *Calliergon stramineum* and *Sphagnum girgensohnii* both have formed nearly continuous cover. These two latter species have developed rapidly during the past five years, whereas *Polytrichum commune* was most abundant during the first five years and has begun to decline in importance.

Soils

The study area is situated on Saulich silt loam soils which, at the suborder level, would be classified as a Histic Cryaquept (US Dep. Agriculture 1975). These soils are formed in silty loam deposits more than 75 cm in depth, are poorly drained with a shallow active layer, and are generally moist to wet. The undisturbed soil has a moss-litter layer (01 to 02) of 25 to 30 cm underlain by approximately 10 cm of a dark grayish-brown silty loam A horizon over a frozen C horizon of olive-gray silty loam.

In the burned stand, about 10 cm of the organic layer was removed by the fire. The remaining organic layer is relatively unchanged since the fire but there has been some decomposition and compaction in the ten post-fire summers. In 1980, the soil profile consisted of a live moss layer that varied from 0 to 3 cm in thickness. Between this and the mineral soil there is usually, but not always, a thin layer, 1 to 3 cm, of moist, dark brown humus. In the ten profiles sampled in 1980, one or more of these three layers was missing, probably as a result of differences in amounts of the forest floor consumed by the fire.

The soil profile in the fireline is more difficult to describe and characterize. In the first few years following the fire it was made up primarily of exposed mineral soil and humus with no easily distinguishable horizons. In 1980, the profile above the mineral soil consisted of three distinct layers; the green moss layer, a layer of dead organic material that seemed to have been formed from partially decayed moss parts developed since the fire, and a layer of dark humus that was probably residual from before the fireline construction. These layers were variable in thickness: the green moss layer averaged 3 cm, the dead organic layer 3 cm, and the humus layer 4.5 cm.

The unburned control illustrates the normal Saulich soil profile. Along the probe line in the control the following were the average thicknesses of the soil horizons. The living green moss layer was 3 to 5 cm in thickness. Beneath this was a 01 layer of forest litter, 10 to 15 cm thick, and a 021 layer of coarse fibrous peat 15 to 20 cm thick. Most of the vascular plant

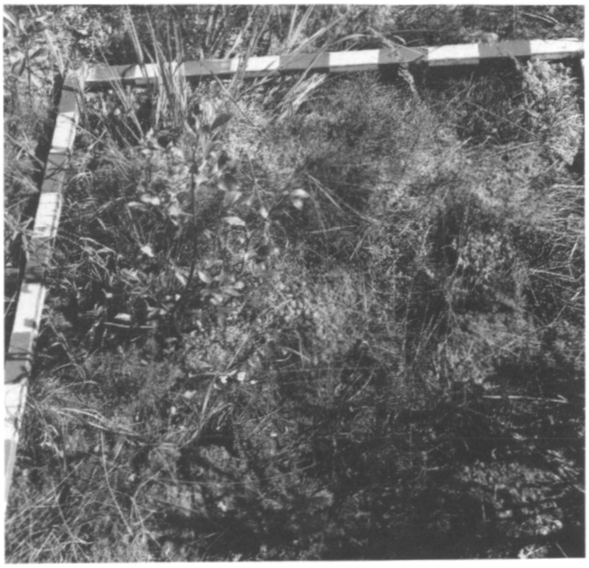

FIGURE 7. Typical vegetation on the fireline in 1980. Mosses, sedges, and grasses are dominant.

roots and rhizomes were in these two layers. Just above the mineral soil was a 022 layer of black fine humus 0 to 10 cm in thickness. The organic layers together averaged about 30 cm. The A horizon was 0 to 10 cm in thickness — a very dark grayish-brown silty loam. Beneath this was a mottled olive-gray silt loam C horizon that was perennially frozen at its lower depth and thawed at the upper limits only during later summer. The permafrost table was approximately 45 cm below the base of the moss surface.

Depth of thaw

The progression of the depth of thaw through the summer months for the years 1972, 1975, 1977, 1979, and 1980 is shown in Figure 8. Data are available for the intervening years but are omitted so as to make the figure easier to understand.

In the unburned stand the thaw begins in early May and progresses slowly until late August. During most years there is little increase in the thaw depth in September and often there is a slight decrease in thaw depth in September and October as the soil freezes up from the permafrost table. There is little variation in thaw depth from year to year and differences at any time of year are usually less than 10 to 15 cm over the eight-year period. Maximum thaw for the nine years has been between 40 and 50 cm.

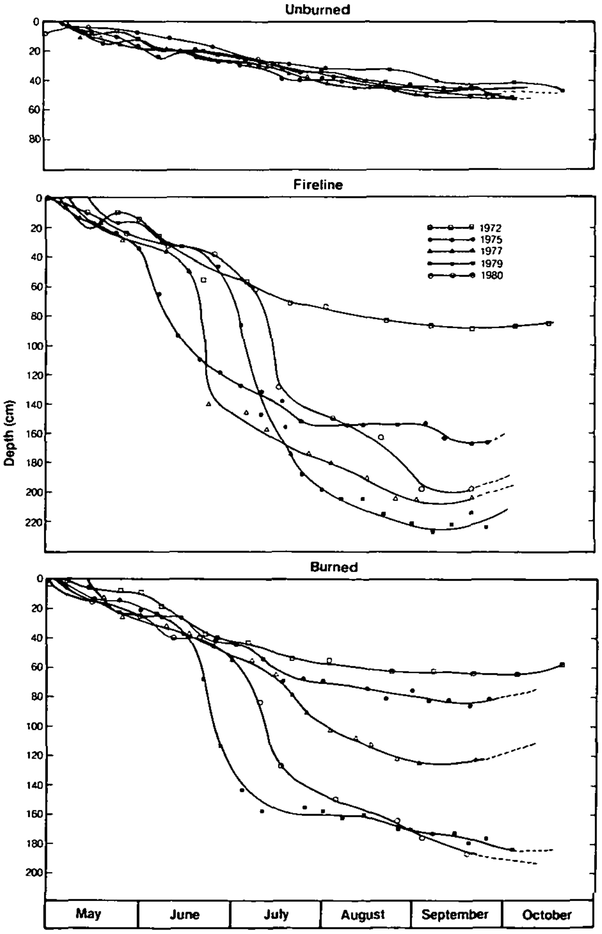

FIGURE 8. Progression of thaw depths from May to October for the selected years of 1972, 1975, 1977, 1979, and 1980 for the unburned control site, the fireline, and the burned stand.

In the burned area the thaw depth pattern in 1972 followed closely that of the unburned stand but the thaw depth was slightly deeper, with the maximum thaw, in late August, of 62 cm, about 20 cm deeper than the control. However, with each following year, there has been an increase in the thaw depth. Through mid-June there seems to be little change in the thawing pattern over the years. However, from mid-June onward there is a change in the thaw pattern with most of the thaw occurring rapidly from mid-June until mid-July. This is especially apparent in the 1979 curve. Another change in the 1979 and 1980 curves is that the maximum thaw depth no longer occurs in late August with a gradual freeze-back, but rather the thaw depth continues to increase through late September and even into October. The relatively cool June of 1980 is shown by the delay in the rapid thaw period of that year.

The pattern in the fireline is more varied but shows the same general form as in the burned stand. The 1972 thaw pattern is nearly linear with a maximum in late August. By 1975, the thaw trend has changed with a rapid thaw beginning in early June and becoming nearly stationary by late July. In contrast, later years have shown a trend toward a later period of rapid thaw, mid to late June in 1977, late June to late July in 1979, and mid to late July in 1980. On the fireline, maximum thaw depth usually occurs in mid-September.

Changes in maximum thaw depth with time

The maximum thaw depths for the three sites are compared over the ten summers from the fire year through 1980 (Figure 9). The control shows no change during the period of study. The burned stand has had a gradual increase in thaw depth between 1971 and 1973, a levelling off during 1974 and 1975, a gradual increase to 1978, followed by a rapid increase between 1978 and 1979, and little change between 1979 and 1980. The fireline shows a more or less consistent increase in thaw depth from 1972 to 1978 with the exception of 1975 to 1976 when the thaw was more rapid. The most significant aspect of the fireline curve is the decrease in thaw depth between 1979 and 1980.

Change in thaw depth with position on the fireline

In order to better understand the changes in thaw depth on the fireline the actual thaw depths beneath the surface for the transect across the fireline have been graphed (Figure 10). In this figure the approximate original surface is shown along with the present (1980) surface level as determined by running a surface profile across the fireline at the probe sites. The thaw depths have been somewhat deeper on the north side of the line than on the south side. This is understandable in that the north side is in full sunshine whereas the south side receives some shading from the unburned black spruce to the south. Subsidence has also been considerably more pronounced on the north side of the line than on the south side. This has resulted in more moisture and water accumulation between points 1 and 7 than between 7 and 10. Because of this, the *Sphagnum girgensohnii* and *Calliergon stramineum* are mostly located on the north side and the *Polytrichum commune* mat is found primarily between probe sites 7 and 10.

The 1972 thaw depths show that the thaw was somewhat less on the south side than on the north side. This was not true in 1976 and 1979; in fact the actual thaw depth from the surface was then greater at points 9 and 10 than it was in the wetter parts of the line. However, a surprising change took place in 1980 — the thaw depths greatly decreased on the south side of the line but remained about the same on the north side. Thus, the lower average thaw depth in 1980 was due primarily to a decrease in thaw depth along the shady side of the fireline and under the dense *Polytrichum commune* mat.

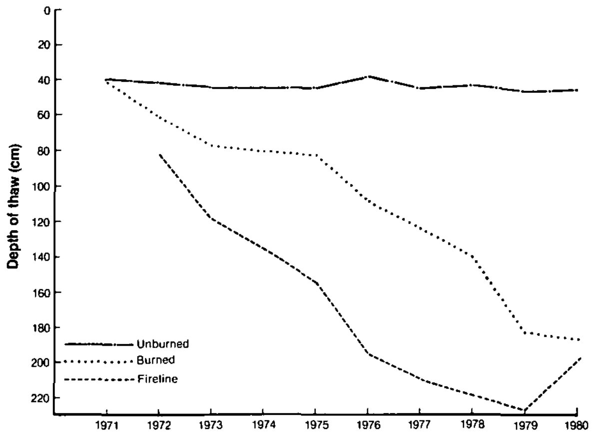

FIGURE 9. Change in the maximum thaw depths of the unburned control, fireline, and burned stand for the years 1971 to 1980.

Freeze and thaw data

From the probe data and the winter soil temperatures the pattern of freezing and thawing for the summer of 1979 and the winter of 1979-1980 has been estimated (Figure 11). It is sometimes difficult to determine the time of freezing from the thermistor data because the freezing process is a gradual one in which the temperature readings stay close to 0°C. After freezing, however, there is usually a more rapid temperature drop and this has been used to indicate that the soil is totally frozen at the level of the probe.

In the unburned stand, the freeze-up began in early October and progressed rather evenly until about mid-December at which time the profile was completely frozen. From October to mid-November,

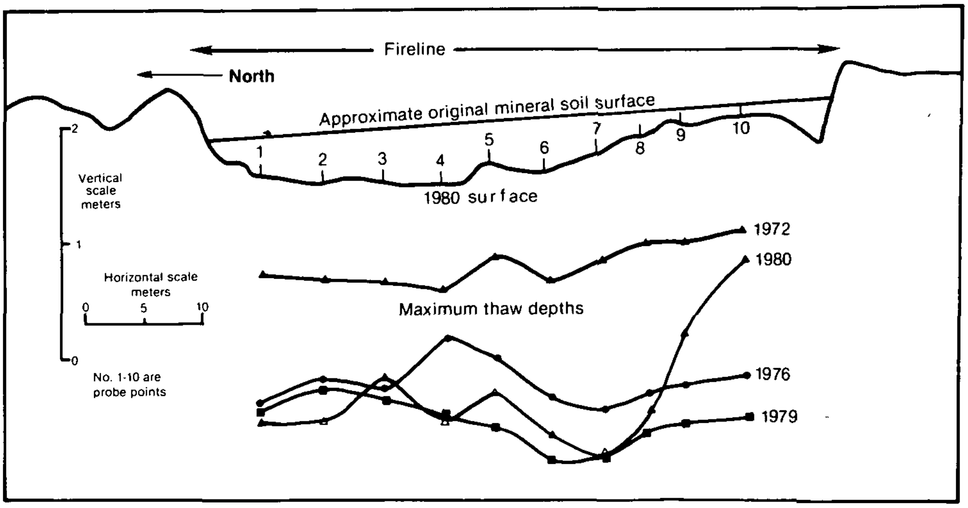

FIGURE 10. Cross section of the fireline showing probe sites, approximate original surface, surface profile in 1980, and the maximum thaw depths for 1972, 1976, 1979, and 1980.

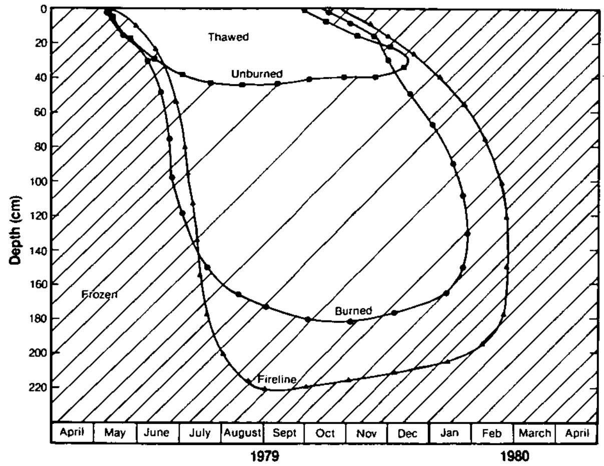

FIGURE 11. Time and depth of the freeze and thaw of the unburned control, fireline, and burned black spruce stand for the period of April 1979 through March 1980 as determined by probing and by soil temperature measurements.

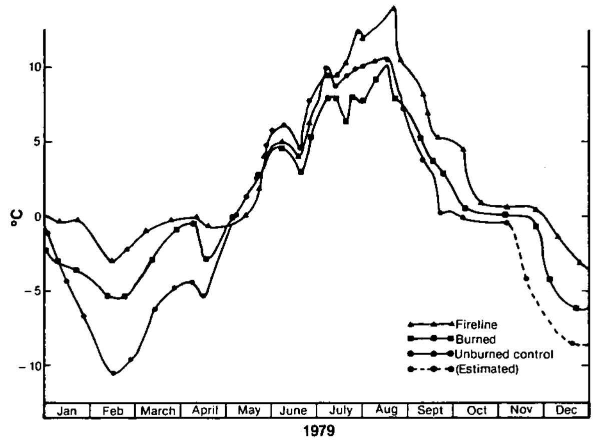

FIGURE 12. Soil temperatures at the 10 cm depth in an unburned black spruce stand, the fireline, and the burned black spruce stand for 1979.

freezing in the burned area followed a similar pattern to the unburned stand except that the freeze was delayed by one to two weeks at any given level. In mid-November, however, the rate of freeze increased so that the entire profile was frozen by late January of 1980.

The fireline soils froze at a much slower rate than did the control or the burn, perhaps because of the warmer summer soil temperatures and the greater amount of moisture in the soil. In the fall, the freeze line was about a month later than the unburned stand. Final freezing of the entire profile was not until late February.

All the freezing curves show some freezing upward from below. This is indicated from the temperatures taken at depths and from data from another of the author's studies where the freeze and thaw have been followed for ten years using frost tubes. The placement of thermistors at 50-cm intervals make it difficult to determine the exact amount of freezing from below but Figure 11 appears to give a general approximation of this freeze-back at depth.

The thaw rates that occurred during the summer of 1979 have been discussed previously. Figure 11, however, provides a good comparison of the thaw curves of the three sites. It can be seen that the thaw on the fireline, as with the freeze, is delayed by about two weeks, due probably to the higher ice content within the fireline soils.

Soil temperatures at 10 cm

One method that has been used for comparison of sites is the calculation of accumulated soil degree days at 10 cm depths. The period of 20 May to 10 September has been used with a base of 0°C for these temperature sums (Van Cleve and Viereck 1981). Ten centimetres was selected as being the depth with the most root development and therefore one at which soil temperature differences might be most significant to plant growth. In the Fairbanks area the soil degree temperature sums measured in degree days Celsius (DDC) range from 2400 DDC on dry south-facing bluffs to 525 DDC in black spruce stands underlain by permafrost. The range for mature black spruce sites was from 525 to 900 DDC.

In this study there was found to be a large range of accumulated soil degree days between the three sites. For 1979, the unburned stand had a soil degree sum of 847 DDC. During the same summer the fireline was about 100 DDC warmer with a heat sum of 940 DDC which might be expected considering the greater thaw and the lack of insulating layer. The burned stand, however, had a soil degree sum of only 722 DDC. This considerably lower figure may be the result of the insulating effect of the dry, partially burned organic layer, but is hard to explain the relationship to the deeper active layer of the burn compared to the unburned stand. Temperatures at 20 and 50 cm, however, were warmer in the burned stand than in the unburned stand. In 1980, the soil degree days were considerably lower because of the cooler summer. The fireline had an accumulation of 768 DDC and the burned stand was again lower with 630 DDC. Unfortunately the thermistors in the unburned stand were not operating during part of the 1980 summer so no accumulation figure can be given for the control.

Soil temperatures at the 10-cm depth for the three

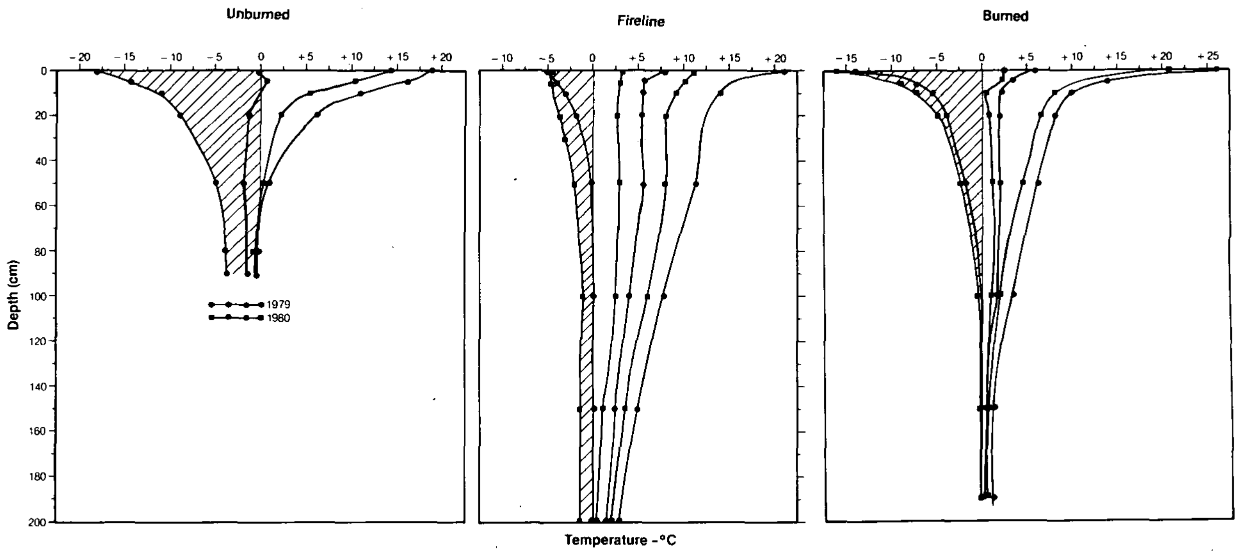

FIGURE 13. Profile of maximum and minimum soil temperatures for 1979 and 1980, for the unburned black spruce stand, the fireline, and the burned black spruce stand.

stands for 1979 are compared (Figure 12). Minimum temperatures were reached during a very cold month of February. At that time, temperatures at 10-cm depth were coldest in the unburned stand (−11°C), and warmest in the fireline (−3°C). The burned stand was intermediate with temperature of −5.5°C. The soil began to warm rapidly after a drop in mid to late April and, by late May, all three sites had soil temperatures at 10-cm depth of between 2.5 and 4°C.

During the summer months, the fireline soil became considerably warmer than that of the control or the burned stand, reaching on August 14 a temperature of 14°C, which is 3 to 4°C warmer than the maximum temperatures in the control or burned stand. The temperatures in the burned stand remained 1 to 3°C cooler than those in the unburned control. This is the opposite of what occurred in an adjacent site in the first years after the fire when it was found that the soil temperatures in the burned stand were 3 to 6°C higher than those in the control (Viereck and Dyrness 1979). In the fall and early winter, the cooling trend at all three sites was similar except that soils in the unburned control cooled slightly faster than those in the burned stands, becoming 2 to 3°C colder by later November.

Ground temperature envelope

Another way of comparing the soil temperatures at the three sites is to graph the maximum and minimum temperatures at depth for each of the sites (Figure 13). Brown (1973) termed this type of figure the "ground temperature envelope". In this figure the warmest, coldest, and average temperatures at each level for both 1979 and 1980 are shown. The control has only the year 1979 for the winter months because the unit was not operating during the winter of 1980.

In the unburned stand, the differences between the two summers can be clearly seen. In 1979, temperatures were approximately 5°C warmer down to the 20-cm level, but the difference becomes much less at 50 cm and there was no difference at 90 cm, the soil being frozen at that depth during all of both summers.

The burned stand shows a wide range in soil temperatures at 10-cm depth but this rapidly becomes much less with greater depth. The 1980 summer soil temperatures were colder than those of 1979 at all depths. The winter minimum temperatures were very similar in both years with the 1980 temperatures being 1 to 2°C colder to one metre. Below one metre the winter cold penetration is slight with temperatures remaining at, or slightly below, the freezing point.

The fireline soil temperature profiles showed considerable differences between the two years, even to the maximum depth of the thermistors, two metres. In the summer of 1979, soil temperatures were 2 to 5°C warmer to the 150-cm depth and 1°C warmer at the two-metre depth. Although the seasonal range at the surface was less than in the control or burn, the seasonal differences were greater at depth, the one-metre depth showing a seasonal range of 7°C and the two-metre depth a seasonal range of 3 to 3.5°C difference between summer and winter.

Discussion

Both burning and fireline construction have caused an increase in soil temperatures and thaw depths at the Wickersham site. Ten summers following the fire, the depth of thaw is still increasing in the burned area. The depth of thaw has increased from 45 cm in the unburned to 187 cm in the burned stand, an increase of slightly more than four times the original thaw depth. This is more than has been reported from other burned areas, but few studies have followed the thawing on one fire site for more than a few years. The one exception to this is the Invuik fire in northwestern Canada where Mackay (1977) reported on thaw depths in an open black spruce tree-line site that burned in 1968. After eight years he found an increase in thaw depth in depressions from 35 to 95 cm (2½ times as deep) and on ridges an increase from 61 to 112 cm (slightly less than twice the depth). At the Inuvik site the depth of thaw became nearly stable five years following the fire, but Inuvik has a colder climate than the Wickersham site with a mean annual temperature of −9.4°C which may account for the more shallow thaw following the fire and the earlier stabilization of the thaw depth.

The question of how long it takes before the depth of thaw under burned areas becomes stabilized and then returns to the preburn level has not been answered. By examining thaw depths of a number of burned areas of known age the author predicted that the maximum depths of thaw would be reached by about 15 years and that the return of the thaw depths to that of the pre-burn levels would have to await the establishment of a tree canopy and the formation of a well-developed feathermoss or sphagnum layer (Viereck 1973). From the work on succession by Foote (1976) it would appear that this would be about 25 to 50 years following fire in interior Alaska.

The thaw depth increase beneath the fireline is greater than that in the burned area, a maximum thaw of 227 cm or five times the original depth. An interesting observation in the fireline is that the 1979 thaw depth was greater than that in 1980 indicating that the thaw depth may be stabilized and may not increase in the future. However, 1980 was a cool summer and the decrease in thaw depth may be the result of the lower thawing degree days rather than the result of the re-establishment of the surface moss layer.

To the author's knowledge no other observations of long-term permafrost depths on firelines have been published. However, studies of other types of disturbance should yield comparable information. Brown and Grave (1978) have reviewed studies of the changes in thaw depth as a result of seismic line construction and of winter and summer road usage. Most of these studies were for only periods of two to three years and reported active layer increases of twice the original depth or less. Most of the studies on which they report were done in tundra or tree-line areas with a colder mean annual temperature than that in the Wickersham area. A study of permafrost retreat under cleared fields in Fairbanks indicates that as long as the natural vegetation cover is prevented from becoming re-established, the thaw depth will continue to increase, at least to a depth of 6.7 metres after 26 years (Linell 1973).

The return of the disturbed sites to their original permafrost condition depends to a large degree on the revegetation process. In the burned area revegetation has been slow and dominated by herbs. In the fireline the wetter soil conditions have resulted in the development of a moss cover, even though the tree canopy has not been re-established. This moss cover may be the main reason that the thaw depth has stabilized in the fireline site.

Most resource managers, especially those charged with responsibilities for fire suppression, have recognized the long-term effects of constructing firelines on ice-rich permafrost sites and have attempted to develop guidelines to lessen the effects of their construction. However, it must be recognized that in the rush and excitement of fire suppression activities firelines will undoubtedly continue to be constructed on ice-rich permafrost sites.

In the past, rehabilitation has been largely by seeding exotic grass species onto the firelines. An herbaceous cover of grasses may be necessary to prevent erosion on some steep slopes but it has little effect on slowing the thawing of underlying permafrost. This present study is in agreement with others which indicate that the moss layer and its build-up of a deep organic layer is the most important control of active layer depth by vegetation. Research in rehabilitation methods should look toward the best method for rapid re-establishment of the moss cover in order to minimize the thaw depths and to stabilize the disturbed site.

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