The Role of Fire in Northern Circumpolar Ecosystems
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CHAPTER 6

Effects of Fire on the Permafrost Ground Thermal Regime

THE LATE R.J.E. BROWN*

Division of Building Resarch, National Research Council of Canada, Ontario, Canada

ABSTRACT

Discontinuous permafrost occurs widely in the boreal forest, while throughout the tundra region permafrost is continuous and may be hundreds of metres deep. Until recent years few investigations have been conducted on the effects of fire on the perennially frozen ground in these northern circumpolar ecosystems. Little modification of permafrost conditions takes place during the actual burning, but the partial or complete destruction of the organic cover produces changes in permafrost lasting many years. There are three major effects of fire on permafrost, which are related to the amounts of vegetation and organic soil that are removed: the deepening of the active layer with resultant thermokarst and instability of newly thawed soils or slopes; an increase in soil temperatures; and changes in the ground surface energy exchange regime. These post-fire conditions prevail for many years as natural restoration of burned sites gradually takes place. Long-term observational programmes, which are lacking at present, are required to assess more fully the effects of fire on permafrost.

6.1 INTRODUCTION

During the past decade there has been a dramatic increase in the number of studies on the biological and engineering aspect of permafrost in northern circumpolar ecosystems. Permafrost was of particular concern to the mining industries because mining of frozen ore was extremely expensive. More recently, the expansion of the oil industry into northern North America was closely followed by a growing public awareness of environmental concerns. This led to a number of studies that focussed on active layer changes and terrain disturbance caused by vehicular traffic and pipeline construction. One of the disturbances associated with industrial activity in the North is the increased frequency of fires, yet information on fire and permafrost has not been particularly well summarized. There have been some investigations on

*It is with deep regret that we must report the untimely death of Dr Brown on 4 November 1980 aged 49. He will be missed by his many colleagues and friends throughout the circumpolar North.

changes in the ground surface energy regime, but very few observations are available on post-fire ground temperatures.

6.2 CHARACTERISTICS AND DISTRIBUTION OF PERMAFROST

Considerable information is available on the general characteristics and the circumpolar distribution of permafrost (Brown, 1970). Recent reviews on the subject are available (e.g., Brown and Péwé, 1973), so only a general review is given here. Permafrost, or perennially frozen ground, is defined as the thermal condition in soil or rock when temperatures below 0°C persist continuously for at least two consecutive winters and the intervening summer. The definition is based purely on thermal conditions. Earth materials in this thermal condition may thus be described by the term 'perennially frozen' (e.g., perennially frozen silt, perennially frozen bedrock) irrespective of their water and/or ice content.

The minimum time span for permafrost is at least one year, as it includes ground which reaches freezing temperatures in one winter and remains at freezing temperatures through the following summer and into the next winter. Such permafrost may be only a few centimetres thick. At the other end of the time scale, permafrost may be thousands of years old and 1000 m or more in thickness. Permafrost is not referred to as 'permanently' frozen ground, because changes in climate and terrain may cause it to thaw and disappear. Thus permafrost is a reflection or expression of the net effect of heat losses and heat gains at the ground surface, at the upper surface of the permafrost (permafrost table), and at the base of the permafrost.

There are two other definitions that are useful in discussing the upper and lower boundaries of permafrost. The active layer is the top layer of ground above the permafrost that thaws each summer and refreezes each autumn (Brown and Kupsch, 1974). The depth of zero annual amplitude is defined as the distance from the ground surface downward to the depth beneath which there is virtually no annual fluctuation in ground temperature (Brown and Kupsch, 1974).

The permafrost region is generally divided into the discontinuous zone in the south and the continuous zone in the north. In the discontinuous permafrost zone, frozen and unfrozen areas exist together. In the southern fringe of this zone, permafrost occurs in scattered islands, a few square metres to several hectares in size, and is confined to certain types of terrain, mainly peatlands. Other occurrences are associated either with the north-facing slopes or with isolated patches in forested stream banks, apparently in combination with increased shading in summer and reduced snow cover in winter. Northwards, permafrost becomes increasingly widespread in a greater variety of terrain types. The depth to the permafrost table ranges from about 50 cm to 3–4 m depending on local surface and terrain conditions. The active layer does not always extend to the permafrost table. Permafrost varies in thickness from a few centimetres at the southern limit to 100 to 150 m at the boundary of the continuous zone in Canada and about 300 m in the Soviet Union. Unfrozen layers sometimes occur between layers of permafrost. The temperature of the permafrost in the discontinuous zone generally ranges from about −0.1°C at the southern limit to −1.0°C at the depth of zero annual amplitude halfway through the zone. In the northern half of the discontinuous zone, where permafrost is widespread, the temperature at the depth of zero annual amplitude ranges from about −1.0°C to −3.3°C.

In the continuous permafrost zone, permafrost occurs everywhere beneath the ground surface except in newly deposited, unconsolidated sediments where the climate has just begun to impose its influence on the ground thermal regime. The active layer generally varies in thickness from about 15 to 60 cm depending on local surface and terrain conditions, and usually extends to the permafrost table. The thickness of permafrost is about 100 to 300 m at the southern limit of the continuous zone and increases steadily to 1000 m or more in the Far North of Canada and 1500 m in northern Siberia. The temperature of the permafrost at the depth of zero annual amplitude varies from about −3.3°C in the south to about −15°C in the extreme north.

The living vegetation and surface peat layers in the permafrost region have varying characteristics throughout the boreal forest and tundra ecosystems. In Canada and Alaska the boundary between the discontinuous and continuous permafrost zones corresponds roughly with the tree line but in Siberia the continuous zone extends far to the south of the tree line.

In the discontinuous zone the permafrost in peatlands occurs mostly in peat plateaux and palsas having a micro relief of about 1–3 m. The predominant tree growth on these features in Canada is black spruce (*Picea mariana* (Mill.) B.S.P.) with some tamarack (*Larix laricina* (Du Roi) K. Koch), and an undergrowth of willow and alder and ground vegetation of Labrador tea (*Ledum groenlandicum*), *Sphagnum* mosses, and lichen (mostly *Cladonia* spp.). On older peat plateaux the lichens are dry and oxidized. The peat layer generally ranges in thickness from about 50 cm to 3 m. In Canada, west of Hudson Bay, virtually all peat plateaux and palsas are forested but east of Hudson Bay, especially in Labrador, many are treeless. In Siberia tree species include pine (*Pinus sylvestris* L.), larch (*Larix dahurica* Turcz.), fir (*Abies* spp.), and spruce (*Picea obovata Ldb.*). Toward the northern boundary of the boreal forest, trees become stunted and sparse and the peat layer is generally thinner. In the tundra, the vegetation consists mainly of sedges, mosses, and lichens.

6.3 IMMEDIATE EFFECTS OF FIRE ON PERMAFROST

The introduction of fire into the ecosystems described above results in some or all of the vegetation and organic matter being consumed. Investigators have measured the direct heat input during the actual burning and found this to be small, because both mineral soil and organic layers are very poor conductors of heat energy. Van Wagner (1970) found heat gradients of 10°C/mm depth of mineral soil and 28°C/mm depth of duff (partly decayed organic material). A surface temperature of about 450°C would therefore have little effect below a 5-cm depth in most forest soils. The duration of active burning at any given site (trees excluded) in northern regions is usually considerably less than half an hour, because of the relatively small quantity of combustible material in the boreal forest or tundra compared with more temperate regions. A heat flow calculation has shown that if the ground surface were at 10°C and the fire maintained a temperature of 500°C for half an hour, the temperature rise at a depth of 30 cm would hardly be perceptible (Mackay, 1977).

6.4 LONG-TERM EFFECTS OF FIRE ON PERMAFROST

Three major long-term effects of fire on permafrost in the boreal forest and tundra are changes in the active layer thickness, alterations in the near-surface ground temperature regime, and modifications to the ground-surface energy exchange. These changes are related to the amounts of vegetation and organic matter removed. The deepening of the active layer, with the resultant thermokarst and instability of newly thawed soils on slopes, rise in soil temperatures, and change in surface albedo, is dependent on whether the fire burns only the tree crowns, or the trees and undergrowth to the ground surface, or whether the surface organic matter is partially or completely destroyed. Burning may be uneven in northern ecosystems, especially where tree growth is sparse, and all three degrees of organic matter removal can occur in a relatively small area (Brown and Grave, 1979; Johnson and Rowe, 1977; Pettapiece, 1974; Rowe *et al.*, 1974; Rowe *et al.*, 1975).

If a fire moves rapidly and only chars the surface of the ground vegetation, it may have little effect on the underlying permafrost. This may occur in early summer fires when organic layers are still cold and wet but when trees have been dessicated from a warm period. On peat plateaux and palsas in the Hudson Bay Lowland and northwestern Manitoba it has been noted that the trees have been burned and the surface of the moss and lichen charred by the fire. However, below a depth of 2.5 cm, the vegetation layer was untouched and its insulating effect on the underlying permafrost was unaltered from nearby unaffected areas that did not burn (Brown, 1968). Also, it has been observed by Rowe and Scotter (1973) that convex landforms, such as peat plateaux and palsas, are more susceptible to burning than surrounding flat, wet terrain.

Figure 6.1 Frost mounds at Inuvik, Northwest Territories, denuded of all peat and surface vegetation by the 1968 fire (from Watmore, 1969. Reproduced with permission of the National Research Council of Canada, Associate Committee on Geotechnical Research)

6.4.1 Effects of Fire on the Active Layer

The most noticeable effect of fire on permafrost soils is the post-fire thickening of the active layer (Scotter, 1971; Wright and Heinselman, 1973). One of the best documented fires in the Canadian boreal forest and tundra with regard to its effects on the active layer occurred at Inuvik, Northwest Territories, from 8 to 18 August 1968 (Bliss and Wein, 1971; Heginbottom, 1971; Mackay, 1970, 1977). The following account is taken from these papers. This forest-tundra fire destroyed 350 km^2 of forest-tundra and 115 km^2 of tundra. The original vegetation in the forest-tundra was scattered spruce and white birch, with willows, alder, Labrador tea, and a spongy ground cover of *Sphagnum*, other mosses, and lichens. Prolonged, abnormally high summer air temperatures and unusually low rainfall produced very dry conditions in the usually moist soil organic matter. The fire killed the trees and burned all organic material down to the mineral soil (Figure 6.1). The soil cover was thus reduced to a layer of ash several centimetres thick. As a direct result of the fire, the active layer thickened over most areas, some bare hillsides became gullied as sediment was transported into otherwise clean lakes, ice-rich

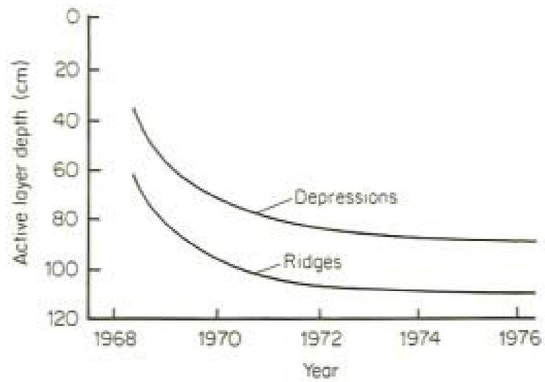

Figure 6.2 Observed thickening of the active layer after the 1968 Inuvik fire (after Mackay, 1977)

Figure 6.3 Water released from melting ground ice on a burned hillside forming a new stream network at Inuvik (from Watmore, 1969. Reproduced with permission of the National Research Council of Canada, Associate Committee on Geotechnical Research)

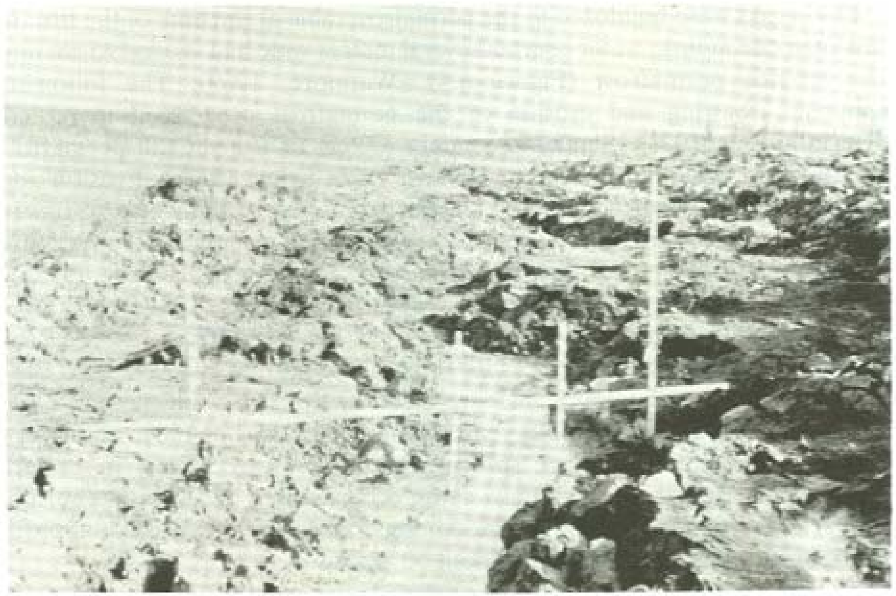

Figure 6.4 Firebreak bulldozed to the permafrost table with resultant thawing and erosion at Inuvik (from Watmore, 1969. Reproduced with permission of the National Research Council of Canada, Associate Committee on Geotechnical Research)

permafrost was exposed to thermokarst activity, flow slides developed, and bulldozed firebreaks subsided.

Natural re vegetation has been rapid in some areas of the burn since 1968. One year after the fire, about 70% of an area on a gentle hillside which was staked out to measure active layer changes was covered with bare ash. Two years after the fire there was a continuous cover of 50-cm high fireweed and other plants. By 1974, willows and white birch had grown to 1 m in height. However, most of the burned trees, which were upright in 1968, had now toppled over. Eight years after the fire, a luxuriant growth and a thickening mat of dead and decaying vegetation covered the ground, leaving no bare ash. The long-term recovery sequence of the vegetation in the Inuvik area is described by Black and Bliss (1978).

In the test area the active layer increased in thickness by about 50 cm over an 8-year period both in shallow depressions and low ridges (Figure 6.2). Rapid thickening occurred in the first 4 to 5 years, and a slight increase was noted even 8 years after the fire. Another effect was that the ground surface subsided from 50 to 100 cm over this period due to the melting of ground ice. So much water was released from melted ground ice on a burned hillside that a new network of streams was formed (Figure 6.3).

Firebreaks were bulldozed to the permafrost table at the time of the fire. In less than one month, water courses several metres wide had eroded 45 cm into the ice-rich permafrost (Figure 6.4) (Watmore, 1969). The following summers, thawing and erosion of the permafrost progressed to 65 cm (Heginbottom, 1971). Similar secondary effects of fire on the permafrost terrain were observed in Alaska (Evans, 1976; Sykes, 1971). Erosion and gully formation occurred where fire lines were cleared with bulldozers. In both instances the fire guards constructed by heavy machinery caused more disturbance than the fires themselves on ice-rich permafrost (Wein, 1975b).

Investigators in Alaska have also observed increases in active layer thickness after fires, followed by a rise in the permafrost table as the vegetation was restored (Viereck, 1973a,b). Wein (1975a) and Wein and Bliss (1973) reported a 130–150% increase in the active layer thickness in early summer after a fire the previous year. An increased thaw of 150% occurred 4 years after a fire in a black spruce/*Eriophorum* tussock-type in eastern Alaska. The same increase in thaw depth occurred in a one-year-old burn in similar vegetation in central Alaska. All these authors indicated that a return to pre-burn thaw levels required about 50 years.

At the northern limits of the boreal forest, fire may result first in a slight lowering of the permafrost table, followed in a few years by a significant rise. Kryuchkov (1968) reported that fire first caused thawing at the permafrost table with a resultant release of moisture from melted ground ice, creating conditions which stimulated the growth of *Eriophorum* cover (tundra vegetation). As a result of the insulating effects of the thicker vegetation mat, the active layer was only 40–45 cm thick a few years after a fire, whereas before the fire it was 50–70 cm. The resultant colder and wetter soils prevented the establishment of tree seedlings and caused large areas of what Kryuchkov termed 'pyrogenic tundra'.

The effects of fire in tundra regions north of the boreal forest have received little study, but some information on their frequency and characteristics has been reported (Wein, 1976). Haag and Bliss (1974) reported results of an experimental controlled fire on tundra at Tuktoyaktuk, North west Territories. The depth of thaw increased from 36 to 46 cm by the end of the first summer. Few fires were reported in the eastern Canadian Arctic until 1973, when fourteen tundra fires were located in the District of Keewatin at the end of an unusually hot and dry period (Shilts, 1975; Wein and Shilts, 1976). The mean July air temperature was 4.5°C above normal and the total rainfall about 4% of the average. Surface grasses burned extensively, as did some soil organic material. Detailed measurements of changes in active layer thickness were not made but lowering of the permafrost table by several centimetres probably took place, especially in areas where the surface was blackened and in the vegetated areas between frost boils. No tundra fires have been reported north of mainland Canada in the Arctic Archipelago since fuel loading is low and fuels are discontinuous because the vegetation is patchy.

Widespread fires occurred on the Seward Peninsula, Alaska, during the summer of 1977 (Racine, 1979; Hall *et al.*, 1978). The fires burned a range of vegetation and relief types which included low-polygonized and upland-tussock tundras. The fire was extremely hot and burned 80–90% of the vegetation, exposing extensive areas of bare soil. The burned areas appeared wetter on the surface than the unburned areas, due to a lack of moisture-absorbing organic matter and the possible release of moisture from the deeper thawed zone. The depth of thaw in the burned areas averaged 35.4 cm along a transect, compared with 26.6 cm in the unburned areas.

One other effect of the deepening of the active layer after fire is the formation of thermokarst (Lutz, 1954; Viereck, 1973a). In areas with high concentrations of ground ice, such as ice wedges, thawing results in a subsidence of areas over the ice wedges, creating a polygonal mound and ditch pattern. The ditches may be 2–3 m deep and frequently remain filled with water through most of the summer. Active thermokarst with trees tipping into the ditches and fresh cracks in the mounds occurs 40–50 years after the fire. Eventually, with the return of black spruce, these sites may become stabilized or small thaw ponds may develop.

Earth flows on slopes can occur quite extensively after fires and develop into retrogressive thaw flow slides. During the summer following the 1968 fire at Inuvik, seventeen earth flows were observed in a burned-over, east-west-oriented stream valley (Heginbottom, 1970). These flows were situated along the south-facing slope with their mean overall length ranging from 200 m to 500 m. Many other examples have been observed from the air in recently burned areas along bluffs of the Mackenzie River and its tributaries. As the slides work back into the hillsides, an increasing quantity of thawed soil and water from melted ground ice is released, causing a steady increase in the depth of the active layer and more thawing.

6.4.2 Effects of Fire on Ground Temperatures

Little work has been carried out on the long-term effects of fire on permafrost ground temperatures but scattered observations indicate a general increase in temperature (Sykes, 1971). In interior Alaska there was a 3°C higher soil temperature at a depth of 2.5 cm in a previously burned 40-year-old birch stand than in a 200-year-old white spruce stand; such differences penetrated the profile to over 40 cm. The mean ground temperature in burned-over areas in northern Saskatchewan was nearly 6°C higher at the 2.5 cm depth and 5.5°C higher at the 7.5 cm depth than in unburned areas. There are, however, no continuous observations on temperature changes over the years in the active layer or the underlying permafrost.

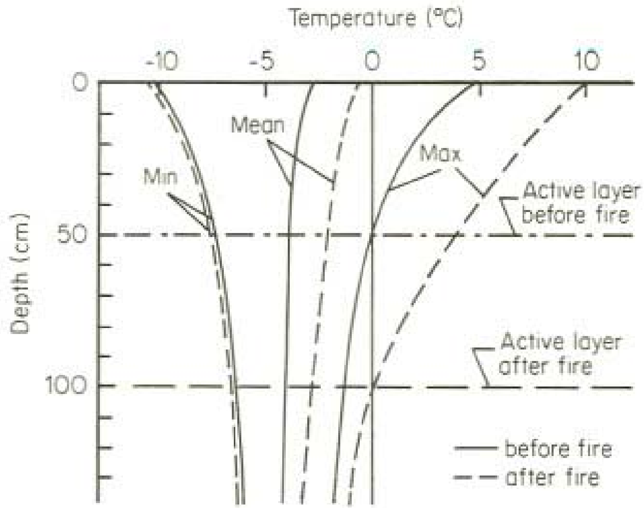

Figure 6.5 Typical permafrost ground temperature regime before and after fire

Several years after a fire, as the active layer increases in thickness, the 0°C isotherm penetrates more deeply and summer ground temperatures are higher by several degrees (up to 5°C) (Figure 6.5). The decreased organic matter cover permits the active layer to freeze more rapidly than normally in the autumn, especially before the snow cover becomes appreciable. Winter ground temperatures tend to remain the same unless there has been a change in the snow cover. This may occur where there was high snow catch in dense tree growth before the fire. Afterwards the increased thickness of the snow cover on the ground could raise the underlying winter temperatures by a degree or so. The net effect, however, is for the amplitude of the near-surface ground temperatures to increase to the maximum side of the envelope, and the active layer therefore must deepen until a new equilibrium thickness is established. This is affected by the gradual but steady regrowth of the vegetation cover through the years.

A problem with burning, especially in organic soil areas, is the possibility of subsurface smouldering in the root systems of trees or thick organic layers long after the fire appears to be out. The sustained, subsurface heat contributes to thickening of the active layer and increasing the near-surface ground temperatures.

6.4.3 Effects of Fire on the Ground-surface Energy Exchange

Even if the vegetation cover is not removed by fire, the blackening of the surface affects the ground-surface energy exchange regime, resulting in some deepening of the active layer and changes in the ground temperature regime as described previously. Changes in albedo of the ground surface have been reported, but consistency of values within a particular cover type is difficult to obtain because of variations in weather conditions and surface moisture at the time of observation. Sufficient long-term measurements of albedo are not yet available to provide reliable generalized values. Jackson (1959) and Davies (1962) measured albedo values at Schefferville, Quebec, of 12% for a spruce-lichen woodland, 10% for a closed crown forest, and 9% for burned areas in these two types. In lichen-tundra the albedo was observed to be 20–25% and 7% for a one-year-old burn (Petzold and Rencz, 1975). Other values include dense forest (14–19%), forest-tundra (15%), and tundra (15%). Observed albedo for burned tundra was 10% (Cailleux, 1974; Haag and Bliss, 1974; McFadden and Ragotzkie, 1967).

Evapo-transpiration is considerably affected by burning of the ground surface (Rouse, 1976; Rouse and Kershaw, 1971; Rouse and Mills, 1976). Whereas about 40% of the radiant energy provided by the sun is used for evapo-transpiration from a mature lichen woodland, for example, only about 30% goes into evaporation from burned areas. This is caused by a number of factors. The trees of the lichen woodland transpire freely, and are able to tap a large volume of soil for their moisture needs. The lichen does not transpire and water vapour must diffuse through the lichen mat, which is a slow process. Therefore, lichen woodland is intermediate between a lake and burned area in its magnitude of evaporation.

On newly burned areas, all water vapour must diffuse across the hot, bare soil surface. As the surface dries, its capillary conductivity is reduced, thus inhibiting the movement of liquid water to the surface. The very high soil temperatures favour vaporization beneath the surface, and the water vapour only slowly diffuses through the upper soil layers. The result is a strong resistance to evaporation. Similar processes inhibit evaporation from an older burn (e.g., 25 years), except that the non-transpiring moss presents the resistance to evaporation. The limited evaporation from burned areas combined with the increased absorption of solar radiation results in an increased sensible heat transfer to the lower air layers.

6.5 CONCLUSIONS

Few investigations have been carried out on the effects of fire on permafrost and quantitative data are therefore scarce. The permafrost is apparently little influenced by the heat of the fire itself. However, long-term effects are substantially more important and include a general thickening of the active layer, a rise in soil temperatures, and changes in the ground-surface energy regime. The studies conducted in recent years have improved our knowledge of the important relationships between fire and permafrost, a unique component of northern ecosystems. More detailed quantitative investigations, extending over many years, are required to monitor changes in the active layer, ground temperatures, and the surface energy exchange from the time of burning to restoration of the vegetation cover.

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