

Effect of Wildfire and Fireline Construction on the Annual Depth of Thaw in a Black Spruce Permafrost Forest in Interior Alaska: A 36-Year Record of Recovery

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Abstract

Maximum thaw depths were measured annually in an unburned stand, a heavily burned stand, and a fireline in and adjacent to the 1971 Wickersham fire. Maximum thaw in the unburned black spruce stand ranged from 36 to 52 cm. In the burned stand, thaw increased each year to a maximum depth of 302 cm in 1995. In 1996, the entire layer of seasonal frost remained, creating a new active layer depth at 78 cm. An unfrozen soil zone (talik) remained between the two frozen layers until 2006 when the entire profile remained frozen. Permafrost returned to the burned site by the formation of a layer of seasonal frost that remained frozen through subsequent years. The fireline displayed a similar pattern with a maximum thaw of 266 cm in 1995 and the establishment of a continuous frozen layer at 69 cm, but the upper frozen layer became discontinuous after several years.

Keywords: active layer; boreal forest; disturbance; fire effects; permafrost.

Introduction

The 1971 Wickersham fire burned 6313 ha in an open black spruce (*Picea mariana* [Mill.] BSP) forest underlain with permafrost in the boreal forest of interior Alaska. As a part of the fire suppression effort, 113 km of fireline were constructed with heavy equipment which removed most of the organic layer and resulted in an increase in depth of thaw. This fire provided an opportunity for long-term studies of the effects of fire and fireline construction on the rate and pattern of permafrost degradation and subsequent recovery. The annual thawing of the active layer in undisturbed vegetation at the site was also documented and vegetation change following the fire was observed. This is one of the longest records of annual active layer measurements in the boreal forest of North America (Brown et al. 2000). Initial results of this study were reported 12 years after the fire (Viereck 1982) and again 33 years after the fire (Viereck et al. 2004).

When wildfire burns through a northern black spruce forest, there is usually a subsequent increase in soil temperature and depth of thaw due largely to reduction in organic layer depth and subsequent loss of thermal insulation (Van Cleve & Viereck 1981, Mackay 1995, Swanson 1996, Burn 1998). Reduced heat loss from decreased evapotranspiration and a lowering of the surface albedo after wildfires also contribute to higher ground surface temperature and an increase in active layer thickness (Mackay 1995, Burn 1998, O'Neill et al. 2002).

We hypothesized that a continuous increase in the active layer would occur initially at the burned site, followed by the

return of a shallow active layer by a gradual freezing back from the lower depth (Fig. 1).

This long-term study presents results of 36 years of annual measurements of the active layer in a burned black spruce site, a fireline in which the organic layer was removed, and in an adjacent undisturbed black spruce forest underlain by ice-rich permafrost. The purpose of this paper is to compare annual depth of thaw among these three sites and to document the recovery of vegetation, soil organic layers, and permafrost after fire and fireline construction.

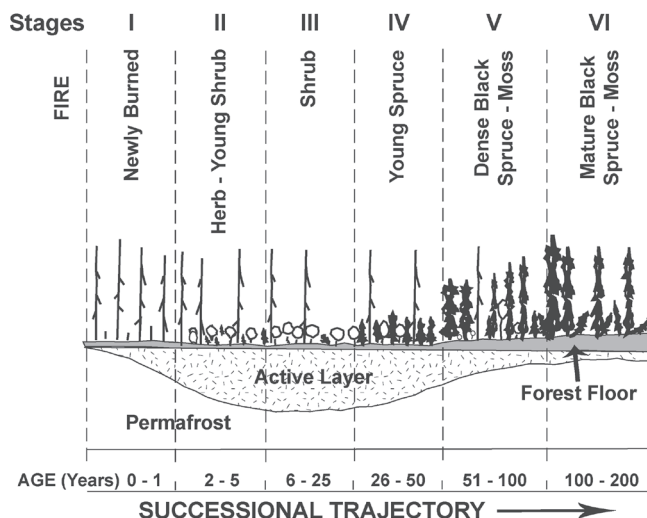


Figure 1. Succession model showing vegetation and active layer changes in a burned black spruce stand. Model modified from Van Cleve & Viereck (1981).

Methods

Study area

The Washington Creek Fire Ecology Research Area, located 50 km northwest of Fairbanks in interior Alaska (65°10'N, 147°54'W, 335 m elevation), was established to study the effects of the June 1971 Wickersham fire. The fire was ignited by lightning and burned 6313 ha in an open black spruce stand underlain by permafrost (Viereck & Dyrness 1979).

The vegetation prior to the fire was a 100- to 150-year-old open black spruce/lichen stand with a moss-derived organic layer 25 to 30 cm thick. The burn severity was originally classified as heavy, but later reduced to moderate. All of the trees and above-ground parts of the mosses, lichens, herbs, and shrubs were killed by the fire, but below-ground parts of some herbs and shrubs remained alive. Approximately one third (10 to 15 cm) of the organic layer was removed by the fire (Viereck & Dyrness 1979). At the time of the fire (June 24–30), the organic layer would have been thawed to only 20 to 30 cm. The soil is in the Saulich series with an active layer that varied from 40 to 50 cm.

Climate

Continuous climate records are not available from the site; the long-term weather record was obtained from the Weather Bureau's Fairbanks airport site. The Fairbanks record was compared with short-term climate studies at the Wickersham site. These include weather records kept at the study site from November 1971 to September 1980 and at the adjacent Washington Creek Fire Ecology Research site from January 1977 to September 1999.

From these records, we have estimated that the mean annual temperature at the Wickersham site is 1°C to 2°C colder than at the Fairbanks airport. Summer months tend to be cooler than Fairbanks, but winter months are warmer because of the lack of a cold inversion layer present during extreme cold spells in Fairbanks (Viereck 1982). The air temperatures at the Fairbanks airport have risen considerably during the period of this study (Hinzman et al. 2006). Since air temperatures at other weather stations in interior Alaska have also risen (Osterkamp & Romanovsky 1999), air temperatures at the Wickersham site are likely to have warmed, but there are no recent measurements to confirm this.

Maximum snow depths for each year at the Fairbanks airport are reported here. Based on only two winters of snowfall records available from the Wickersham fire (1977 and 1980), snow accumulation at the study site is usually about 25 cm greater than in Fairbanks (Viereck 1982).

Experimental design

A 25 m wide fireline was constructed up and down the slope between a heavily burned black spruce stand and an unburned stand, which before the fire was continuous and very similar to the stand that was burned. Most but not all of the organic layer was removed by the bulldozers in the construction of the fireline.

Three study sites were established in: 1) the heavily burned stand, 2) the fireline where vegetation and organic material were removed down to the frozen layer, and 3) the adjacent unburned black spruce stand that served as a control to compare the fireline and burned areas. At each site, 10 permanent probe points were established at 2 m intervals across the slope and perpendicular to the fireline. Maximum thaw depths were measured annually from 1971 to 2006 at each sample point using a metal probe.

A permanent transect of fixed points at 1 m intervals was established across the fireline from the burned stand on the north side to the unburned stand on the south side. At the center of this transect were ten poles that were used as probe sites to obtain the average thaw for the fireline. Across the entire width of the fireline, active layer depths were measured annually. Levels to the soil surface of the transect were made with a theodolite at intervals of three to five years, and changes in surface level relative to a fixed point were measured. Using these surface levels, it was possible to plot the profile of the surface and the depth of the active layer annually across the transect.

In 2002, a 6.5 m deep borehole was drilled in the burned site and a string of thermistors installed at 25 and 50 cm intervals to record temperatures. These temperatures have been logged both manually and with a logger at intermittent periods between 2002 and the present.

Vegetation

The vegetation of each of the sites was recorded at varying intervals. In the early years of the study, the vegetation of the burned and unburned stands was determined with a 20-plot system (Viereck 1982). In 1980, 1995, and 2004, vegetation of the burned, unburned, and fireline sites was measured by plots centered on the ten active layer probe sites. Moss, lichen, herb, and shrub percent cover was measured in 1 m² plots centered on the probe poles. Shrub cover was measured on 4 m² circular plots centered on the probe poles. Tree density and diameters were measured on larger circular plots.

Organic layer thickness

The thickness of the organic layer was originally measured in the 20 vegetation plots in the burned and unburned stands. Organic layer thickness of the fireline transect was assumed to be negligible at the beginning of the study. Organic layer thickness was remeasured along the probe lines in 1980, 1995, and 2004.

Results

Vegetation

The general vegetation type is a black spruce/moss/lichen community (*Picea mariana* / feathermoss / *Cladonia*—open needleleaf forest community) (Viereck 1982). Previous to the fire, the vegetation consisted of an open canopy of black spruce with an average diameter of 5.2 cm at 1.3 m height, a density of 1240 trees/ha and 45% canopy cover. In 1971, the age of most of the trees was 70 years, but there were a few scattered trees of 135 to 140 years in the stand. There

was an open tall shrub layer of *Salix pulchra* and *Betula glandulosa* and a low shrub layer of *Ledum groenlandicum* and *Vaccinium vitis-idaea*. The moss and lichen layer was made up primarily of *Pleurozium schreberi* and scattered *Sphagnum* species, and several species of *Cladonia* and *Peltigera* (Viereck 1982).

Unburned control site: Vegetation data recorded in 1980, 1995, and 2004 at the control site showed that the stand did not change significantly during that period and was similar to that recorded in 1971. Cover of the black spruce canopy was 22% in 2004. There was an open tall shrub layer of 8% mostly of *Salix pulchra* and *Betula glandulosa* and a low shrub layer of 47% *Ledum groenlandicum* and *Vaccinium vitis-idaea*. The moss and lichen layer of 95% cover was made up primarily of *Sphagnum girgensohnii*, *Pleurozium schreberi* and *Cladonia rangiferina*.

Burned site: Revegetation was slow for the first 9 years following the fire, probably as a result of the 10 to 20 cm organic layer that remained after the fire and provided a poor seedbed for invading pioneer species (Viereck 1982). Early revegetation was primarily from roots and underground rhizomes that had survived the fire. *Equisetum sylvaticum* and *Calamagrostis canadensis* and an occasional *Epilobium angustifolium* provided nearly 70% cover by 1980. Early successional mosses, *Ceratodon purpureus* and *Polytrichum juniperinum*, covered 35% of the surface. A few black spruce seedlings had become established, but provided less than 1% cover.

From 1980 to 2004, development of the site toward a mature black spruce stand continued at a somewhat faster pace. Black spruce reestablished with a cover of 17%. The tall shrub cover of *Betula glandulosa* and *Salix pulchra* reached 12%, while a low shrub layer primarily of *Ledum groenlandicum* and *Vaccinium vitis-idaea* developed a cover of 40%. The herbaceous layer of 55% cover is still dominated by *Equisetum sylvaticum* with some scattered clumps of *Calamagrostis canadensis*. The moss layer with 55% cover is still dominated by *Polytrichum juniperinum*, but feather mosses have developed a combined cover of 20%. Although *Ceratodon purpureus* has disappeared from the stand, the first small clumps of *Sphagnum* species (<1% cover) are now present in the stand. There has not been a significant return of any lichens to the stand after 36 years.

Fireline site: Invasion of herbaceous species and shrubs by seed was rapid in the first nine years after the fireline construction because of the exposed mineral soil and the wet condition of the surface. Herbaceous species of wet habitats accounted for nearly all of the 52% herbaceous cover. Since 1980, the herbaceous cover has been reduced drastically to 31% in 1995 and 18% in 2004. Tall shrub cover was nearly constant at 33% to 36% from 1980 to 2004. The moss layer changed dramatically throughout the 36-year period. Total moss cover dropped from 75% in 1980 to 44% in 2004. As of 2004, no lichens had established on the fireline. Although a few black spruce seedlings established near the edge of the fireline transect in the first few years following the fire, they had achieved a cover of only 4% by 2004.

Organic layer thickness

Unburned control site: The study area, situated on Saulich silt loam soils, originally had a combined organic layer thickness of 25 to 30 cm at the time of the fire (Viereck 1982). The profile was comprised of decaying mosses and litter (O1 and O2 layers). The organic layer of the unburned control stand was measured again in 1980 and 1995. The organic layer consisted of mosses and peat, formed primarily of *Sphagnum*. The average thickness of these layers was 33 cm, ranging from 16 to 45 cm.

Burned site: In the burned stand, the fire removed an average of 10 cm of the organic layer, although depths were variable (Viereck 1982). In 1980, the organic layer consisted of a 0 to 3 cm thick moss layer overlying a 1 to 2 cm layer of dark humus. By 1995, the organic layer consisted of 3 cm of mosses, primarily *Polytrichum* species, overlying 5 cm of dry, decaying mosses and the previously developed 2 cm layer of humus for a total organic layer of 10 cm. In 2004, the organic layer still consisted of 3 cm of moss, but the decaying moss layer had decreased to 3 cm and the humus layer had increased to 6 cm, for a total organic layer of 12 cm.

Fireline site: The irregular organic layer of the fireline is difficult to characterize. Although most of the organic layer was removed by the fireline construction, pockets and areas of the original humus layer remained. The surface of the fireline remained very wet, and several semi-aquatic mosses and *Sphagnum* species developed quickly. By 1980, the organic layer consisted of approximately 5 cm of live and decaying mosses overlying 4 to 5 cm of humus, for a total organic layer of 9.3 cm. The overall organic layer thickness was less in 1995 with a small decrease in both the moss and the humus layers. However, by 2004, the overall organic layer had increased to 12 cm. Although the humus layer had decreased since 1995, a fibrous layer of decayed sedges and grasses had developed to account for the increase.

Active layer thickness

The primary objective of this study was to document the changes in the annual depth of thaw (the active layer) following the 1971 fire (Fig. 2).

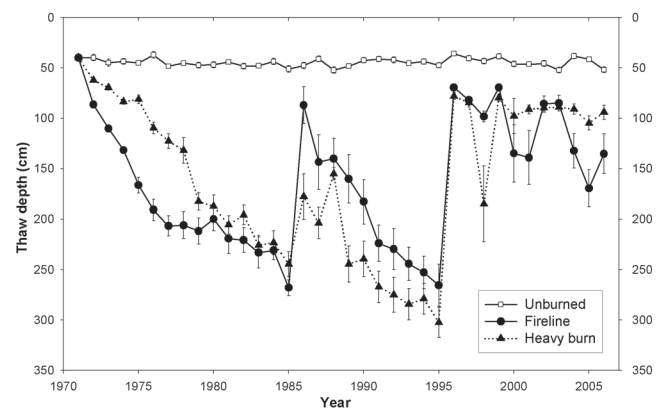


Figure 2. Maximum thaw depth of an unburned black spruce stand, a burned black spruce stand, and a fireline from 1971 to 2006. Values represent the mean ($n = 10$) and standard error.

Unburned control site: Maximum thaw ranged from 36 cm in 1996 to 52 cm in 1988, 2003, and 2006. The average thaw depth over the 36-year period was 45 cm. There was a tendency for deeper thaws to be associated with higher snowfall the previous winter and higher thawing degree days the following summer. For example, the minimum thaw depth of 36 cm in 1996 followed a previous cold winter with low snowfall through the month of January.

Burned site: Annual maximum thaw depth increased rapidly in the first 14 years following the fire to a maximum depth of 245 cm in 1985. In 1986, however, seasonal frost remained in 3 of the 10 probe sites resulting in an average thaw of 178 cm. An upper layer of frozen soil remained at some of the probe sites for the next 2 years resulting in an average thaw of only 155 cm in 1988. These upper layers melted out completely in 1990 and the depth of thaw continued to increase to 302 cm in 1995. In 1996, following a winter with light snow and cold temperatures, the upper seasonal frost layer remained at all 10 probe sites, giving an average thaw of only 78 cm. This upper layer has remained frozen, except in 1998 when 4 of the probe sites reached the bottom thaw layer of over 300 cm, to give an average thaw depth of 185 cm. From 1998 to 2006, the upper layer has remained frozen, and the thaw depth has ranged from 80 to 105 cm.

Mean annual temperatures and snow depths from the Fairbanks International Airport (Fig. 3) show that the two summers when seasonal frost first remained (1986 and 1996)

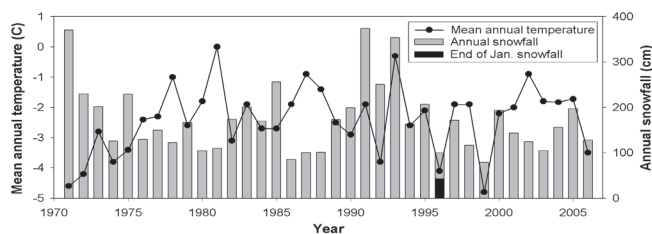


Figure 3. Mean annual temperature and mean annual snowfall for Fairbanks, Alaska from 1971 to 2006.

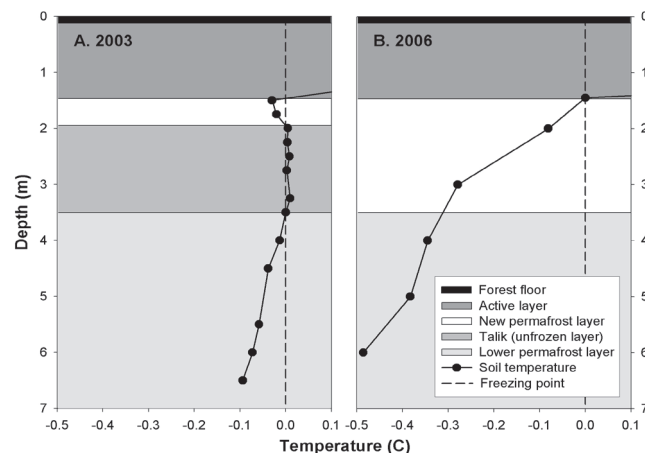


Figure 4. Soil temperature profiles from the burned site borehole, A) 2003 profile shows a new frozen layer approximately 50 cm thick extending from 1.4 to 1.9 m below the active layer, B) 2006 profile shows complete freezing of the talik and new permafrost extending 1.45 m below the present active layer.

followed winters of low snowfall. In addition, 1996 had a below average mean annual temperature.

Fireline site: For the first 25 years following the fire, the thaw depth under the fireline followed much the same pattern as the burned site. There was an annual increase in thaw depth from 1971 to a maximum of 268 cm in 1985. In 1986, the upper layer of seasonal frost remained frozen across the entire fireline. For the next six years, the upper seasonal frost layer began to thaw, and the number of probe points that penetrated through to the lower frozen layer increased from three in 1987 to all ten of the probe points in 1992, when the thaw depth approached the pre-1986 level. This condition continued until 1995 when a thaw depth of 266 cm was recorded.

In 1996, a winter of light snow and below average temperatures (Fig. 3) resulted in a seasonally frozen layer that persisted throughout the following summer. The average depth of thaw in 1996 was only 69 cm. Unlike the burned area, the shallow layer of frozen soil did not remain along the probe line. From 1997 through 2006, there was an increase in the number of probe points that reached the pre-1996 level. By 2006, only 2 points along the probe line had thaw depths less than 100 cm, and the average thaw depth of all 10 points was 135 cm.

At this time, it is impossible to predict if the upper frozen layer will continue to melt or if a light snow year with cold temperatures, such as occurred in 1996 and 2006, will result in the reestablishment of a continuous upper frozen layer.

Borehole profile

The thickness of the upper frozen layer was impossible to determine using our probing method. In 2002, we drilled a 6.5 m deep borehole in the burned site near the probe line and installed a series of thermistors to obtain temperatures throughout the soil profile.

A temperature profile from the borehole during the period of maximum thaw in September of 2003 (Fig. 4A) shows an active layer of 1.4 m. The new frozen layer was approximately 50 cm thick and extended from 1.4 to 1.9 m below the current active layer. This new permafrost layer divided the active layer and the talik formation. The talik temperatures were very close to 0°C. Below 3.4 m, the temperatures of the original permafrost layer decreased to -0.1°C at the bottom of the borehole (6.5 m). The lower permafrost depth stabilized at 3.5 to 4.0 m, and an unfrozen soil zone (talik) remained between the two frozen layers. However, in September of 2006, the temperature profile (Fig. 4B) shows the disappearing talik layer. The permafrost temperature at 6 m depth is more than 0.3°C colder after 3 years. The new permafrost development, since 1996, accelerated the refreezing of the talik layer. As a result of the three years of permafrost aggradations, the ground temperature profile is becoming similar to the pre-fire thermal conditions.

Fireline cross section

To better understand the changes in thaw depth across the fireline, cross sections of the fireline were measured

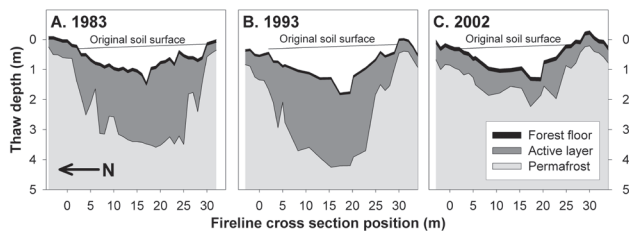


Figure 5. Cross section of the fireline in A) 1983, B) 1993, and C) 2002, showing considerable lowering of the original surface, and the reestablishment of permafrost in an uneven band across the entire fireline.

periodically during the 36 years of the study. Changes prior to 1980 are described by Viereck (1982). Figure 5 shows the cross section in 1983; 1993, when thaw was near the maximum; and 2002, the most recent cross section where the new layer of seasonal frost had persisted.

Surface: Figure 5 shows a considerable lowering of the surface level over time through subsidence and erosion. In 1983 (Fig. 5A), the surface lowered about 1 m through erosion and subsidence with slightly more on the northern side of the fireline. By 1993 (Fig. 5B), a small intermittent stream that formed from water captured upslope in the fireline had created a ditch that was approximately 75 cm deeper than the surrounding surface. The 2003 profile of the surface (Fig. 5C) shows that there has been some filling of the ditch and a slight rise in the surface of the fireline, which may be the result of vegetation buildup, deposition, and expansion due to the refreezing of water into ice in the newly frozen upper layer.

Depth of thaw: The cross sections in Figure 5 show that the depth of maximum annual thaw and the reestablishment of permafrost occur in an uneven band across the fireline. In 1983 (Fig. 5A), the deepest thaw occurs near the middle of the fireline beneath the small stream. There is a very steep rise of the permafrost on the south side of the fireline, due perhaps to the shading of that side of the fireline by trees to the south. The cross section in 1993 (Fig. 5B) shows that the thaw is fairly even across the middle of the fireline and rises sharply on both edges to the level of the active layer in the adjacent undisturbed vegetation. By 2002 (Fig. 5C), the upper surface of the newly developed permafrost is uneven, but in general follows the surface layer.

Estimated fireline cross section: Figure 6 illustrates a conceptual fireline cross section during the late 1990s and early 2000s, when the upper zone of permafrost (newly established in 1996) was intact. It shows the surface of the fireline, lowered through erosion and subsidence, and the uneven surface of the new upper frozen layer. The base of this layer is estimated from the measured thickness in the burn site (approximately 150 cm) at a similar period. Below this is an unfrozen layer of talik that is surrounded above and below by the permafrost in the adjacent unburned area. For the base of the talik, we have used the depth of thaw taken in 1995 when the thaw was at its deepest. Below the talik is the zone of permafrost that was there before the fire and reaches an unknown depth.

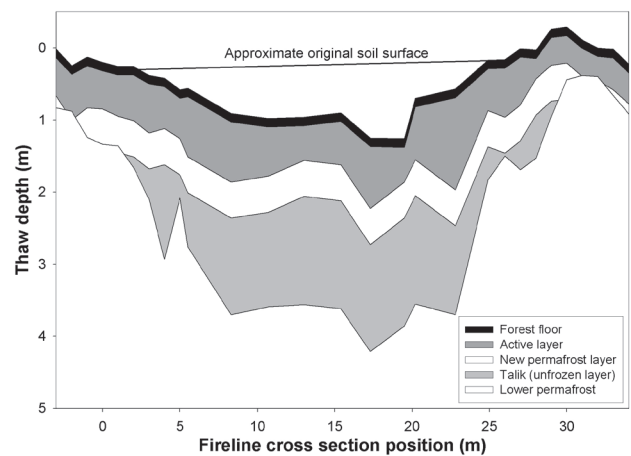


Figure 6. Conceptual fireline cross section during the period (1996–2003) that the upper zone of newly established permafrost was intact.

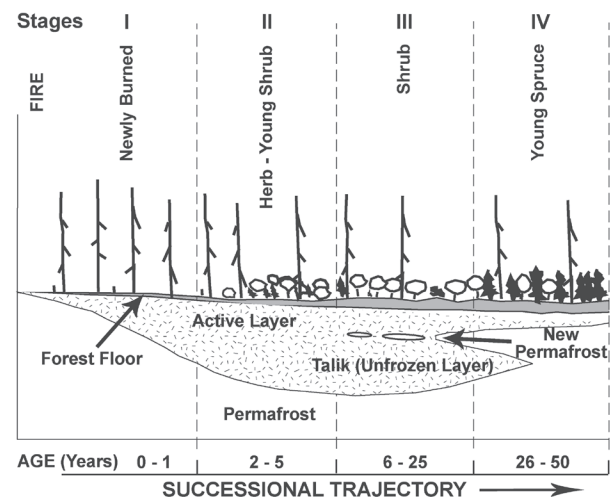


Figure 7. Successional changes observed in vegetation and the active layer at the burned site following the Wickersham fire.

Conclusion

Long-term observations such as those made on active layer and vegetation changes over the last 36 years at the Wickersham fire site are extremely valuable for developing an understanding of the effects of fire and fireline construction in the boreal forest of Alaska. We originally hypothesized that a shallow active layer would return to the burned site by a gradual freezing back from the lower depth (Fig. 1). We expected to observe a continuous increase in the active layer to a maximum depth during the first 30 to 50 years after the fire. Next, a gradual decrease in the active layer was expected to return the active layer to its approximate pre-fire depth 100 years following the fire. Other long-term measurements of active layer recovery following wildfire in the southern Yukon Territory (Burn 1998) and near Inuvik, N.W.T., Canada (Mackay 1995) reported that permafrost aggraded upward in a return to pre-fire conditions.

Surprisingly, a layer of seasonal frost formed at the Wickersham burned site that eventually remained frozen throughout the entire year and continued to remain frozen for

the next ten years (Fig. 7). The active layer did increase for the first 25 years following the fire as originally hypothesized. However, an upper layer of seasonal frost remained frozen 17 years after the fire and then became discontinuous for the next 10 years. Since 1996, the seasonal frost layer has remained frozen. This created a new permafrost layer with an active layer of 90 cm and an unfrozen talik layer between the upper and the lower frozen layers. This new permafrost layer accelerated the refreezing of the talik layer, and by 2006, the talik layer disappeared (Fig. 4B) and the permafrost has returned to the pre-fire thermal conditions.

Another important observation of this study is that under present climate conditions, permafrost is reforming at the Wickersham fire site on the burned stand but not on the fireline. The increased maximum thaw depth pattern for the two sites is similar, with a maximum thaw of 266 cm for the fireline and 302 cm for the burned site in 1995 (Fig. 2). Also, the development of an upper frozen zone in 1986 and 1996 was similar. The difference on the fireline is that the upper frozen zone has become intermittent, but it may be rejuvenated by another cold snowless year.

In addition to the permafrost differences at the burned and fireline sites, there is a significant difference in rate of vegetation recovery between the burned area and the fireline. The vegetation of the burned area is beginning to have many features of the original black spruce stand, whereas the fireline has remained very different with few features and species of the original stand.

Acknowledgments

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