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CRREL

Fate and Effects of Crude Oil Spilled on Subarctic Permafrost Terrain in Interior Alaska

Fifteen Years Later

Charles M. Collins, Charles H. Racine and Marianne E. Walsh

August 1993

Abstract

The effects of two large experimental oil spills conducted in the winter and summer of 1976 in the permafrost-underlain black spruce forest of interior Alaska were assessed 15 years after the spills. Effects on the permafrost, as determined from measurements of active layer thaw depths and of the total amount of ground subsidence, were far more pronounced on the winter spill because it had a larger area with oil on the surface. The winter spill also had a more drastic effect on the vegetation. Where the black, asphalt-like oil is present on the surface, black spruce mortality is 100% and there is very little live vegetation cover, except for cottongrass tussocks. Changes in oil chemistry vary with depth; surface samples show signs of microbiological degradation, whereas some subsurface samples taken just above the permafrost show no evidence of degradation and still contain volatiles.

Cover: Experimental oil spill site 15 years after the original spill.

For conversion of SI metric units to U.S./British customary units of measurement consult *Standard Practice for Use of the International System of Units (SI)*, ASTM Standard E380-89a, published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

CRREL Report 93-13

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

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PREFACE

This report was prepared by Charles M. Collins, Research Physical Scientist, Dr. Charles H. Racine, Research Ecologist, both of the Geological Sciences Branch, Research Division; and Marianne E. Walsh, Research Physical Scientist, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory.

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Fate and Effects of Crude Oil Spilled on Subarctic Permafrost Terrain in Interior Alaska
Fifteen Years Later

CHARLES M. COLLINS, CHARLES H. RACINE AND MARIANNE E. WALSH

INTRODUCTION

From 1975 through 1978, two large experimental oil spills in Caribou–Poker Creeks Research Watershed (Fig 1), 48 km north of Fairbanks, Alaska, were studied by CRREL researchers (Jenkins et al. 1978, Sparrow et al. 1978, Johnson et al. 1980) to see what happened when crude oil was spilled on the permafrost-underlain black spruce forest of interior Alaska. The experimental oil spills each consisted of 7600 L of Prudhoe Bay crude oil, with one spill taking place in February 1976 and the other in July 1976.

In 1990 we revisited these spills to assess their long-term effects on permafrost and vegetation, as well as long-term changes in oil chemistry. These experimental spill sites present unique opportunities to study the long-term effects of crude oil on a subarctic black spruce forest ecosystem with cold, wet, permafrost-underlain soils, since the oil was spilled under controlled conditions on a well-characterized site that has since remained undisturbed.

The discovery of oil at Prudhoe Bay on the North Slope of Alaska during the late 1960s led to the construction of the Trans-Alaska Pipeline System (TAPS), and the subsequent large-scale extraction

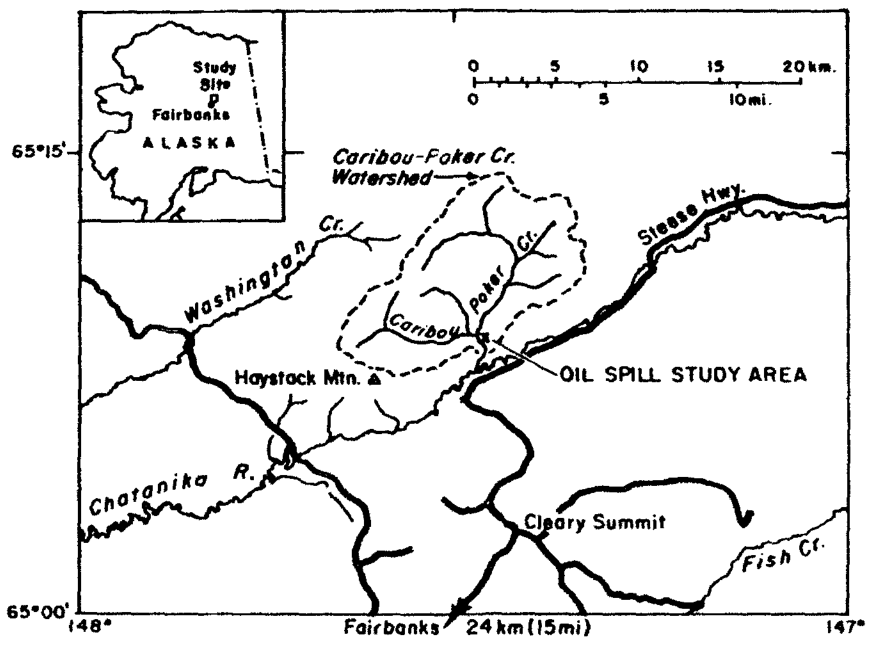


Figure 1. Caribou–Poker Creeks Research Watershed and experimental crude oil spill site.

and transport of crude oil overland through it. The discovery also created the possibility of crude oil spills on terrestrial ecosystems in cold regions. So, research was begun in the early 1970s to determine the effects of oil spills on vegetation, hydrology, and the physical, chemical and biological properties of soil in taiga and tundra ecosystems of Alaska and northern Canada (Deneke et al. 1974, Atlas and Brown 1978).

Most of these studies were short-term, generally less than 5 years, and were usually small scale, on the order of a few square meters (Dickman and Lunardini 1973, Wein and Bliss 1973, Everett 1978, Sextone et al. 1978, Walker et al. 1978). The 1976 CRREL study was one of the few that has tried to simulate the effects of large crude oil spills. Only the large (50 barrel [7950 L]) experimental point spill at Norman Wells, Northwest Territories, in 1973 also tried to simulate a large crude oil spill (Mackay et al. 1974a,b, Mackay et al. 1975, Hutchinson et al. 1976, Hutchinson and Freedman 1978, Hutchinson 1984). Prior to these two studies, few had examined the long-term effects of large crude oil spills on northern terrestrial ecosystems.

Results of previous CRREL study

Scientists from CRREL started the research program in 1975 on a site that is typical of valley lowlands and north-facing slopes in interior Alaska where discontinuous permafrost occurs. Open, low-growing black spruce *(Picea mariana)* forest with an understory of "sphagnum mosses, sedges, grasses, and heath or ericaceous shrubs covers much of interior and south-central Alaska, occurring on poorly drained, cold wet soils" (Viereck and Little 1972).

The objectives of the original study at Caribou-Poker Creeks Watershed were to:

1. Document the *physical effects* of crude oil spills on a black spruce forest in interior Alaska, emphasizing a) the mode of transport, b) changes in the size and shape of the affected area with time, and c) the effects on the underlying permafrost.
2. Determine the *chemical fate* of crude oil spilled in subarctic terrestrial environments.
3. Determine the effect of crude oil spills on *soil microbial populations*.
4. Evaluate the effects of crude oil spills on *vegetation*.

To meet these objectives, CRREL conducted the two experimental crude oil spills on 26 February and 14 July 1976. The oil was heated for each spill to 60°C in a closed tank, approximately the operating temperature of the pipeline. The oil was spilled through a 5-m-wide perforated pipe header at the top of 10- × 50-m test plots and allowed to flow freely downslope. The oil spilled in the winter flowed mostly along the frozen ground surface, going below the surface only in the spring as the ground thawed. By 1978 total area covered by the winter spill was 188 m^2 with 40% of the winter spill area (75 m^2) having surface oil visible. In contrast, most of the crude oil spilled in the summer flowed into the ground and then spread downslope to produce a large, subsurface oiled area. The summer spill covered 303 m^2 with only 10% of the area (30 m^2) having visible surface oil (Johnson et al. 1980). Figure 2 is a plan view of the winter and summer experimental spills showing the surface and subsurface oiled areas.

The site was studied intensively prior to and for 3 years following the oil treatments. By the third season after the spills, average seasonal thaw depths to permafrost increased to 70 cm in the winter spill, with areas having oil-blackened surfaces increasing to as much as 88 cm, versus 57 cm for the undisturbed control site (Johnson et al. 1980). There was little or no change in the composition of the crude oil in the soil, except for the loss of volatiles near the soil surface. There was no evidence of rapid biological degradation of the oil. Within the areas where the oil flowed on the surface, vegetation mortality was virtually complete; damage to vegetation overlying subsurface flows was delayed and far less extensive. Overall soil microbial activity was increased, with some components of the microbial population growing while others declined in the areas heavily affected by the oil (Sparrow et al. 1978).

Since the initial studies, there has been no comprehensive reevaluation of the long-term effects of the oil over the ensuing 15 years; neither vegetation changes nor compositional changes in the crude oil have been assessed. Collins (1983) found that thaw depths under the spill-affected areas were still increasing 6 years after the spill; whether ground temperature equilibrium had been reached was not known. Sparrow and Sparrow (1988) studied selected soil chemical and microbiological properties in the heavily affected portions of the site; they found that microbial biomass and activity and nutrient recycling were lower than in the control plot.

Since this site has remained undisturbed since the spills, except for minimal disturbance by scientific observations and sampling, it allows us to monitor long-term vegetation, permafrost and crude oil chemistry changes. By monitoring this site, the resiliency of this ecosystem and its ability to recover from a crude oil spill disturbance can be better understood.

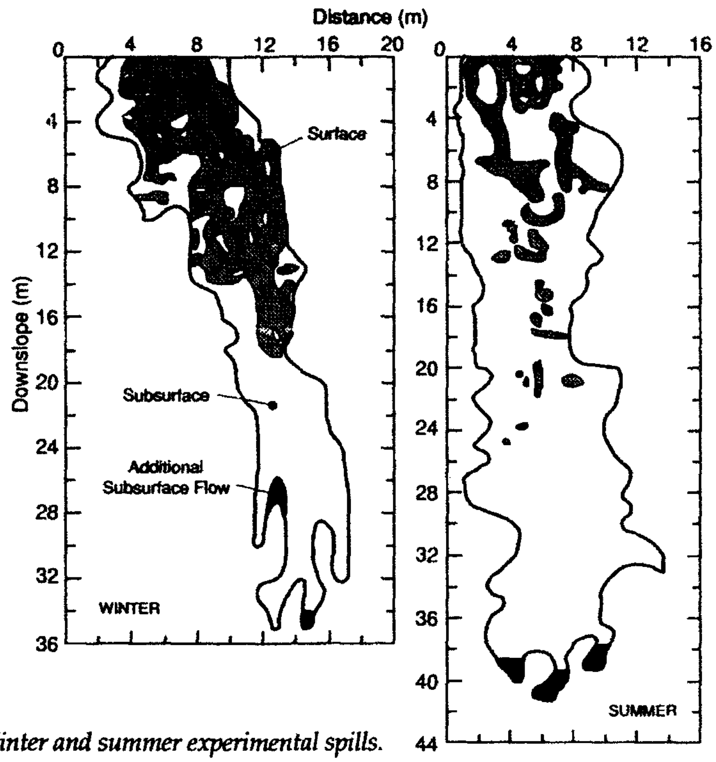


Figure 2. Winter and summer experimental spills.

Objective of the present study

Our specific objective was to document long-term changes in the two oil spills after 15 years. We were interested in any additional physical movement of the oil downslope, below the furthest extent of the oil spill as documented in Johnson et al. (1980), as well as vertical movement of the oil down into the soil horizon. We wanted to evaluate additional effects on the underlying permafrost, and to document the long-term chemical fate of the oil to see if it had degraded and changed over time. We also wanted to document long-term effects on the vegetation and see if there had been any recovery after 15 years.

METHODS

Site description

The study area is located in the Caribou–Poker Creeks Research Watershed (Fig. 1). For the original study, two 10- by 50-m plots, with their long axes oriented downslope, were established on a west-facing, low-angle (7%) slope, east of the confluence of Caribou and Poker creeks. A control plot was located just upslope of the two spill plots. The two study plots were widened after the spills to completely encompass the boundaries of the spills, the summer spill to 12 m, the winter spill to 16 m. Catwalks were laid out across the plots every 5 m to allow access to their interiors without unduly disturbing the vegetation (Fig. 3). A coordinate system was used to map oil distribution in the plots, sample locations and vegetation plot locations. The coordinates were based on the distance across the plot followed by distance down the plot starting from an origin point at the upper left hand corner of the plot as one looked upslope. Thus, a coordinate of (W-5,17) would be a point on the winter spill plot 5 m to the right and 17 m down from the origin point.

The vegetation in the study area is an open black spruce (*Picea mariana*) forest (Fig. 3). Small black spruce trees do not exceed 12 m in height and 20 cm in diameter and the total tree canopy cover is less than 60%. Shrubs 0.6 to 0.7 m tall include resin birch (*Betula glandulosa*) and willow (*Salix* spp.), with lower shrubs, 0.3–0.5 m, of Labrador tea (*Ledum decumbens*) and blueberry (*Vaccinium uliginosum*). The ground surface is covered with mosses and lichens, with scattered (10%) cotton grass tussocks (*Eriophorum vaginatum*) (Johnson et al. 1980). The organic moss and peat layer can be up to 30 cm thick and is composed of *Hylocomium* spp., *Pleurizium* spp., *Polytricha* spp., and *Dioiarum* spp.

This type of open black spruce forest occupies over 50% of the land area in interior Alaska (Neiland and Viereck 1977). Wildfires are important in the succession of forest types in interior Alaska and the site was likely burned within the last 75 years.

Figure 3. Experimental spill plot, viewed downslope.

The study area is underlain by permafrost, with an active layer thickness of 40 to 60 cm in undisturbed areas. The soil is cold and wet, a Histic Pergelic Cryaquept (Rieger 1983), typical of the Saulich Series soil found on the lower slopes of the watershed (Rieger et al. 1972). A representative soil profile consists of a 5-cm surface layer of moss and lichen above a 15-cm horizon of undecomposed fibrous peat (O1). This lies above a 5-cm horizon of decomposed dark brown to black organic peat (O2), which is above a 5-cm horizon of very dark grayish brown silt loam that is mixed with organic peat (A1). Below this is grayish brown silt loam mineral soil (C2). The silt loam mineral soil is at least 3 m thick over shattered schist bedrock, but thins to less than 1 m over shattered bedrock uphill from the study area. The bottom of the seasonal thaw zone or active layer in the study area generally is just below the A1/C2 horizon boundary. The mineral soil within the active layer is saturated during thaw periods because of the underlying impermeable permafrost.

Physical movement of oil

Downslope movement

The rate and extent of oil flow downslope in each of the two spill plots were originally determined by probing the organic and soil layers on a 1-m grid with thin wooden dowels. The presence of the crude oil was readily discerned by sight and smell on the bare wood of the dowel. When questionable, the presence of oil was confirmed by UV-fluorescence (Jenkins et al. 1978). We again used wooden dowels to determine if there was any further downslope movement of the oil past the last mapped boundary. In addition, soil and organic layer samples were collected downslope of the mapped oil boundary. These samples were analyzed by solvent extraction followed by Gas Chromatography (GC) to determine the possible presence of oil components not detectable by physical inspection and probing by the wooden dowels.

Vertical movement

The vertical positions of oiled zones within the soil profile were noted when soil cores were taken to obtain samples for chemical analysis. Pits were excavated to observe relationships among oil locations, soil profiles and rooting regimes of various plant species.

Thermal effects of oil on active layer

Active layer thicknesses and changes in the depth of thaw were characterized in the original study by six cross sections laid out 1, 3, 6, 9, 14 and 20 m downslope from the spill point in each plot. Probes were made at 1-m intervals along these cross sections at the end of the thaw season when thaw depths were at a maximum, usually late September. We relocated each of the cross sections and measured the maximum depth of thaw using a metal probe rod at the end of the thaw season in late September 1990 and early October 1991. We measured the total amounts of ground subsidence (attributable to increased thaw depth and the melting of ice-rich permafrost) since the original spills by stretching a horizontal line across the spill plots at each cross section and measuring the distance down to the ground surface at 1-m intervals along the line.

Chemical analysis of oil

Sample collection

In early June 1991, four partially frozen soil cores were collected from both the summer and winter spill sites using a 3-in. (7.6-cm) SIPRE coring auger. One core each was collected in an area 1) where oil was visible on the soil surface; 2) with subsurface oil, immediately downslope from an area with surface oil; 3) with subsurface oil, several meters downslope from an area with surface oil; and 4) where oil was not detectable, downslope of the spill. The unfrozen portions of each core (generally the top 15 cm) were placed in 16-oz (475-mL) I-Chem glass sample jars and the frozen portions (generally from 15–30 cm) were placed in 1-qt (0.95-L) wide mouth glass canning jars. An additional sample was collected from the wall of the hole left by the auger by inserting a plastic corer (i.d. = 2 cm) horizontally at the interface of the organic and mineral soil layers (O2/A1 interface) and collecting a 20-mL core (Hewitt et al. 1992). This core, which was collected for headspace analysis of volatile organics, was immediately placed in a 1-oz (30-mL) I-Chem Septa-Jar™ and tightly sealed. An additional horizontal core was taken at each site, placed in a Whirl-Pak™ and submitted for sheen screen test analysis at the Northern Testing Laboratories to determine the presence of oil-degrading bacteria (Brown and Braddock 1990). All samples for chemical analyses were frozen and shipped to CRREL.

In August 1991, additional samples were collected for headspace analysis from the walls of the pits excavated to determine the vertical profiles of the oil.

Characterization of oil in soil samples

Volatiles. Samples that were collected for analysis of volatile organics were equilibrated at room temperature for 24 hours. Then, a 500-µL gas-tight syringe was used to sample the headspace. A sample of the original crude oil collected from a pool at the winter spill site on 15 June 1976 and stored in a freezer was placed in a Septa-Jar, equilibrated at room temperature, and the headspace sampled. All headspace samples were analyzed by GC under the following conditions:

1. Gas chromatograph: Hewlett Packard 5890 Series II equipped with a Flame Ionization Detector (FID).
2. Analytical column: J and W GS-Q gas-solid porous polymer open tubular Megabore column (30 m × 0.53 mm).
3. Oven temperature: programmed from 70°C (2-min hold) to 170°C (10-min hold) at 10°C/min.
4. Flow rate: 20 mL/min of helium carrier gas.

The output from the GC-FID was recorded on a Hewlett Packard digital integrator. Peak retention times in the chromatograms from soil samples were compared with those in the chromatogram from the original crude oil.

Extraction of oil from the soil. Frozen soil samples were subsampled using a knife or bandsaw. Each subsample was approximately 50 g. Oil was extracted from the subsamples and fractionated using methods similar to those used in the original study (Johnson et al. 1980). Successive 50-mL aliquots of chloroform were added to each subsample, which were allowed to stand for 15 minutes and then filtered into a beaker of known weight. The process was repeated until the chloroform extract was colorless or pale yellow. The chloroform was evaporated and the beaker was reweighed to obtain the mass of the oily residue. Nine samples that were collected on 19 July 1979 and stored in a freezer were also extracted for comparison.

Oil fractionation. Crude oil is a complex mixture of hydrocarbons composed mainly of alkanes (straight chains, branched chains and cyclic), aromatics (unsaturated cyclic hydrocarbons with one or more rings), asphaltenes (high molecular weight hydrocarbons) and Nitrogen, Sulfur and Oxygen containing compounds (NSOs). To determine the relative amounts of the major oil components, the oily residue extracted from each soil subsample was fractionated as follows. Approximately 0.25 g of the oily residue was deasphaltened with pentane and fractionated by silica gel-alumina column chromatography (Johnson et al. 1980a). The alkane, aromatic and NSO fractions were obtained by sequential elution of the column with pentane, toluene and methanol respectively. The amount of each fraction was determined gravimetrically after solvent evaporation.

The alkane fraction from each sample was dissolved in methylene chloride and characterized by gas chromatography under the following conditions:

1. Gas chromatograph: Hewlett Packard 5890 Series II equipped with an FID.
2. Analytical column: HP-1 (100% dimethylpolysiloxane) capillary column (25 m × 0.2 mm × 0.33 µm).
3. Oven temperature: programmed from 60°C (1-min hold) to 300°C (5-min hold) at 6°C/min.
4. Injection: 1-µL split (100:1), 275°C.
5. Carrier: nitrogen.

Ratios of pristane (2,6,10,14 tetramethylpentadecane) to n-C_{17} (heptadecane) were obtained by peak height measurements made on a Hewlett Packard 3396A digital integrator.

A limited number of the aromatic fractions were analyzed by gas chromatography/mass spectrometry under the following conditions:

1. Instrument: Hewlett Packard 5890 Series II gas chromatograph and Hewlett Packard 5970 mass selective detector (70-eV ionization voltage, mass scan range 29–400).
2. Column: HP-1 capillary column (12 m × 0.2 mm × 0.33 µm).
3. Oven temperature: programmed 75°C (3-min hold) to 275°C (5-min hold) at 7°C/min.
4. Injection: spiltless, 0.2 µL.
5. Carrier: helium, linear velocity 37.5 cm/s.

Vegetation

Before and after the 1976 spills, Johnson et al. (1980) characterized the vegetation of both the winter and summer plots using a number of 1-m-square quadrats aligned along each side of the centerline down through each plot. During June 1991 we were able to relocate several of these 1- × 1-m quadrats and used them to evaluate the condition and recovery of the ground cover, including mosses, lichens, shrubs and herbaceous species. L.A. Johnson visited the site in August 1991 with us and inspected several of his 1975 quadrats. He provided some baseline vegetation data as well as his evaluation of vegetation recovery after 15 years.

We determined the location, height and condition (ranked as living, dying or dead) of all black spruce growing in the surface and subsurface oiled areas of both the summer and winter plots, beginning at the top of each plot and extending downslope 20 m (the maximum downslope extent of spruce mortality). A dead spruce contained no live (green) needles or branches. A dying spruce contained at least one live branch but more than 50% of its foliage and branches was dead. The location of each spruce was recorded according to the *x* and *y* coordinate system and a map plotted that was overlaid on a map showing the distribution of surface and subsurface oil (Fig. 2). In this way each tree could be assigned a position in relation to the distribution of crude oil 1) within the area of surface oil, 2) within the area of subsurface oil, 3) at the edge between subsurface and surface oil or, 4) at the edge between no oil and subsurface oil. In addition, all *E. vaginatum* tussocks growing on areas having surface oil were counted, mapped and their height and diameter measured.

RESULTS

Physical movement

Horizontal distribution

For the original study (Johnson et al. 1980), maps of the distribution of the oil in each of the two spills were prepared showing the total extent of the spills and the areas where oil was visible on the surface. Figure 2 updates those maps, showing the maximum extent of the surface vs subsurface oiled areas as mapped in 1978 and the areas, newly mapped in 1991, of additional subsurface oil movement. The maximum additional downslope movement of the winter spill was 2 m along one lobe and approximately 1 m between two small lobes. The total increase in subsurface spill area was approximate 3 m^2. The maximum additional downslope movement of the summer spill was 1.5 m along one lobe and lesser amounts along two others, for a maximum increase in subsurface spill area of approximately 2 m^2. Thus, both spills had only very minor additional movement of oil downslope since 1978. The total area affected by the winter spill increased by 1.6% and the distance that the oil had moved downslope from the original spill point increased by 5.7%. The total area affected by the summer spill increased by 0.7% and the distance that the oil had moved downslope increase by 3.7%.

Vertical distribution

In general, the thickness of the oiled zone within the soil profile thinned downslope on both spills. In the areas of both spills where oil was on the surface, the oiled zone was thick, going from the surface down to mineral soil. The vertical distribution of subsurface oil varied from just beneath the living moss to a thin zone, 20 cm or more below the surface. The subsurface oil was generally located at greater depth downslope (more than 10 m downslope) than that oil which moved downslope above and within the decayed peat (O2) horizon, above the mineral soil. Near the downslope edge of both spills, the oiled zone is generally 20 to 30 cm below the surface and only 1 cm or so thick. The oil is confined to the O2 horizon, just above mineral soil. Only minor amounts of oil were visible along some roots penetrating down into mineral soil. Because the mineral soil is water saturated throughout the summer thaw season, located as it is just above impermeable frozen soil, the oil has not penetrated down into mineral soil to any appreciable degree, even after 15 years.

At 13.5 m downslope on the winter spill, within the surface oiled area, the oil was located from the surface down to 17 cm, just reaching the mineral soil horizon. At 21 m, just downslope of the leading edge of the surface oiled area at 18.5 m, the top of the oiled zone was just a few centimeters under the surface. Farther downslope at 23 m, the top of the oil was located 10 cm below the surface, at the interface between the undecomposed peat and more decomposed peat (O1/O2) horizons. Near the downslope end of subsurface oil (31.5 m), the oil was in the decomposed peat (O2) horizon between 15 and 21 cm. At 34 m downslope the oiled zone was even deeper, between 25–29 cm, but also in the O2 horizon. At 18 m downslope on the winter spill and off to the side of the surface oiled area, where there was only subsurface oil, it was entirely in the top centimeter of the mineral soil at 20 cm.

In general the subsurface oil on the summer spill tended to form a thicker band than on the winter spill and was generally closer to the surface; at 34 m downslope on the summer spill, two pits revealed an oil band between 7 and 18 cm below the surface. It is difficult to ascertain whether the oil has moved vertically any deeper on either spill since the earlier study because they made fewer observations of vertical movement then. The saturated mineral soil appears to serve as a limiting lower boundary for vertical penetration on both spills.

Thermal effects

Active layer thaw depths

The average thaw depths for each of the six cross sections in the winter, summer and control plots, as well as the average thaw depths for each plot based on the averages of the six cross sections in each plot, are summarized in Table 1. The thaw data are for the periods 1976–1982, 1990 and 1991, and they are based on maximum seasonal thaw depths obtained at the end of the thaw season each year. The average thaw depths for the winter, summer and control plots, based on the average of all six cross sections within each plot, are shown in Figure 4. The average thaw depths for the winter spill have consistently been the deepest of the three plots since the original spills.

Thaw depths were greatest in the first three cross sections of each of the two spill plots. This is also the region of the spills with the most surface oiled area (Fig. 5). The increase in thaw depths between 1982 and 1990 was most dramatic in the upper 6 m of the winter spill, with its very high percentage of surface oiled area (Fig. 2).

Thaw depths in the summer spill were shallower because of its smaller amount of surface oiled area.

Table 1. Average thaw depths (cm) for winter spill, summer spill and control plots.

	1976	*1977*	*1978*	*1979*	*1980*	*1981*	*1982*	*1990*	*1991*
Winter spill									
1*	55	73	88	115	125	137	126	181	193
3	54	67	81	102	111	122	119	163	171
6	54	67	75	86	91	100	100	130	141
9	50	56	63	72	76	83	81	128	110
14	45	53	58	64	67	69	67	70	64
20	47	53	55	56	58	60	58	70	64
Whole plot	51	62	70	82	88	95	92	124	124
Summer spill									
1	49	58	66	75	79	81	79	87	91
3	44	58	60	70	75	76	77	84	91
6	45	52	60	68	75	77	77	91	101
9	47	55	62	72	77	77	77	81	79
14	48	54	57	63	66	66	66	76	76
20	51	55	59	61	61	60	60	68	66
Whole plot	47	55	61	68	72	73	73	81	84
Control									
1		62	64	66	67	66	68	70	70
3		62	62	65	67	63	65	69	70
6		52	52	59	60	61	60	61	62
9		52	52	55	56	57	57	57	61
14		55	54	57	60	57	56	58	59
20		56	56	59	60	61	61	64	64
Whole plot		56	57	60	62	61	61	62	64

* Distance downslope (m) of cross sections.

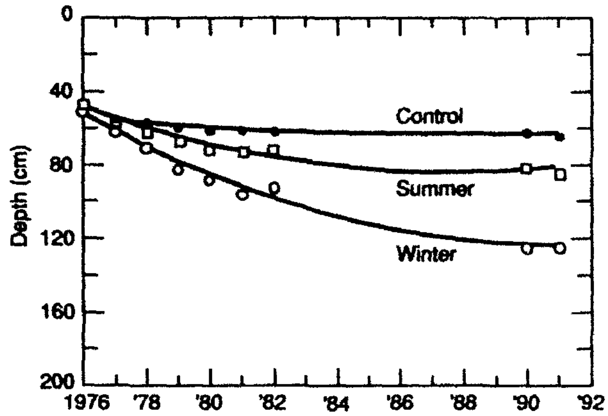


Figure 4. Average thaw depths for the winter, summer and control plots for 1976–1982 and 1990–1991.

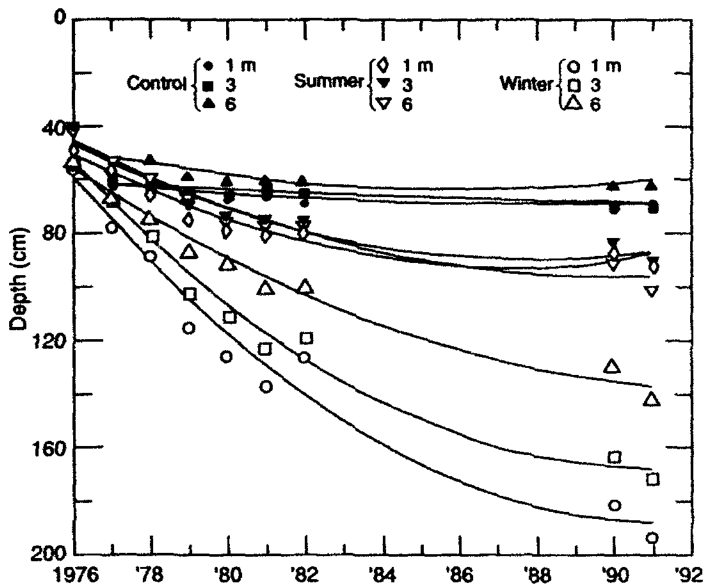


Figure 5. Average thaw depths for each of the first three cross sections of each of the plots.

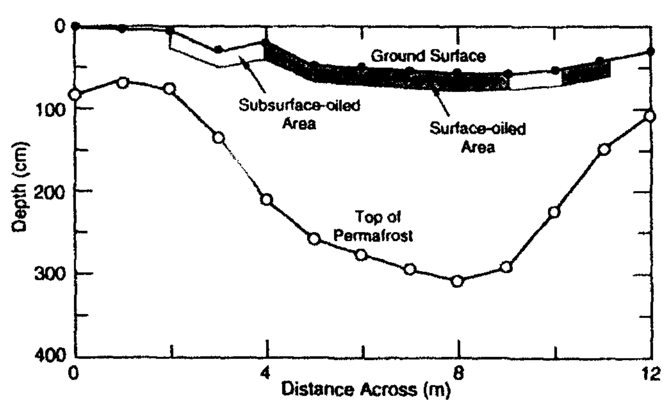


Figure 6. Profile of the 3-m cross section on the winter spill showing both the active layer thickness and ground subsidence.

The average thaw depths for the entire winter and summer plots may be reaching an equilibrium (Fig. 4). However, the thaw continues to increase in the upper 6 m of the winter spill. Equilibrium may not be reached here until natural revegetation reestablishes some of the insulation and shading lost.

The original ground surface subsides when ice-rich permafrost soil thaws as the active layer thickness increases because of changes in heat transfer at the surface. The increased heat transfer into the ground, owing to the much lower albedo of the oil-blackened moss surface, and the decreased insulation of the thinner, now dead, moss layer cause deeper thaw of the active layer. Subsidence is cumulative as the active layer continues to increase year after year, as has happened in the winter spill. The subsidence is greatest in the upper area of the winter spill, with its high percentage of oil-blackened moss. In the winter spill subsidence along the 1- and 3-m cross sections is as much as 60 cm. The total effect of the oil spill on permafrost soil would be the sum of the subsidence plus the increased thaw depth. Subsidence plus active layer depth is greater than 3 m along the 1- and 3-m cross sections of the winter spill. Figure 6 is a profile of the winter spill's 3-m cross section, showing both the active layer thickness and ground subsidence. Figure 6 also portrays (not to vertical scale) the subsurface and surface oiled areas of the cross section, showing the relationship between surface oiled area and maximum depth of thaw.

Chemical characterization of oil

Volatiles

The loss of volatiles is the first major process in the weathering of oil after a terrestrial spill (Johnson et al. 1980). No volatiles were detected in oil from pools on the surface or from oiled moss 17 months after the spill. However, volatiles were still detectable in the organic and mineral soils, indicating retention of these compounds longer than was originally thought probable (Sextone et al. 1978, Johnson et al. 1980).

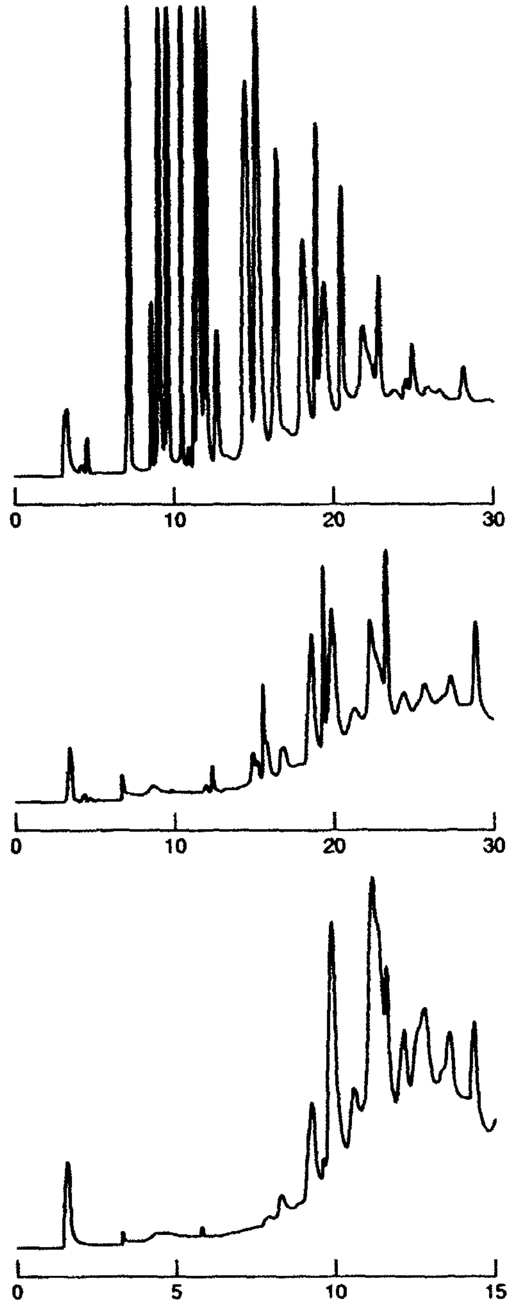
We collected samples at the O2/A1 soil horizon interface 15 years after the spill. In a sample from the area of the winter spill with subsurface oil that was 24 m downslope (W-14, 24), collected at a depth of 14 cm, volatiles (C_5 – C_9) were still detectable (Fig. 7). Two other samples, one collected in August 1991, 1 m away from the first sample, and a sample collected from the summer spill (5–7, 22), at a depth of 15 cm, also contained volatiles (Fig. 7). Retention of these compounds for this length of time was unexpected and indicates that the flux of air is very limited at certain locations in the spill area. The low-boiling compounds in crude oil are toxic to plants if there is contact between them and the plant's roots (Bossert and Bartha 1984). Since we found these compounds below the root zone, their toxic effect may be minimal on the shrubs and black spruce.

Compositional changes in major oil components

Previously (Johnson et al. 1980), relative changes in the composition of the oil with time were assessed using two different methods. For the first method, the ratio of the alkane to aromatic fraction was computed. Since the alkane fraction tends to degrade microbially at a faster rate than the aromatic fraction, this ratio should decrease over time as the oil degrades. For the second method, the ratio of pristane to n-C_{17} was used as an indicator of microbiological degradation. Since straight chain alkanes, such as n-C_{17}, are more easily metabolized than branched chain alkanes, such as pristane, this ratio is expected to increase with time. Johnson et al. (1980) reported "very little or no compositional change through the first two years after the spill with respect to these parameters." Therefore, as of 1978, microbial activity had not modified the alkane fraction of the oil to any great extent.

For samples collected in June 1991, the ratios of pristane to n-C_{17} (Table 2), as well as the gas chromatograms (Fig. 8), indicate significant compositional changes in some samples and almost no change in others. In general, samples collected close to the surface were more degraded than deeper samples. For example, at a surface oiled site on the summer spill (S-5,2) (samples 22–24), little n-C_{17} was detectable at the surface (0-8 cm); the pristane-to-n-C17 ratio was 10.6. At 8–15 cm depth, the pristane-to-n-C_{17} ratio was 1.03, while deeper at 15–23 cm, the ratio was 0.83. These ratios are all greater than the ratio of 0.55 measured for the original oil. Since alkanes are metabolized aerobically, the trend of decreasing pristane-to-n-C_{17} ratios with depth reflects decreasing oxygen availability. For the subsurface samples collected 24 m downslope (Fig. 2) on the winter spill at W-14,24 (samples 9 and 10), degradation of the oil was insignificant; pristane-to-n-C_{17} ratios were 0.79 and 0.53 at 8–14 and 14–16 cm. The presence of volatiles at this site confirms little compositional change in the oil.

The alkane-to-aromatic ratios did not reflect the change in the composition of the oil in the degraded samples, indicating that the aromatic fraction has also changed. The aromatic fraction of some sam-



a. Oil taken from a pool on the winter spill site on 15 June 76.

b. Oily soil from S-7,22 (15 cm deep) in August 1991.

c. Oily soil from W-14,24 (25 cm deep) in August 1991.

Figure 7. Headspace chromatograms.

ples was analyzed by GC/MS to identify which compounds have persisted. Samples analyzed included the original crude oil, two samples collected in July 1979, the two most heavily degraded samples (as indicated by the pristane-to-n-C_{17} ratio) collected in June 1991 (samples 18 and 22), and the least degraded sample collected in June 1991 (sample 10). Chromatograms (Fig. 9) show a significant change in the degraded samples (samples 18 and 22). Specifically, there is a decrease in the relative amounts of the lower molecular weight aromatics (naphthalenes) compared to the higher molecular weight aromatics (phenanthrenes). The highest peak in the chromatograms from each of these degraded samples was identified as 2,5-dimethylphenanthrene, a chemical known to be persistent in the environment.

Presence of oil-degrading bacteria

Four samples were analyzed using the sheen screen MPN procedure (Brown and Braddock 1990).

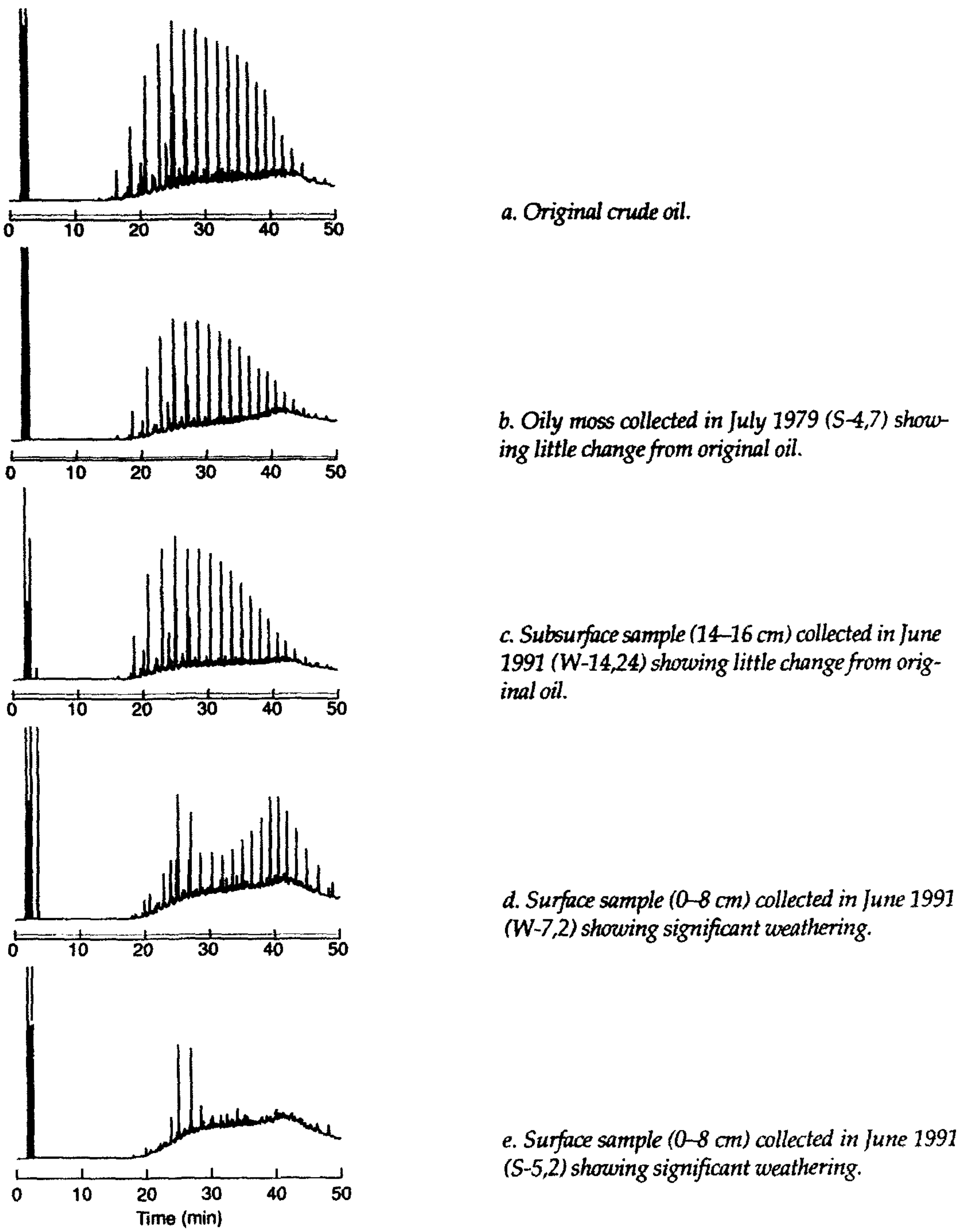


Figure 8. Chromatograms of alkane fractions showing composition of original crude oil and compositional changes in samples collected in 1979 and 1991.

The presence of oil-degrading bacteria is determined by inoculating media with a diluted sample in a microliter well plate. A sheen of sterile Prudhoe Bay Crude oil is applied and the samples incubated for 21 days. The wells are then examined for disruption of the oil sheen that results from microbiological emulsification of the oil. In all four samples submitted for this test, oil degrading bacteria were present. Thus, the lack of degradation is not ascribable to lack of bacteria but some other deficiency, such as in temperature, oxygen or nutrients.

Vegetation mortality and recovery

Ground cover

Where the black, asphalt-like oil residue is present on the surface, there is scant live vegetation. Most

Table 2. Alkane to aromatic and pristane to n-C_{17} ratios for samples collected in 1991 and 1979 from the experimental crude oil spills.

Collected	*ID no.*	*Grid coordinates*	*Depth (cm)*	*Site type*	*Alk/Arom*	*Pris/n-C_{17}*
4 June 91	1	W-16,40	0–13	No detectable oil	NA	NA
4 June 91	9	W-14,24	8–14	Subsurface oil	1.15	0.79
4 June 91	10	W-14,24	14–16	Subsurface oil	1.36	0.53†
4 June 91	12	W-14,24	20–35	Subsurface oil	*	*
4 June 91	18	W-7,2	0–8	Surface oil	1.22	2.5
4 June 91	19	W-7,2	8–15	Surface oil	1.37	0.8
4 June 91	27	W-11,18	8–15	Subsurface oil	1.66	1.45
4 June 91	28	W-11,18	15–28	Subsurface oil	*	*
4 June 91	4	S-7,44	0–10	No detectable oil	NA	NA
4 June 91	15	S-6,31	8–16	Subsurface oil	1.36	1.68
4 June 91	16	S-6,31	16–30	Subsurface oil	*	*
4 June 91	22	S-5,2	0–8	Surface oil	1.07	10.6
4 June 91	23	S-5,2	8–15	Surface oil	1.42	1.03
4 June 91	24	S-5,2	15–23	Surface oil	1.68	0.83
4 June 91	31	S-5,16	8–18	Subsurface oil	2.85	1.03
4 June 91	32	S-5,16	18–30	Subsurface oil	*	*
15 Aug 91		S-7,22	10	Subsurface oil	1.81	0.56†
19 July 79		W-19,33	duff**	Subsurface oil	1.37	0.56
19 July 79		W-9,9	moss	Surface oil	1.64	0.86
19 July 79		W-9,9	duff	Surface oil	1.68	0.57
19 July 79		W-9,9	mineral	Surface oil	1.28	0.55
19 July 79		S-4,7	moss	Surface oil	1.43	0.68
19 July 79		S-4,7	duff	Surface oil	1.28	0.53
19 July 79		S-12,42	moss	Subsurface oil	1.55	0.51
19 July 79		S-12,42	duff	Subsurface oil	1.26	0.53
4 June 76		Crude oil from pool			1.07	0.55†
4 June 76		Oiled moss taken from very beginning of oil spill			1.35	0.56†

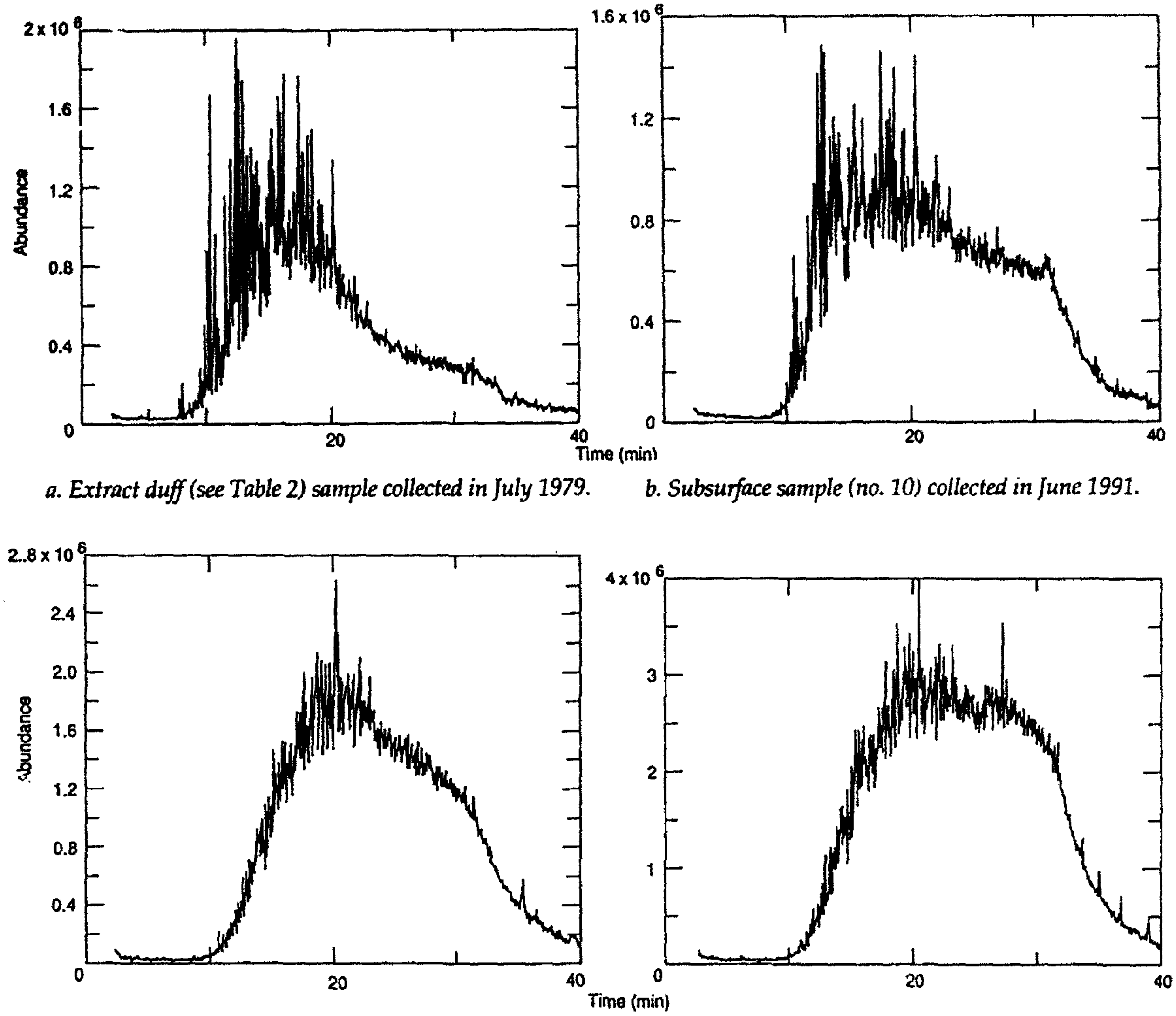
* Too little oil extracted for accurate ratio measurements.
† Volatiles detected in these samples.
** Moss = top layer of soil profile, consisting of live vegetation; duff = peat and mixed organic layer between moss and mineral soil; mineral = histic pergelic cryaquept soil.

mosses, lichens and shrubs were killed soon after the original spills (Johnson et al. 1980), and with few exceptions the only vegetation on the surface oiled areas is scattered cottongrass tussocks of *E. vaginatum*. By late August, when tussock leaf growth was at its maximum, these covered about 50–65% of the surface oiled area of both the winter and summer spills. We counted 58 living tussocks on the surface oiled area of the winter spill (75 m^2) and 39 on the surface oiled area (30 m^2) of the summer spill. The size distribution of these tussocks shows that they are younger on the summer spill than on the winter spill, and that some may have become established here over the past 15 years (Fig. 10). In addition, comparisons of photos taken before the spills of the permanent 1- × 1-m quadrats established by L.A. Johnson (Johnson et al. 1980) show that many of the cottongrass tussocks present at the time of the spill have increased dramatically in size and have even flourished (Fig. 11). Most of the associated dwarf shrubs visible in Figure 11a have disappeared.

Three of the tussocks on the surface oiled area of the winter spill were excavated in August. The annual root system of these tussocks grew down through the oiled organic horizon into the mineral soil. The tightly packed root zone suggested possible resistance to oil penetration. However, chloroform extraction of the inside of one root mass showed the presence of oil, suggesting that the annually produced roots are capable of penetrating down through the oiled horizon to reach unoiled mineral soil.

A few areas of surface oil have a sparse cover of fruticose lichens, including primary squamules and occasional mosses *(Polytrichum* spp.).

Where there is subsurface oil only, it is difficult to detect any changes in the ground cover.



a. Extract duff (see Table 2) sample collected in July 1979. *b. Subsurface sample (no. 10) collected in June 1991.*

c. Surface sample (no. 22) collected in June 1991. *d. Surface sample (no. 18) collected in June 1991.*

Figure 9. Chromatograms of aromatic fractions showing compositional changes.

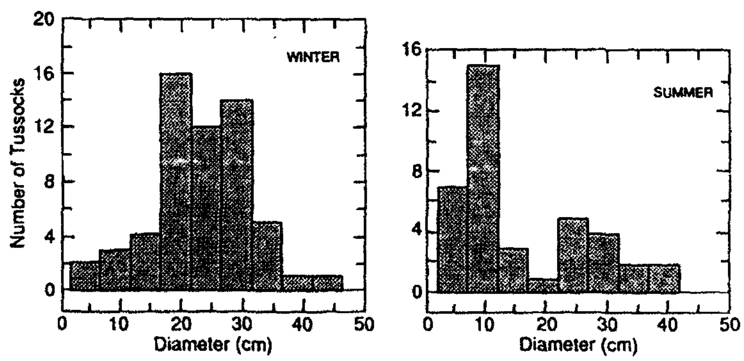
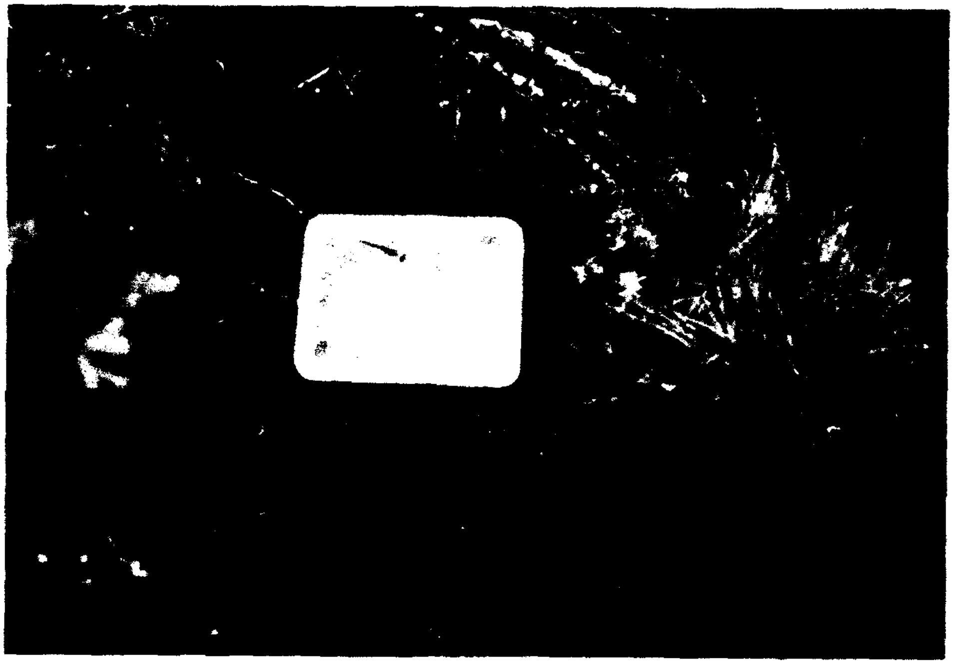


Figure 10. Diameter frequency distribution of E. vaginatum *tussocks on surface oiled areas of the experimental crude oil spills; measured in August 1991.*



a. 1977.

b. 1991.

Figure 11. Growth of E. vaginatum *tussock from 1976 to 1991.*

Black spruce (Picea mariana)

The numbers of black spruce trees in the upper 12- × 20-m plots of both spills were very similar (151 on the winter spill plot vs 155 on the summer spill plot): 82 of these trees were located on the oiled area (either surface or subsurface oil) of the winter plot and by coincidence 82 were also counted on the oiled area of the summer plot. (None of the trees outside the oiled area on either spill plot were dead.) Of the trees in the oiled areas, over half (56%) were dead on the winter spill compared with 38% on the summer spill (Fig. 12). On both spills, an

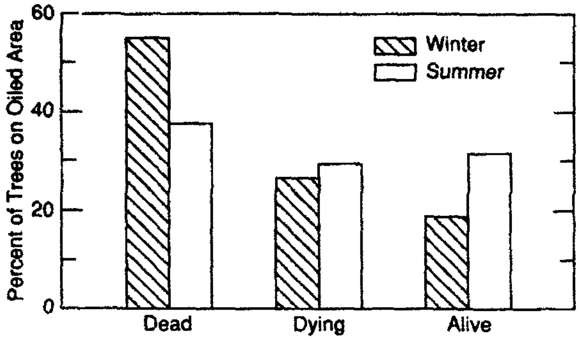


Figure 12. Condition in 1991 of black spruce trees on surface and subsurface oiled areas of the experimental oil spills.

additional 27–30% of the trees appeared to be dying. Therefore, only 18% of the trees were alive and appeared healthy on the winter spill and 33% were alive and healthy on the summer spill. No black spruce seedlings were counted in either plot, although cones were noted on many of the trees. We saw no sign of black spruce recovery, neither new seedlings nor regrowth of damaged trees.

Essentially, all the dead trees on the summer spill were located in the upper half of the plot (0–10 m downslope), with the last dead spruce 15 m downslope from the spill. On the winter spill, the last dead spruce was 20 m downslope, and there were significant numbers of the dead trees in both the upper and lower halves of the plot.

The location of dead black spruce trees correlates highly with the distribution of surface oiled areas (Fig. 13). There are no live spruces on areas of surface oil. On the winter spill, most of the dead trees are located in or on the edge of areas with surface oil. On the summer spill most of the dead trees are located on the edge between surface and subsurface oil or on islands of subsurface oil surrounded by surface oil.

The numbers and locations of dead black spruce in 1990 and 1991 can be compared with those in 1977 and 1978 (Fig. 14). Before the spill in 1976, there were no dead trees in either plot. One year after the spill (1977) Jenkins et al. (1978) reported 26 dead black spruce on the summer spill and 20 on the winter spill. By July 1978 an additional 2 trees had died on the summer spill while 10 additional trees died on the winter spill. They concluded that 2 years after the spill, vegetation damage appeared more rapidly and was more extensive on the summer spill (Johnson et al. 1980). Our counts in 1990 and 1991 showed that during the past 12 and 13 years only an additional 2 trees have died on the summer spill plot while 12 more have died on the winter spill plot. This confirms their conclusion (based on 2 years of observations after the spills) that vegetation was

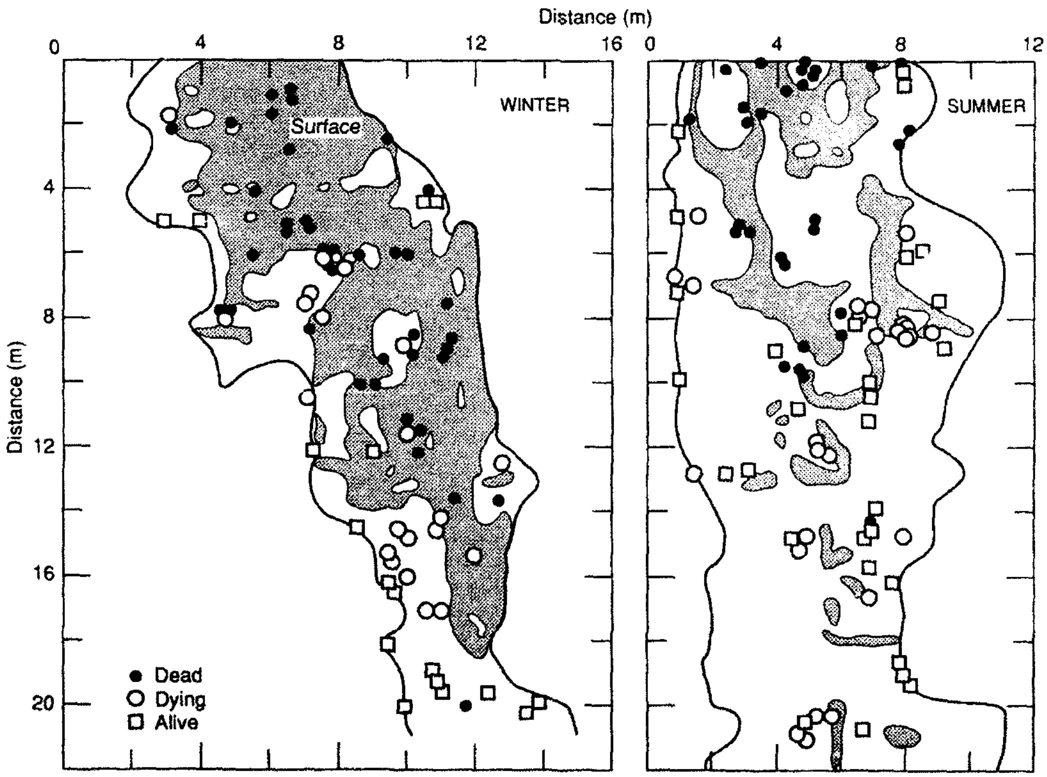


Figure 13. Black spruce trees on spill plots.

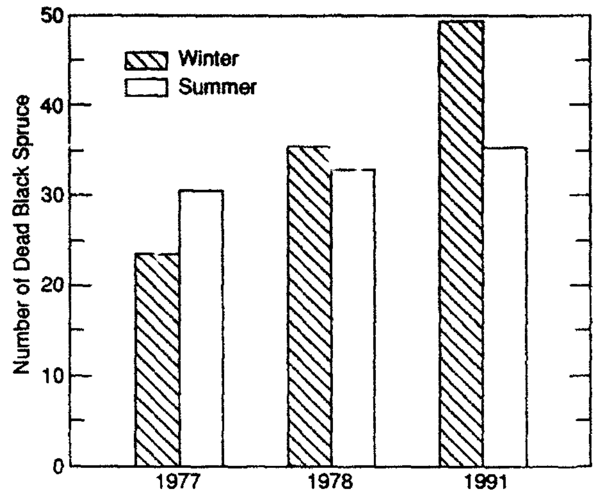


Figure 14. Number of dead black spruce trees in 1977, 1978 and 1991 on the experimental oil spills.

damaged more rapidly on the summer spill than on the winter spill. The downslope extent of dead black spruce trees has increased by 5 m on the summer spill over the past 13 years but has not changed since 1978 on the winter spill.

Excavation of two live spruce trees on the summer spill showed the location of oil in relation to the distribution of the tree roots. The two excavated root systems were near the surface (0–7 cm), apparently permitting tree survival in the shallow, unoiled organic horizon above the oiled zone.

DISCUSSION

Between 1978 and 1991 there was only a minor amount of additional oil movement in each of the two spills. We do not know when this additional movement happened because the site was not monitored during this time. The small amount of movement suggests that the oil is not very mobile; the additional movement probably occurred soon after the 1978 measurements. Hutchinson and Freedman (1978) attributed considerable additional horizontal spreading of oil at their large experimental spill to a severe rainstorm 4 years after the original spill; the unusually large rainstorm evidently remobilized the oil and considerably increased the spill area. There was at least one extreme rainstorm during the summer of 1989 in the Caribou–Poker Creeks Research Watershed since the original spill. In addition, there were large snowmelt runoffs during the springs of 1990 and 1991. None of these produced significant additional spreading of oil. The extreme rainfall may have taken place too many years after the initial spill to cause significant additional movement.

The large increases in the active layer seen in the winter spill during the last 15 years are much greater and persist much longer than those reported for other experimental spills in a permafrost-underlain forest (Wein and Bliss 1973, Mackay et al. 1975, Hutchinson et al. 1976, Hutchinson and Freedman 1978). Hutchinson (1984), however, reports significant increases in the thaw depth below an experimental diesel spray spill compared to the control (85 vs 50 cm) 15 years later, and lesser but significant increases below a crude oil spray spill in a burnt forest site. He attributed the increase in the diesel plot to the greater toxicity for the ground flora of the diesel compared to the crude oil. The fine-grained soils at our site lent themselves to probing of the active layer thickness, unlike the Norman Wells sites where gravely soils made probing difficult.

The large increases in thaw depths that we have noted over 15 years are similar to the magnitude of increases noted by Dyrness (1982) for experimental mechanical disturbances of forest floor cover and by Viereck (1982) for wildfires and fire line construction. Both studies were in similar vegetation settings, had similar fine-grained permafrost soils and took place over the same period.

The deep thaw that we measured in the upper part of the winter spill is caused by the large concentration of oil within the upper organic horizons of the soil, the almost total death of vegetation within this area (except for the 50% cover by cottongrass tussocks that develops by August), and the resulting extensive blackened surface oiled areas that have caused a major change in the surface albedo. The presence of crude oil modifies the ground surface heat flux in a number of ways, any or all which may be causing the increased thaw. These effects include 1) the decreased albedo of the oiled surface, leading to surface heating; 2) the removal of the tree canopy by the death of black spruce, thus increasing solar radiation influx to the surface; 3) the alteration of thermal diffusivity of the organic layer by the presence of oil; and 4) the compaction of the now dead insulating organic layer. Mackay et al. (1975) and Wein and Bliss (1973) discuss these factors as they apply to their experimental spills and attempt to model the maximum effects on thaw depth increases. The depths that they predicted and measured are considerably less than those that we measured, with the differences owing to different soil type (gravely soil vs ice-rich silt) and our longer term measurements.

The winter spill had an average spill intensity of 40 L/m^2 (7600 L spread over 188 m^2), with the greatest intensity in the upper plot where the entire organic horizon is saturated. These spill intensities are higher than those reported for other experimental spills in winter. For example, Mackay et al. (1975) reported 14 L/m^2 for cold oil and 20 L/m^2 for hot oil. Their spill plots were on gravely soil and they were unable to report any thaw depth increases associated with their spills. The surface oiled area of the winter spill is also much larger (75 m^2) than other experimental spills, which also may contribute to the deeper thaw. For example the 10,000-L point spill in the summer at Norman Wells, Northwest Territories, had a surface oiled area of only 36 m^2 (Hutchinson et al. 1976). This is comparable in size to our summer spill with its total of 30 m^2 of surface oiled area.

Some of the increases in thaw depth following the spills can be attributed to the trampling that unavoidably occurs when the thaw depth measurements are made. Hutchinson and Hellebust (1978) and Hutchinson and Freedman (1978) reported a 25% increase in thaw depths in their trampled study plots vs an untrampled control. Our original study (Johnson et al. 1980) tried to avoid the worst of the trampling problems by installing elevated walkways every 5 m across the plots, which we continue to use whenever possible. The slight increase (10%) in thaw depths in the control plot during the first 3 years (Fig. 4) may be attributable to trampling effects. The heavily oiled organic layer in the upper winter spill plot may be more susceptible to compaction from the limited trampling that does occur than are subsurface oiled or unoiled areas that contain living vegetation.

While little or no microbial or other types of weathering of crude oil were apparent in samples collected up to July 1978 (Johnson et al. 1980) or in the samples collected in July of 1979, we found significant weathering in some samples collected in June 1991. Surface samples were more degraded than subsurface samples, suggesting that warmer surface soils and aerobic microbiological activity are responsible for some of the changes in oil composition. Retention of volatile compounds in some samples indicates that the flux of air is very limited at certain locations in the spill area. Conversely, the organic soils in which the oil was found, above the saturated mineral soil, appeared to be well aerated when we examined them in late June and August 1991. The lack of extensive peat decomposition in these types of soils seems more related to low temperatures and slow rates of annual thaw than to low oxygen supplies (Neiland and Viereck 1977). The presence of volatile organics in samples collected from the winter and summer spills, 15 years after the original spills, is illustrative of just how persistent crude oil can be when spilled on permafrost-underlain soils. However, the presence of oil-degrading bacteria, as indicated by the sheen screen tests, suggests that bioremediation techniques could be used to enhance natural biodegradation in this type of setting if the factors limiting microbial activities are ameliorated.

The 1976 crude oil spills killed most of the vegetation on the surface oiled areas. Black spruce is particularly sensitive to the presence of crude oil in the root zone, and mortality is 100% in surface oiled areas. In addition, there has been little or no recovery of shrubs on the surface oiled areas; only cottongrass tussocks that survived the initial spill have regrown vigorously, probably in part because of competitive release. Fetcher and Shaver (1982) and Fetcher (1985) showed that the tillering and flowering of *E. vaginatum* tussocks increased with decreasing competition or cover by shrubs and mosses. The surface oil acted to kill the mosses and shrubs that frequently 'parasitize' tussocks, and thereby remove the shading caused by competition with shrubs growing in the tussocks. Tussocks may be resistant to oil spill mortality because of their raised growth form and their annual root regrowth that penetrates the oiled horizon to reach the mineral soil by late summer (Chapin et al. 1979, Johnson et al. 1980). Mosses and lichens are particularly adept at floating over the surface, even on surface oiled areas, and there is evidence of some lateral growth in some areas after 15 years. The lateral growth occurs from individuals on raised features that were not oiled, such as tussock and tree bases.

Although oil covered a larger total area on the summer than on the winter spill, most of the oil flowed beneath the surface. Subsurface oil at a depth greater than 10 cm on both the summer and winter spills has produced little detectable effect on the vegetation. Soil profiles and excavation of spruce root systems show that roots are confined to surface organic layers. On the summer spill most of the oil is located below the surface so that the shallow-rooted black spruce has been able to survive in the shallow, 10- to 15-cm organic O1 horizon above the oiled zone in the O2 horizon. The rooting depths of most species of trees and shrubs that grow in this type of forest are shallow enough to avoid the predominantly subsurface oil found on the summer spill. Hutchinson (1984), however, found an increasing area of vegetation deaths over the subsurface portions of the Norman Wells, Northwest Territories, spill in a black spruce forest. The area of dead vegetation had increased from 60 to 200 m^2 after 4 years.

Since the winter spill produced over twice as much surface oiled area than the summer spill did, the winter spill had a more drastic overall effect on the vegetation. Jenkins et al. (1978) concluded that the summer spill produced more vegetation damage than the winter spill. Our reevaluation of this site 15 years after the spills suggests that the winter spill produced more damage. Although the effects of the summer spill were almost instantaneous, with all but 2 of the 30 dead trees dying within the first 2 years following the spill, on the winter spill black spruce have continued to die since 1978. Thus, the effects of the oil on black spruce have been long term and chronic on the winter spill and were relatively short term and acute on the summer spill. The reason for this continued die-off may be black spruce being dormant at the time of winter spill but actively growing at the time of the summer spill.

CONCLUSIONS

Johnson et al. (1980) used a flow chart to represent the responses after three growing seasons of this subarctic permafrost community to a large crude oil spill. Based on our observations 15 years after the oil spills, the model needs to be revised to reflect the longer term fate and effects of surface vs subsurface oil. Since surface oiled areas show far more vegetation mortality, as well as significantly greater increases in active layer thicknesses, spills that spread laterally and saturate the surface are far more damaging. Whether the oil moves laterally over the moss layer or vertically through the moss layer into the organic horizon above the mineral soil depends on the season. Since lateral movement is favored when the ground is frozen, a winter spill will produce a larger surface oiled area than a summer spill in a subarctic permafrost community. The effects that we observed 15 years after the summer and winter spills are summarized in Figure 15.

On the basis of our observations, restoration activities, if any, should focus on the surface oiled areas. Since removal of the contaminated surface may cause more damage in permafrost areas with ice-rich, fine-grained soils, treatment of the surface-oiled area to enhance microbiological activity followed by revegetation with native species such as *E. vaginatum* tussocks should be evaluated.

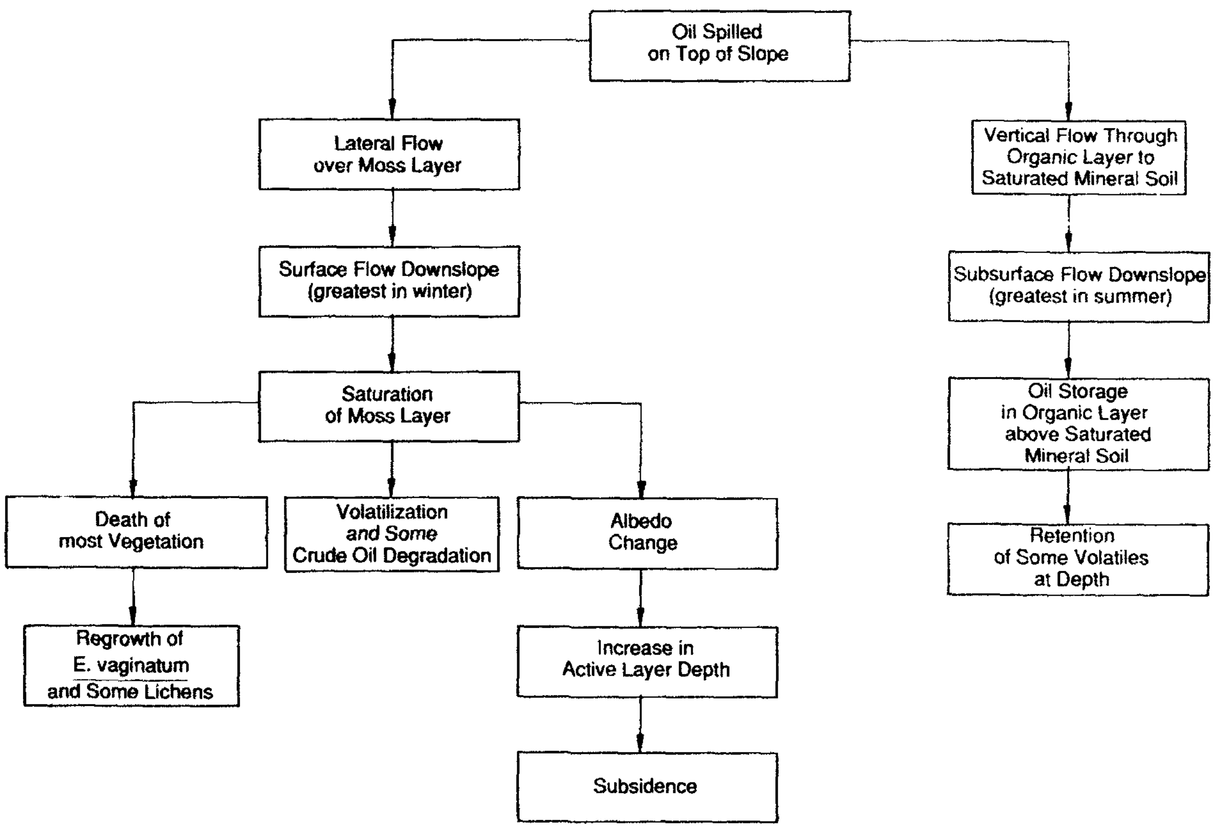


Figure 15. Observed effects of the crude oil spills on a subarctic permafrost site 15 years after the spill.

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Charles M. Collins, Charles H. Racine and Marianne E. Walsh

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U.S. Army Cold Regions Research and Engineering Laboratory
72 Lyme Road
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The effects of two large experimental oil spills conducted in the winter and summer of 1976 in the permafrost-underlain black spruce forest of interior Alaska were assessed 15 years after the spills. Effects on the permafrost, as determined from measurements of active layer thaw depths and of the total amount of ground subsidence, were far more pronounced on the winter spill because it had a larger area with oil on the surface. The winter spill also had a more drastic effect on the vegetation. Where the black, asphalt-like oil is present on the surface, black spruce mortality is 100% and there is very little live vegetation cover, except for cottongrass tussocks. Changes in oil chemistry vary with depth; surface samples show signs of microbiological degradation, whereas some subsurface samples taken just above the permafrost show no evidence of degradation and still contain volatiles.

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