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Ecological Effects of a Crude Oil Spill on a Subarctic Right-of-Way

by

David Charles Seburn ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Department of Geography

Edmonton, Alberta
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Now I've lost my equilibrium

my car keys and my pride

Tom Waits

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Ecological Effects of a Crude Oil Spill on a Subarctic Right-of-Way** submitted by **David Seburn** in partial fulfillment of the requirements for the degree of **Master of Science.**

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S.C. Zoltai

S. C. Zoltai

R. W. Wein

Date: Sept. 17/'93

for

Carolyn

Her encouragement, patience, love and back rubs made this process not only endurable, but frequently enjoyable.

ABSTRACT

Research was undertaken from 1988 to 1991 at the Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS) site near Fort Norman, NWT, in a black spruce forest underlain by permafrost. An experimental crude oil spill (20 imperial barrels) was undertaken in August of 1988, simulating a leak from a belowground pipeline. Three environments were examined: the Forest, Right-of-Way (ROW), and Trench.

The mean maximum thaw depths of all environments significantly increased after the oil spill. The greatest increases were experienced in the undisturbed Forest (150%) and moderately disturbed ROW (75%). Microclimatic data indicated that complete freeze-back occurred in even the deepest active layer of the unoiled areas (1.5 m). It is unclear whether further degradation of permafrost will occur.

Cuttings of *Salix arbusculoides* planted in oiled areas three years after the spill, fared better or no worse than cuttings planted in unoiled areas. Survivorship values were as high as 75% at the end of the growing season, but declined to less than 15% by the end of winter. The late spring of 1992 necessitated a premature evaluation of the cuttings. Rooting success indicated that potential survivorships were as high as 61%. This shrub could be a valuable revegetation species for subarctic oil spills.

To examine the effects of the oil on the existing plant communities, study plots were stratified into three classes: heavily and lightly oiled, and apparently unoiled. The number of species or species assemblages present significantly declined on only the heavily oiled ROW (>50%). The total plant cover on the heavily oiled ROW decreased by almost 80%. On other areas, total plant cover significantly increased above pre-spill values. A total of 19 species or species assemblages out of 34 significantly declined after the oil spill on at least one type of environment. Only six species or species assemblages increased in abundance after the oil spill. Half of these species were grasses or sedges.

ACKNOWLEDGEMENTS

As is usually the case on a project of this size, a number of people have contributed to its humble success. First of all, I wish to thank my supervisor, Dr. Peter Kershaw. SEEDS has been his dream (and nightmare) for many years. His boundless enthusiasm, energy, and homebrew eased some of the apparently insurmountable obstacles I have encountered over the past months. Thanks Pete!

Joining the SEEDS team mid-way through its life has allowed me to benefit from all the hard work accomplished by the previous SEEDSters. Much of my work was made easier by the work of Teresa deGrosbois, Bonnie Gallinger, Lynn Maslen, and Sabine Nolte. Bonnie and Sabine also boosted sagging spirits through the exchange of favourite SEEDS horror stories.

My own work was ably assisted by a number of field assistants over my time in the bush. I especially want to thank Kim (Winnikinick) Winnicky for help with the whips (it would have been no fun doing it alone) and Craig Olsen who put in two tours of duty at SEEDS. Craig provided much needed comic relief in the spring of '92 when the two of us manned SEEDS along with a meter of snow. I never realized how much fun could be had with a shotgun and tin of canned ham...

Carolyn Seburn helped out on all aspects of the research. Not only did she assist in the fieldwork, but she provided emergency statistical counselling. Discussions with her also helped to clarify my thoughts on a number of aspects of the research. Perhaps most importantly she provided moral support through what seemed a never-ending project.

I also wish to thank the members of my committee for their contributions to this thesis. Ross Wein of Forest Science gave me access to his extensive collection of references on the subject of oil spills in northern environments. He also challenged some of my basic ideas about reclamation projects. Steve Zoltai of Forestry Canada generously made time for me to discuss the degradation of permafrost. His patience with this novice and interest in my work are deeply appreciated.

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TABLE OF CONTENTS

Chapter 1

Introduction

Chapter 2

Changes in the active layer as a result of a crude oil spill

Chapter 3

Experimental revegetation of a crude oil spill using willow (*Salix arbusculoides*) cuttings

Chapter 4

Plant community responses to an experimental crude oil spill on a Subarctic Right-of-Way

Chapter 5

Conclusions

LIST OF TABLES

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF FIGURES

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 1
INTRODUCTION

This research project is part of a larger multi-disciplinary study. The Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS) was designed to investigate the effects of human-induced disturbances on a black spruce (*Picea mariana*) forest (Kershaw, 1988).

To date research has been focussed on both physical and biological processes at work in the system. Permafrost studies have determined there have been significant increases in the active layer over time and pronounced subsidence of the ground surface as a result of the disturbance (Gallinger, 1991; Nolte, 1991). Research on vegetation at the site has demonstrated the potential for regeneration of willows from surviving root systems (de Grosbois et al., 1991) and the ability of some native species to act as recolonizers (Maslen, 1989). Research continues on the ongoing effects of the disturbance on a variety of aspects including microclimate and small mammal communities.

The development of an oil spill component of the larger study was designed to address a perceived gap in information on controlled oil spills on such environments. While a number of experimental spills have been conducted in arctic (Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Holt, 1987) and boreal (Jenkins et al., 1978; Hutchinson and Freedman, 1978) ecosystems these studies have all been conducted in undisturbed environments. Knowledge on how a crude oil spill will affect the actual operating corridor of a pipeline is limited. For example, Kershaw (1990) determined that the SEEDS spill had a higher coverage of oil than was predicted based on other experimental spills. This was thought to be a result of the removal of the absorptive organic layer in the creation of the trench.

This particular study has three distinct components. Chapter 2 focuses on the effects of the oil spill on the active layer. While some researchers have reported large increases in the active layer (e.g. Lawson et al., 1978; Collins, 1983) others found small or negligible increases (Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). The SEEDS experiment was to examine this question in an already disturbed environment with a substantially increased active layer.

Chapter 3 addresses the potential of a willow species (*Salix arbusculoides*) in the reclamation of oil spills. Establishing a vegetative cover can help reduce erosion and minimize thawing of the frozen soil (Younkin, 1976; Bliss, 1979; Johnson, 1981). *S. arbusculoides* was selected because it is a common deciduous shrub species in the western

Arctic (Porsild and Cody, 1980) and its proven performance on other disturbance experiments at the SEEDS site (Maslen, 1989).

Chapter 4 provides an examination of the effect of the crude oil on the plant species found at the site. Most researchers in northern ecosystems have reported immediate and drastic declines in species abundance and total plant cover (Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). The SEEDS site has been dramatically modified from its initial state as a decadent black spruce forest. Mature trees and shrubs were removed and a number of agronomic species have been seeded on the trench. Knowledge of which species are particularly sensitive or resistant to a crude oil spill is important for proper management of such environments.

SITE DESCRIPTION

Background

The SEEDS site (64° 58′ N., 125° 36′ W.) was established 10 km north of Fort Norman, Northwest Territories, at the confluence of the Mackenzie and Great Bear Rivers (Fig. 1-1). The site is situated within an homogenous area of decadent (> 200 year) black spruce forest.

Beginning in 1985, the forest canopy was hand-cleared, over a period of two summers, to create a 25-m-wide clearing simulating a transportation or pipeline corridor. The north-south oriented corridors were identified as Rights-of-Way (ROW) 1, 2, and 3 from west to east. The two connecting links were referred to as the North and South Link. ROW 1 and 3 were cleared in 1985 while ROW 2 was created in 1986.

Within the ROW, a 2-m-wide trench was dug to the base of the active layer (40.4 cm $\pm$ 10.8) and then the surface organics, including the moss and lichen layer, were mixed in with the mineral soil as backfill. This action simulated the construction of a buried pipeline. The Trench area was then sown with a mixture of agronomic grass seed identical to the mixture used on the Norman Wells pipeline, the only major crude oil pipeline currently operating in northern Canada.

The result was the creation of three distinct environments: a relatively undisturbed Forest, a moderately disturbed ROW, cleared of trees and shrubs, but with the organic layer intact; and a severely disturbed Trench, with all vegetation removed and the soil profile altered.

Geology and Soils

The region surrounding the SEEDS site is flat to gently sloping glaciolacustrine and morainal plain with local hummocky micro-relief

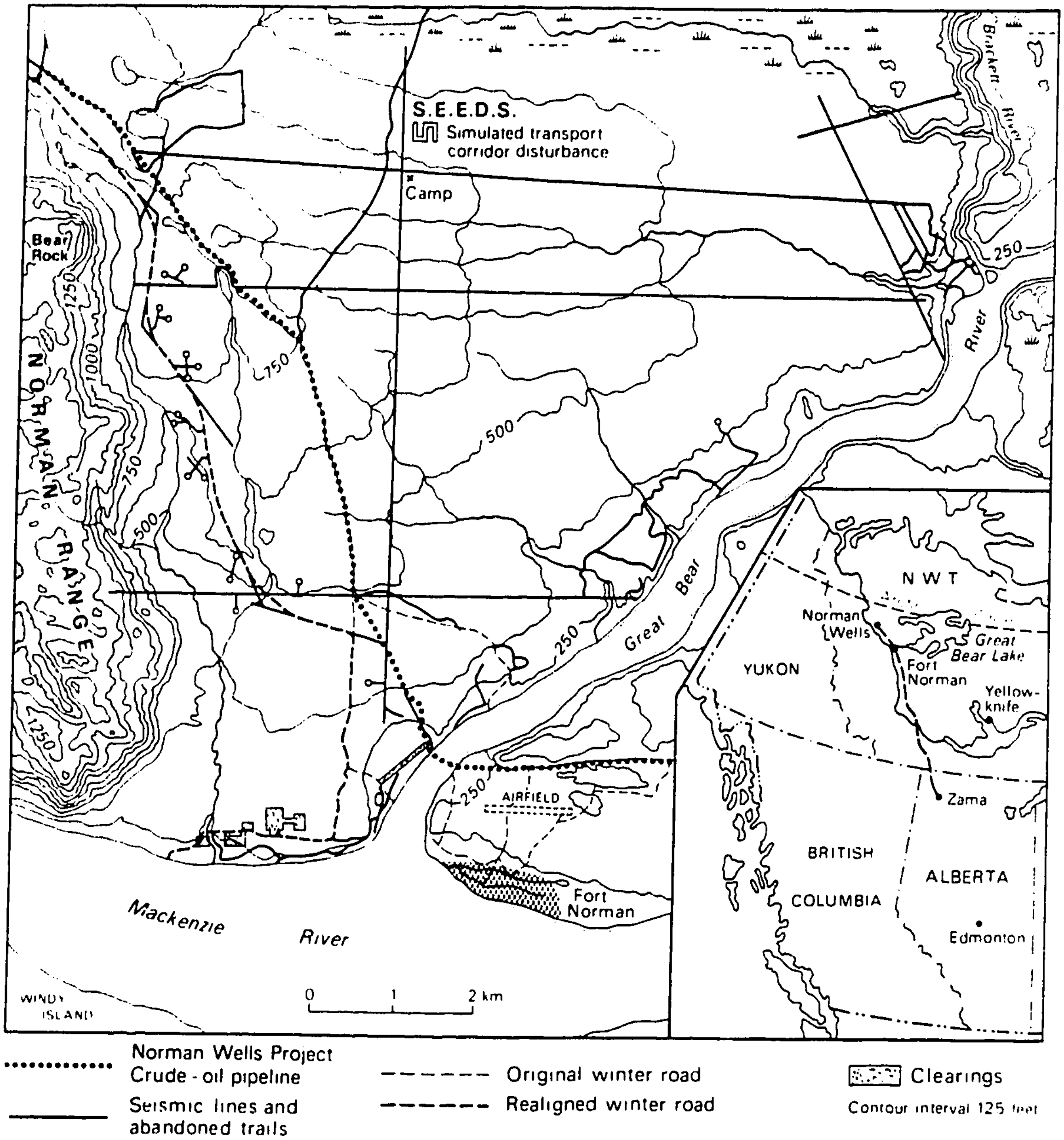

Figure 1-1. Location of the simulated corridor disturbance for the Studies of the Environmental Effects of Disturbances in the Subarctic (SEEDS), near Fort Norman, NWT.

(Reid, 1974; Zoltai and Tarnocai, 1975). More specifically, the site is on a gentle (1.5°) NNE-facing slope. The underlying geology consists of Devonian dolomitic and limestone breccias with depths of greater than five m to bedrock mantled by Quaternary sediments (Hughes et al., 1973; Reid, 1974).

Kershaw and Evans (1987) classified the soil at the site as a silty loam Gleysolic Turbic Cryosol with a 15-30 cm organic soil horizon. Generally, the soil is topped with a layer of moss and lichen ranging from three to five cm overlying the organics. The pH of the upper horizons tended to more acidic than the lower horizons reflecting the acidic nature of the surface peat. Soil moisture ranged from 40-1500%, generally decreasing with depth within the active layer. In addition, high ice content values were found at the top of the permafrost table (50-160%).

The study site is located within the discontinuous permafrost zone (Brown, 1970), although permafrost underlies the entire site. In this area permafrost generally does not exceed a depth of 50 m, with mean annual surface temperatures ranging from -1 to -3° C (Judge, 1973). In 1986, the active layer was 40.4 ($\pm$ 10.8) cm in the undisturbed forest.

Climate

The climate of the SEEDS region has been classified as Subhumid High Boreal (Ecoregions Working Group, 1989). The winters are long and cold, while the summers are short and cool (Fig. 1-2). The nearest meteorological station is at Fort Norman (10 km south of the site) and it has a mean annual temperature of -6.3° C and a mean annual precipitation of 324.9 mm (Atmospheric Environment Service, 1982).

Vegetation

The study site is located within a relatively homogenous, subarctic boreal forest community dominated by black spruce (*Picea marina*) and larch (*Larix laricina*) in excess of 200 years old. The open-canopied forest ranges in height from 4-6 m.

The dominant shrub species are the willow *Salix arbusculoides*, shrubby cinquefoil (*Potentilla fruticosa*) and dwarf birch (*Betula glandulosa*). Understorey vegetation is dominated by such species as Labrador tea (*Ledum groenlandicum*), bearberry (*Arctostaphylos rubra*), bog cranberry (*Vaccinium vitis-idaea*), bog blueberry (*V. uliginosum*), and crowberry (*Empetrum nigrum*). Non-vascular species provide an almost continuous cover on the ground surface. Common moss species include the feather moss *Hylocomnium splendens*, as well as *Tomenthypnum nitens* and *Aulacomnium palustre*. Lichen species are dominated by the genus *Cladonia*.

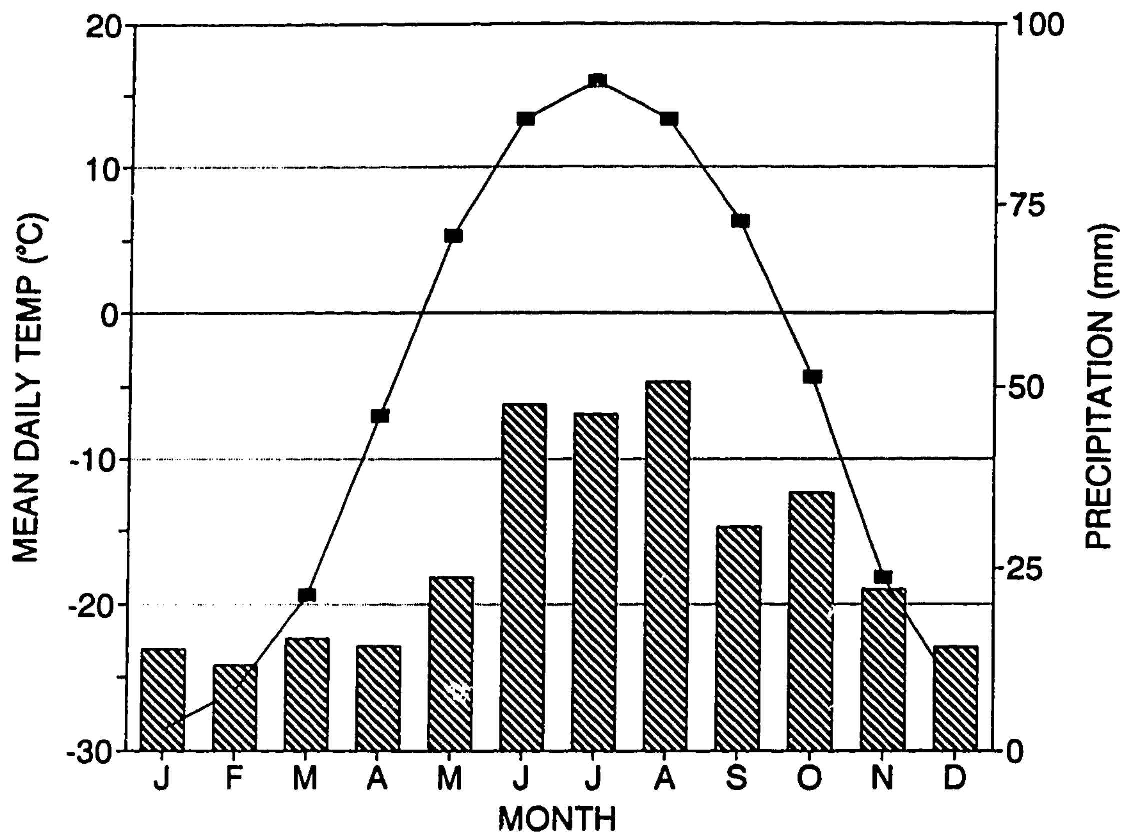

Figure 1-2. Mean monthly temperature and precipitation normals for Fort Norman, NWT for the period 1951-1980.

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CHAPTER 2

Changes in the active layer of a Subarctic Right-of-Way as a result of a crude oil spill

INTRODUCTION

Permafrost is circumpolar in its distribution in the northern hemisphere. In Canada, permafrost underlies almost 50% of the country (Stearns, 1966). Hence it is an important characteristic of much of northern Canada.

The ongoing presence of permafrost is dependent on the balance of several environmental factors, mainly climate, vegetation, and soil properties (Brown, 1970; Brown, 1973; Gold and Lachenbruch, 1973). If the regional climate changes then a new thermal equilibrium will eventually result causing the aggradation or degradation of permafrost (Smith, 1983; Smith and Riseborough, 1983). This is especially true in areas of discontinuous permafrost where mean annual permafrost temperatures tend to be between -1 and 0° C.

It is well known that human developments in permafrost areas generally lead to degradation of permafrost, and the associated increase in active layer thickness and thermokarst subsidence (e.g. Brown, 1970; Goodrich, 1983; Grave, 1983).

Ecosystems underlain by permafrost are often characterized as being more sensitive to environmental change and surface perturbation than non-permafrost environments. With the potential increase in northern oil and gas development, there is growing concern over the effect of crude oil spills on ecosystems. While a number of studies have examined the effect of crude oil on Arctic plant communities (e.g. Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Linkins and Fetcher, 1983; Kershaw and Kershaw, 1986; Holt, 1987) and subarctic plant communities (e.g. Hutchinson and Freedman, 1978; Jenkins et al, 1978) there have been few studies exclusively on the effects of crude oil on the active layer and permafrost characteristics of a subarctic site (but see Collins, 1983). However, a number of the plant community papers also report some of the effects of crude oil on the active layer.

The reports on the effects of crude oil on the active layer are somewhat conflicting. While some reseachers have reported large increases in the active layer (e.g. Lawson et al, 1978; Collins, 1983) others had small or negligible increases (Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). Part of this discrepancy may be a result of the size of the spill involved. Large spills have tended to result in a large increase in active layer depth (e.g. Collins, 1983). In addition, oil application method may be important. Most experimental spills that have reported small or negligible increases in active layer depth have used a spray application method to uniformly coat the vegetation (e.g. Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). Such a method may not affect the soil conditions as much as the pooling of oil from a point-source spill.

All of these oil spill studies have been conducted in natural forest or tundra areas. The effects of a crude oil spill on an operating pipeline corridor are poorly understood. If a small oil spill caused widespread permafrost degradation and ground subsidence then this could subject the pipeline to increased stress and the possibility of a pipeline rupture.

This project, undertaken at the SEEDS site, examined the effects of a crude oil spill on three distinct environments -- a relatively undisturbed black spruce (*Picea mariana*) Forest; a moderately disturbed Right-of-Way (ROW) where the trees and shrubs had been removed by hand; and a severly disturbed Trench environment, where in addition to removing the trees and shrubs, the surface organic layer of mosses and lichens had been removed and the area excavated and re-filled, to simulate the construction of a buried pipeline. Extensive work has already been completed on permafrost degradation and ground subsidence related to the creation of the ROWs and Trenches (Gallinger, 1991; Nolte, 1991).

The spill was initiated in late summer of 1988 (Kershaw, 1990). To mimic an actual belowground oil pipeline rupture, crude oil was pumped into an open-ended pipe buried at a depth of one metre in an existing simulated pipeline trench. Over the course of 24 hours 3273 L (20 imperial barrels) of Norman Wells crude oil were pumped into the pipe. In total, the oil covered an area of over 670 m^2 with an average concentration of approximately 4.86 $L \bullet m^{-2}$ (205.54 $m^2 \bullet m^{-3}$)(Kershaw, 1990).

METHODS

Field Methods

The seasonal progression of active layer development has been monitored at SEEDS since 1986. At that time, four parallel frost probe transects were established (Figure 2-1). Each transect consisted of 84 probe points, extending 290 m through the relatively undisturbed forest, the hand-cleared rights-of-way (ROWs), and the severely disturbed trenched areas. Probe points were separated by 10 m in the forest, 2.5 m on the ROW, and 0.5 m on the Trench.

Three oil spill frost probe transects were established in August of

1989. Oil spill probes were conducted at 1.0 m intervals. Within the oil spill, there were three transects through the ROW and Trench, however, only one of them crossed into the oiled forest because of the nature of the spill (Figure 2-1). In 1989, the oil spill transects were only probed at the end of the field season (August 24). In 1990 and 1991 the site was probed five and six times, respectively. The date of the last frost probing varied from 20 August in 1990 to 28 August in 1991. Frost probing occurred approximately every two weeks in the spring and late summer.

Until 1991, frost probing was conducted with a 2-m-long graduated aluminum rod, 1 cm in diamter. In 1991, a 3-m-long frost probe was employed in an effort to measure thaw depths greater than 2 m.

Data Analysis

A one-metre buffer was established between the Trench and ROW to minimize edge effects. This was not needed between the ROW and Forest because of the spacing between probe points. Anomalous data points were also encountered in the dataset. These included thaw depths which stabilized at a shallow depth early in the thaw season, likely due to the frost probe encountering a rock or root, and very deep thaw depths experienced at the edge of the Trench in the ROW, even with the buffer zone. All such values were removed prior to analysis. Analyses were conducted using the QuattroPro and Biometry software programs.

Mean maximum thaw depths were transformed using natural logarithms to meet the normality requirements of analysis of variance (Sokal and Rohlf, 1981). Multiple comparisons were conducted using the GT2-method because of unequal sample sizes (Sokal and Rohlf, 1981).

Thaw rates were calculated by subtracting the minimum thaw depth of each frost probe point from the maximum thaw depth and dividing by the number of days between first and last frost probing. The seasonal progression of the thaw rate was obtained by examining thaw depths over time. Linear regression was performed on the thaw depths. The square root of time (in days) was used as the independent variable, based on the well-documented observation that depth of thaw is proportional to the square root of time (Terzaghi, 1952; Jahn, 1985).

Microclimate stations were first established at the SEEDS site in early 1985. A variety of data were collected, including net radiation, relative humidity, wind speed, precipitation, and air and soil temperatures at various heights and depths. Data were collected on Campbell Scientific 21X dataloggers. Calculation of cumulative degree-days required some interpolations because of gaps in the dataset. Mean monthly temperatures were used where extensive gaps existed.

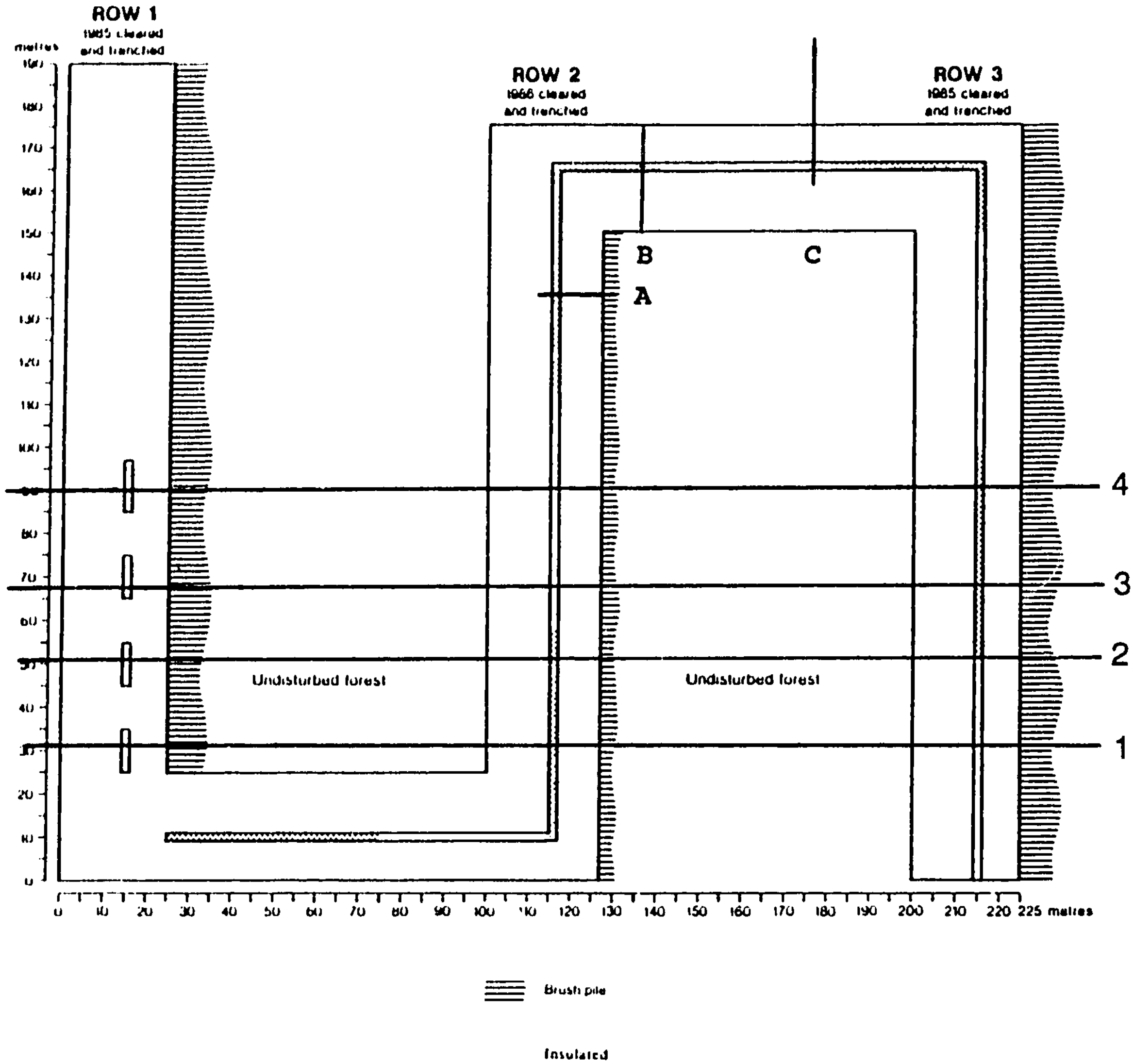

Figure 2-1. Location of the four unoiled frost probe transects (1-4) and the three oiled transects (A-C) at the SEEDS site, near Fort Norman, NWT.

RESULTS

Overview

In all years, large differences were found among the mean maximum thaw depths of the various unoiled disturbances (Table 2-1). In all cases, the Trench was deeper on average than the ROW and the ROW was deeper, on average, than the Forest. In general, the mean maximum thaw depths increased over time. The only exception to this was the Trench which became shallower in 1990, even though it reached its greatest mean maximum thaw depth in 1991.

The oiled environments did not display as strong a difference among types of disturbance (Table 2-1). Once again, however, the Trench was deeper than the ROW and the ROW was deeper than the Forest. While mean maximum thaw depths increased from 1989 to 1991, in all cases the 1990 mean maximum thaw depths were shallower than the 1989 results.

Overall, there are some large differences between the oiled and unoiled site types (Figure 2-2). On average, the oiled forest was over twice as deep as the unoiled Forest. The oiled ROW was deeper than the unoiled ROW and was approximately as deep as the unoiled Trench. In general, the oiled Trench was no deeper or only slightly deeper than the unoiled Trench.

Gallinger (1991) reported that the mean maximum thaw depth of the undisturbed forest was 40.4 $\pm$ 10.8 cm in 1986, when the frost probe transects were first set up. Using this value as an estimate of the pre-disturbance mean maximum thaw depth it is possible to examine the percentage increase in yearly mean maximum thaw depths (Figure 2-3). During the course of this study, the percentage increase in mean maximum thaw depths ranged from approximately 50% for the Forest in 1989 to almost 400% for the Trench in 1991.

Because mean maximum thaw depths are still increasing to some degree for the three environments, disentagling the effect of the oil from the type of disturbance is problematic. Comparing the percentage increase in mean maximum thaw depth for a given oiled environment to its unoiled counterpart for a specific year provides a good indication of the oil's effect (Figure 2-4). The effect of the oil was immediate and in some cases quite dramatic. Percentage increases in oiled mean maximum thaw depths varied from 20% for the Trench to 160% for the Forest.

Thaw Depths

ROWs 1 and 3 were cleared and trenched in 1985, while ROW 2 was created in 1986. Therefore, each ROW and Trench were compared to see if the different ages of the disturbances influenced mean maximum thaw depth.

Table 2-1. Mean maximum thaw depths for ththree levels of unoiled and oiled disturbance. Values have been averaged over frost probe transects. Thaw depths are reported in cm with standard deviations in parenthesis. Ground subsidence has not been accounted for.

	1989	1990	1991
UNOILED			
FOREST	59.6 (13.4)	59.9 (15.5)	63.7 (17.5)
ROW	84.9 (23.5)	93.0 (29.5)	110.4 (39.2)
TRENCH	163.4 (24.0)	149.0 (17.6)	167.6 (31.5)
OILED			
FOREST	155.4 (30.9)	140.9 (28.0)	165.6 (32.4)
ROW	157.3 (29.8)	154.5 (24.4)	181.6 (21.0)
TRENCH	178.8 (24.2)	163.4 (17.9)	200.7 (9.4)

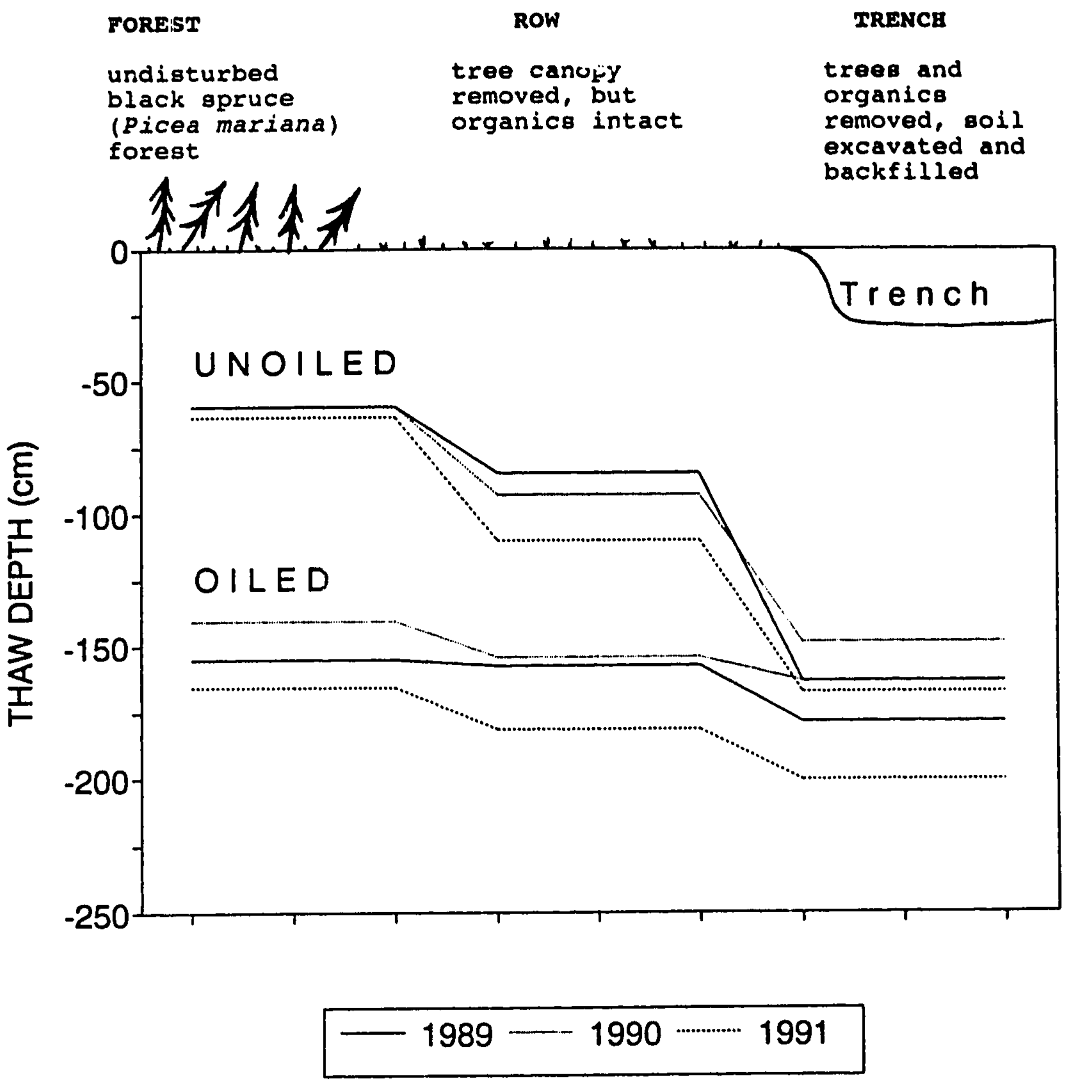

Figure 2-2. Generalized profile of permafrost degradation over the course of this study, for both unoiled and oiled Forest, ROW, and Trench. Surface subsidence has not been considered in this diagram.

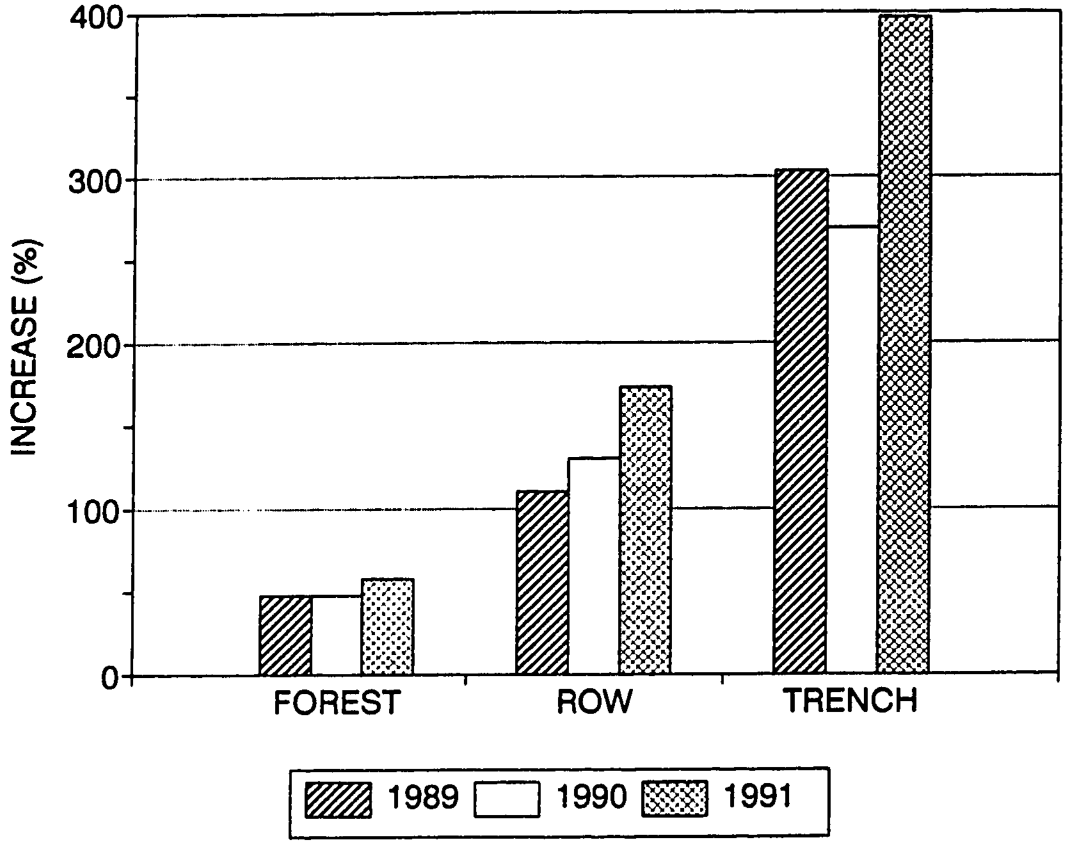

Figure 2-3. Yearly percentage increase in mean maximum thaw depths of the unoiled Forest, ROW, and Trench compared with the pre-disturbance value (1986) of the active layer for the Forest.

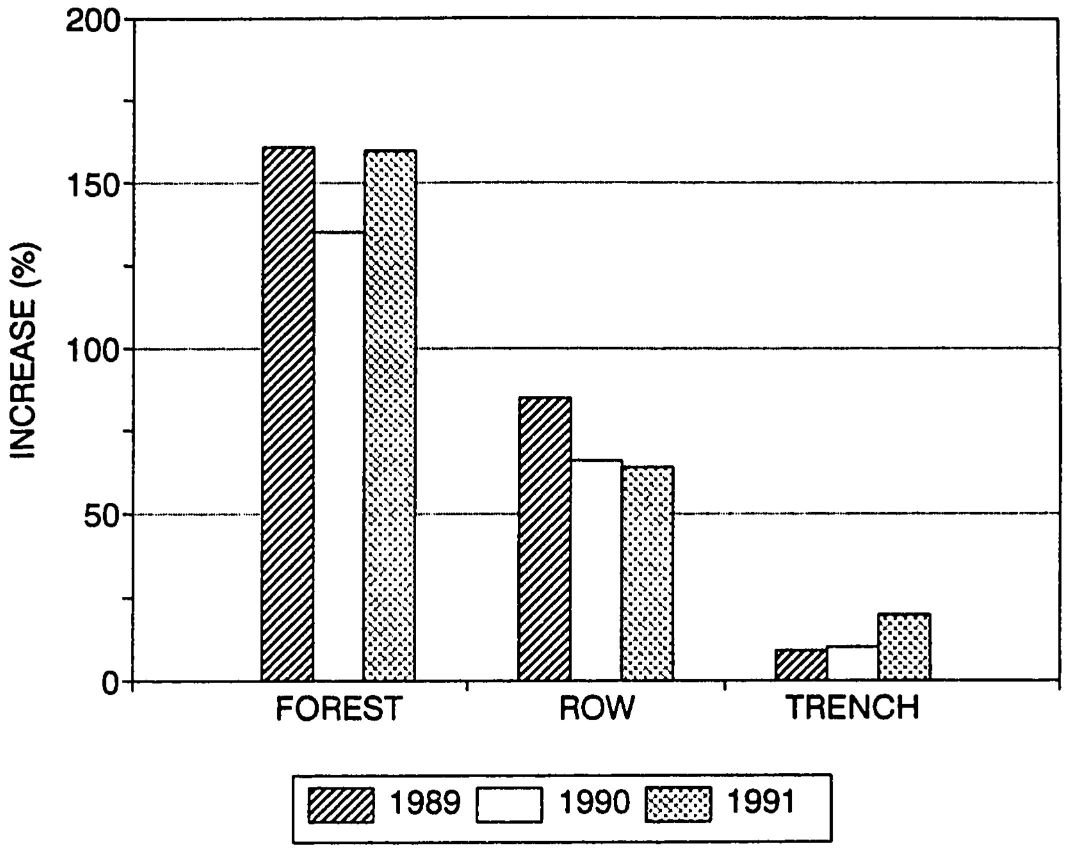

Figure 2-4. Yearly percentage increase in mean maximum thaw depths of the oiled Forest, ROW, and Trench compared with the respective mean maximum thaw depth of the unoiled disturbance type of that year.

Analysis of variance performed on the 1989 data revealed no significant differences among any of the ROWs ($F = 0.51$, $p > 0.5$) or Trenches ($F = 2.24$, $p > 0.1$) (Table 2-2). The three ROWs and Trenches were then pooled for all subsequent analyses in this, and the following two years of the study.

Next, unoiled environments (Forest, ROW, Trench) were compared to determine if there were significant differences among types of disturbances. For all three years of the study, there were significant differences ($p < 0.0001$) among environments (Table 2-3).

Since the ANOVA tests indicated significant overall differences among mean maximum depths of thaw, pairs of individual types of disturbance were then compared. Again, for all three years of the study, there were significant differences ($p < 0.01$) between types of unoiled disturbances (Table 2-4).

Next, oiled maximum thaw depths were compared (Table 2-5). Because oil concentration rates varied, each ROW and Trench probe line were compared. There was only one oiled Forest transect so no comparison was possible. Analysis of variance revealed no significant differences among any of the mean maximum thaw depths for the three individual oiled ROW probe transects in any of the three years of the study. Mean maximum thaw depths for the three Trench transects did not differ significantly from each other in 1989 or 1990. However, in 1991, Trench C had a mean maximum thaw depth significantly shallower than the other two Trenches ($p < 0.001$).

The data for ROW transects A,B,C and Trench transects A,B,C for each year were then pooled to form an overall mean maximum thaw depth for the ROW and Trench for each year (Table 2-1). The only exception to this was the 1991 Trench, where only Trench A and B could be pooled. Next, oiled environments (Forest, ROW, Trench) were compared for each year. There were no significant differences among environments in either 1989 or 1990, however environments did differ significantly ($p < 0.05$) in 1991 (Table 2-6).

As the overall ANOVA was insignificant for 1989 and 1990 multiple comparisons between pairs of means was only possible for the 1991 data. Only the Trench was significantly deeper ($p < 0.05$) than the Forest (Table 2-7). Next, oiled and unoiled environments were compared over the three years of the study (Table 2-8). All environments differed significantly over time, except for the unoiled and oiled Forest.

Multiple comparison tests were then performed on the unoiled data from the ROW and Trench (Table 2-9). Although the mean maximum thaw depth of the ROW became deeper each year, the difference was not significant.

Table 2-2. Results of ANOVA tests comparing mean maximum thaw depths for individual unoiled ROWs and Trenches for 1989. All comparisons based on log transformed data. Means with the same superscripts are not significantly different at $p < 0.05$.

UNOILED TRANSECTS	Mean (cm)	Stand. Dev.	n
ROW 1	82.9 ^{a}	21.6	36
ROW 2	88.2 ^{a}	25.2	40
ROW 3	83.2 ^{a}	23.6	36
Trench 1	160.2 ^{b}	26.3	20
Trench 2	172.1 ^{b}	18.0	20
Trench 3	157.8 ^{b}	25.6	29

Table 2-3. Summary of ANOVA results comparing mean maximum thaw depths for the three levels of unoiled disturbances (Forest, ROW, and Trench). Sample sizes (n) refer to number of probe points for the Forest, ROW, and Trench, respectively. All comparisons based upon log transformed data.

AMONG UNOILED DISTURBANCES	n	F	p
1989	127, 112, 60	411.4	< 0.0001
1990	128, 109, 59	284.4	< 0.0001
1991	127, 109, 57	257.1	< 0.0001

Table 2-4. Summary of multiple comparisons using the GT2 method for pairs of mean maximum thaw depths for types of unoiled disturbances. Sample sizes (n) refer to number of probe points for the environments being compared, respectively. All comparisons based upon log transformed data.

BETWEEN UNOILED DISTURBANCES	n	m	p
1989			
FOREST VS. ROW	127, 112	11.5	< 0.001
FOREST VS. TRENCH	127, 60	28.7	< 0.001
ROW VS. TRENCH	112, 60	18.7	< 0.001
1990			
FOREST VS. ROW	128, 109	12.8	< 0.001
FOREST VS. TRENCH	128, 59	23.5	< 0.001
ROW VS. TRENCH	109, 59	12.6	< 0.001
1991			
FOREST VS. ROW	127, 109	14.1	< 0.001
FOREST VS. TRENCH	127, 57	21.8	< 0.001
ROW VS. TRENCH	109. 57	10.0	< 0.001

Table 2-5. Results of ANOVA tests comparing mean maximum thaw depths for individual oiled ROWs and Trenches. Comparisons are only among groups of ROWs or Trenches for a given year and are based on log transformed data. Means of a given group with the same superscript are not significantly different at $p < 0.05$; means with different superscripts are significantly different at $p < 0.001$.

OILED TRANSECTS	Mean (cm)	Stand. Dev.	n
1989			
ROW A	163.3 [a]	37.7	8
ROW B	165.4 [a]	27.4	9
ROW C	143.8 [a]	21.6	9
Trench A	173.3 [b]	33.3	3
Trench B	178.5 [b]	28.6	3
Trench C	184.7 [b]	17.9	3
1990			
ROW A	167.4 [c]	26.2	8
ROW B	148.1 [c]	20.5	10
ROW C	150.1 [c]	25.0	9
TRENCH A	162.7 [d]	16.7	3
TRENCH B	170.7 [d]	18.9	3
TRENCH C	157.0 [d]	22.3	3
1991			
ROW A	193.8 [e]	28.8	8
ROW B	173.3 [e]	18.8	10
ROW C	179.9 [e]	8.8	9
TRENCH A	197.7 [f]	2.3	3
TRENCH B	203.7 [f]	13.7	3
TRENCH C	143.0 [g]	10.6	3

Table 2-6. Summary of ANOVA results comparing mean maximum thaw depths for the three types of oiled environments (Forest, ROW, and Trench). Sample sizes (n) refer to number of probe points for the Forest, ROW, and Trench, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

AMONG OILED ENVIRONMENTS	n	F	p
1989	15, 26, 9	1.78	N.S.
1990	15, 27, 9	2.67	N.S.
1991	15, 27, 6	3.98	< 0.05

Table 2-7. Summary of multiple comparisons using the GT2 method for pairs of mean maximum thaw depths for types of oiled environments. Sample sizes (n) refer to number of probe points for the environments being compared, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

BETWEEN OILED DISTURBANCES	n	m	p
1991			
FOREST VS. ROW	15, 27	1.96	N.S.
FOREST VS. TRENCH	15, 6	2.56	< 0.05
ROW VS. TRENCH	27, 6	1.34	N.S.

Table 2-8. Summary of ANOVA results comparing mean maximum thaw depths for each unoiled and oiled environment (Forest, ROW, and Trench) over time. Sample sizes (n) refer to number of probe points for 1989, 1990, 1991, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

AMONG 3 YEARS	n	F	p
UNOILED			
FOREST	127, 128, 127	2.59	N.S.
ROW	112, 109, 109	16.25	< 0.0001
TRENCH	60, 59, 57	8.02	< 0.001
OILED			
FOREST	15, 15, 15	1.67	N.S.
ROW	26, 27, 27	8.19	< 0.001
TRENCH	9, 9, 6	5.89	< 0.01

Table 2-9. Summary of multiple comparisons using the GT2 method for pairs of mean maximum thaw depths for types of unoiled environments between years. Sample sizes (n) refer to years being compared, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

UNOILED BETWEEN YEARS	n	m	p
1989-1990			
ROW	112, 109	1.86	N.S.
TRENCH	60, 59	3.12	< 0.01
1990-1991			
ROW	109, 109	3.71	< 0.01
TRENCH	59, 57	3.77	< 0.01
1989-1991			
ROW	112, 109	5.59	< 0.01
TRENCH	60, 57	0.70	N.S.

between 1989 and 1990 ($p > 0.10$). However, the 1991 thaw depth was significantly deeper than both the previous years ($p < 0.01$). The Trench became significantly shallower in 1990 compared with 1989 ($p < 0.01$). In 1991 the Trench attained its greatest thaw depth. This was significantly deeper than the 1990 thaw depth ($p < 0.01$), however it was not significantly different from the original 1989 thaw depth ($p > 0.10$).

Next, multiple comparisons were made on oiled environments between years (Table 2-10). The oiled ROW became somewhat shallower in 1990 although this difference was not significantly less than the 1989 value ($p > 0.10$). In 1991, the oiled ROW was significantly deeper than both previous years ($p < 0.01$). The oiled Trench also became somewhat shallower in 1990 compared with 1989 although not significantly ($p > 0.10$). In 1991 the oiled Trench attained its greatest thaw depth. This was significantly deeper than the 1990 thaw depth ($p < 0.01$), however it was not significantly different from the original 1989 thaw depth ($p > 0.10$).

Comparisons of oiled and unoiled environments were then undertaken (Table 2-11). In 1989, the oiled Forest had a maximum thaw depth well over twice as deep as the unoiled Forest ($p < 0.0001$). In the same year, the oiled ROW was almost twice as deep as the unoiled ROW ($p < 0.0001$). While the oiled Trench was over 15 cm deeper than the unoiled Trench, this difference was not significant ($p > 0.05$).

In 1990 and 1991, all three oiled environments had maximum thaw depths significantly greater than the unoiled environments (Table 2-11). Again, the greatest difference in mean maximum thaw depths was between the oiled and unoiled Forest. For the 1991 Trench data, the pooled data of oiled Trench A and B were used. When oiled Trench C was compared with the mean maximum thaw depth for the unoiled Trench, no significant difference was found ($F = 1.8$, $p > 0.05$).

Thaw Rates

Thaw rates were calculated assuming a constant rate of thaw between first and last frost probing during a thaw season. Considering only the unoiled transects, there is great variation among disturbances in terms of mean thaw rate, however, there appears to be little variation among years (Table 2-12). Mean minimum thaw depths are relatively similar for all disturbances over all years of study, with the exception of the Trench in 1989, which is somewhat deeper.

Within the oil spill, thaw rates are less variable among disturbances (Table 2-13). Mean minimum thaw depths for the oiled ROW

Table 2-10 Summary of multiple comparisons using the GT2 method for pairs of mean maximum thaw depths between types of oiled environments between years. Sample sizes (n) refer to number of probe points for the environments being compared, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

OILED BETWEEN YEARS	n	m	p
1989-1990			
ROW	26, 27	0.21	N.S.
TRENCH	9, 9	1.36	N.S.
1990-1991			
ROW	27, 27	3.60	< 0.01
TRENCH	9, 6	2.97	< 0.01
1989-1991			
ROW	26, 27	3.35	< 0.01
TRENCH	9, 6	1.76	N.S.

Table 2-11. Summary of ANOVA results comparing mean maximum thaw depths between unoiled and oiled environments. Sample sizes (n) refer to number of probe points for unoiled and oiled environments being compared, respectively. All comparisons based upon log transformed data. N.S. -- Not significantly different at $p < 0.05$.

UNOILED VS. OILED	n	F	p
1989			
FOREST	127, 15	274.0	< 0.0001
ROW	112, 26	122.4	< 0.0001
TRENCH	60, 9	2.8	N.S.
1990			
FOREST	128, 15	179.8	< 0.0001
ROW	109, 27	75.1	< 0.0001
TRENCH	59, 9	4.5	< 0.05
1991			
FOREST	127, 15	199.3	< 0.0001
ROW	109, 27	63.5	≤ 0.0001
TRENCH	57, 6	6.7	< 0.025

Table 2-12. Mean minimum, maximum, and delta thaw depths (in cm), and thaw rates (in cm/day) for unoiled environments as determined by frost probing. Values are averaged over the four transects. Standard deviations are given in parenthesis beneath the means.

UNOILED	MINIMUM	MAXIMUM	DELTA	RATE
1989				
FOREST	11.8 (5.9)	59.6 (13.4)	47.8 (13.7)	0.49 (0.14)
ROW	11.7 (5.2)	84.9 (23.5)	73.1 (22.7)	0.75 (0.23)
TRENCH	19.9 (11.2)	163.4 (24.0)	143.5 (27.1)	1.46 (0.28)
1990				
FOREST	12.4 (7.1)	59.9 (15.5)	48.4 (17.6)	0.48 (0.18)
ROW	11.8 (5.6)	93.0 (29.5)	81.5 (30.3)	0.81 (0.30)
TRENCH	10.8 (7.6)	149.0 (17.6)	138.1 (18.8)	1.38 (0.19)
1991				
FOREST	11.9 (7.3)	63.7 (17.5)	51.8 (20.0)	0.46 (0.18)
ROW	14.2 (9.6)	110.4 (39.2)	96.2 (37.9)	0.86 (0.34)
TRENCH	13.7 (7.2)	167.6 (31.5)	153.9 (33.4)	1.37 (0.30)

Frost probing dates:

	Miniumum	Maximum
1989	May 16	August 24
1990	May 13	August 20
1991	May 8	August 28

Table 2-13. Mean minimum, maximum, and delta thaw depths (in cm), and thaw rates (in cm/day) for oiled environments as determined by frost probing. Forest values are from Transect C. ROW and Trench values are averaged over the three transects, with the exception of 1991 Trench values which are averaged over Transect A and B. Standard deviations are given in parenthesis beneath the means.

OILED	MINIMUM	MAXIMUM	DELTA	RATE
1990				
FOREST	26.8 (11.3)	140.9 (28.0)	114.0 (30.0)	1.15 (0.30)
ROW	12.3 (6.6)	154.5 (24.4)	142.2 (26.9)	1.44 (0.27)
TRENCH	12.3 (5.5)	163.4 (17.9)	151.1 (17.7)	1.53 (0.18)
1991				
FOREST	28.9 (9.8)	165.6 (32.4)	136.7 (31.2)	1.22 (0.28)
ROW	16.7 (6.7)	181.6 (21.0)	164.8 (22.7)	1.47 (0.20)
TRENCH	13.6 (3.1)	200.7 (9.4)	187.1 (9.7)	1.67 (0.09)

Frost probing dates:

	Miniumum	Maximum
1989	May 16	August 24
1990	May 13	August 20
1991	May 8	August 28

and Trench are similar and are comparable to the unoiled mean minimum thaw depths, however, the oiled Forest appears to have a deeper mean minimum thaw depth than any other disturbance, oiled or unoiled.

To attempt to correct for the assumption of a constant rate of thaw from the first to last frost probe session the mean thaw depths for each frost probe session for each disturbance were examined for all years (Figure 2-5 to Figure 2-9). Unfortunately, a large gap of six to nine weeks exists in the dataset for each year during the early summer when the camp was unoccupied. Nonetheless, the graphs are useful for seeing the general trend of the development of the active layer.

In terms of the unoiled thaw depths, for all three years the Trench quickly became the environment of deepest thaw, consequently, there was a clear separation of the three curves (Figs. 2-5, 2-6, 2-8). In contrast, based on the oiled thaw depths the Forest quickly became the environment with the deepest thaw, at least initially (Figs. 2-7, 2-9). In addition, there was little separation between the three curves, unlike the unoiled curves.

Thaw rates were again calculated, this time using least squares linear regression using the square root of time as the independent variable (Figure 2-10 to Figure 2-14). The coefficients of determination (r^2) were all quite high, ranging from 0.97 to 0.99.

Year to year variation in the mean thaw rate (or the slope of the regression equation) for the Forest was minimal. The maximum thaw rate was 7.7 cm•day$^{-0.5}$ in 1989 and decreased over the next two years to 6.6 cm•day$^{-0.5}$ by 1991.

The ROW also had little annual variation in the mean thaw rate. It was only 11.8 cm•day$^{-0.5}$ in 1989 and it marginally increased in both 1990 and 1991 until it reach 12.2 cm•day$^{-0.5}$. In general the mean thaw rate of the ROW was almost double that of the Forest.

Like both the Forest and the ROW, the Trench experienced little variation over the three years. Like the Forest, its rate of thaw was greatest in 1989 (21.8 cm•day$^{-0.5}$) and declined slightly in both 1990 and 1991 until it reached 20.2 cm•day$^{-0.5}$. The rate of thaw of the Trench was almost double that of the ROW.

In contrast, there was small variation in the average thaw rates among the oiled environments. In both years, the slope of the Forest's curves was lowest, despite the fact that the Forest started off being deeper.

Year to year variation was greatest for the oiled Forest. It increased just over 2 cm•day$^{-0.5}$ from 1990 to 1991. With thaw rates of 17.0 and 19.1 cm•day$^{-0.5}$, for 1990 and 1991, respectively the oiled Forest

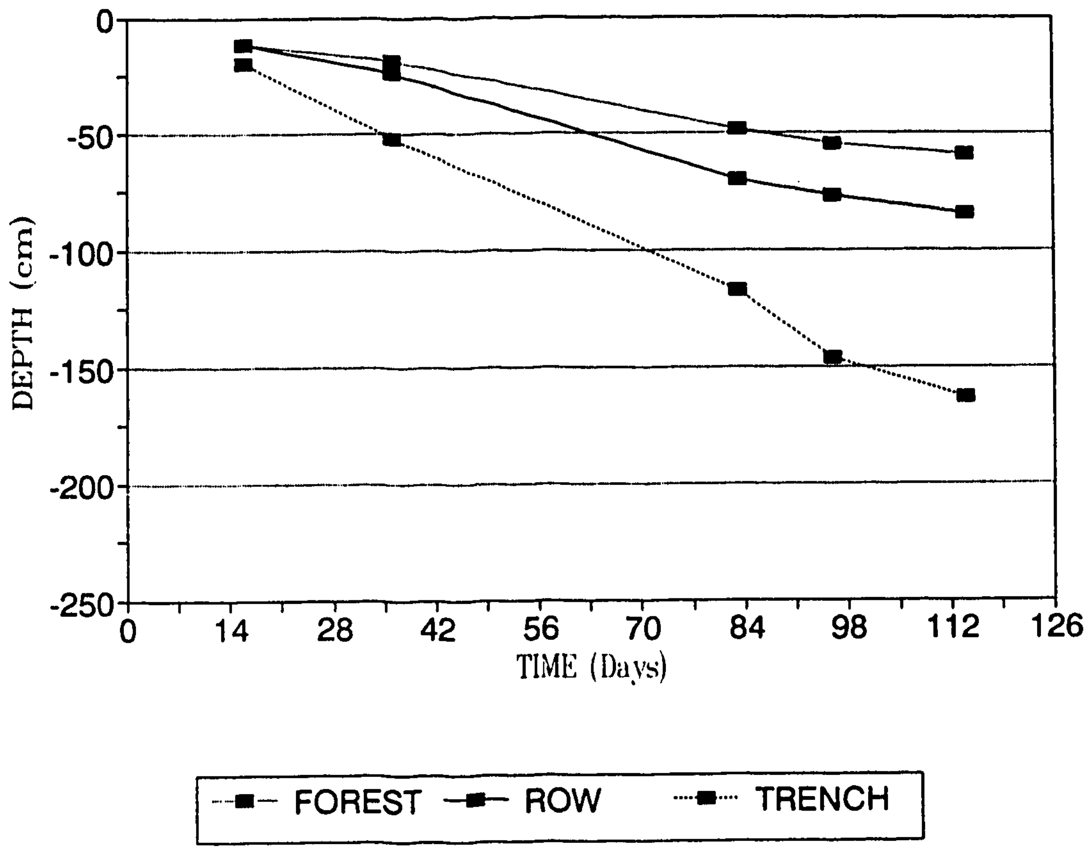

Figure 2-5. Seasonal progression of thaw depths for the unoiled Forest, ROW and Trench in 1989. Day 1 = May 1.

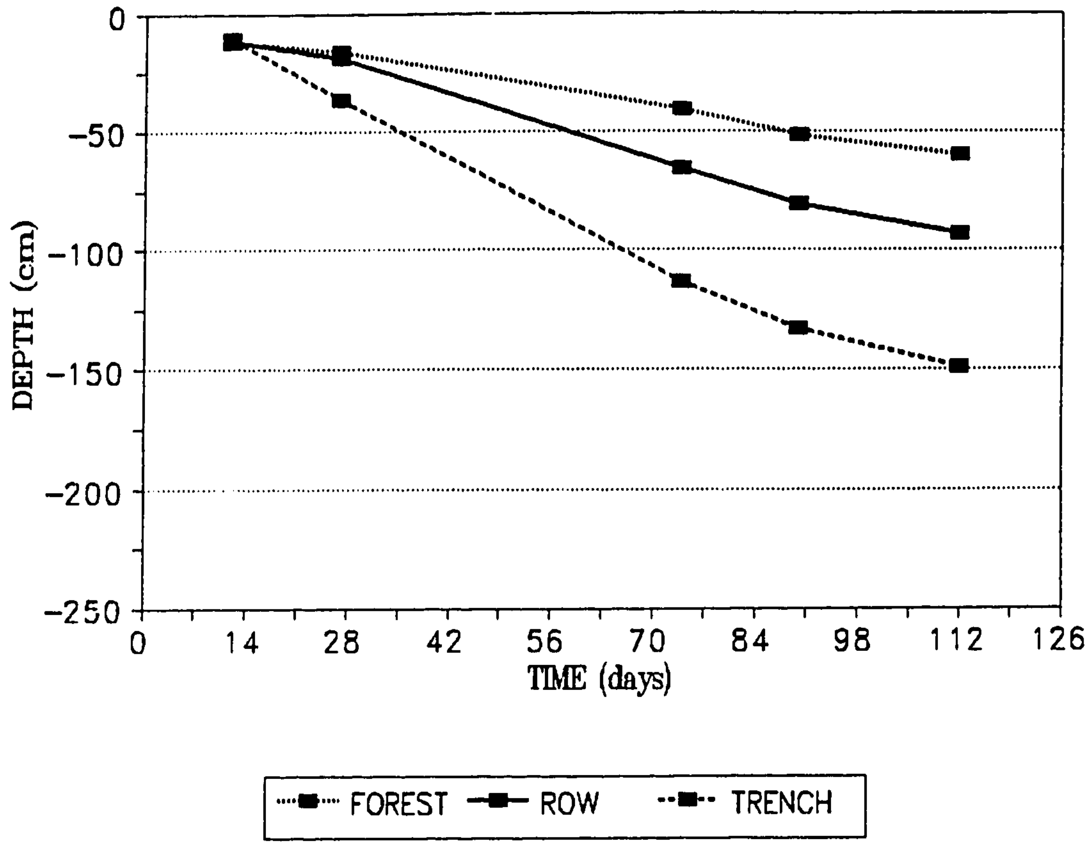

Figure 2-6. Seasonal progression of thaw depths for the unoiled Forest, ROW and Trench in 1990. Day 1 = May 1.

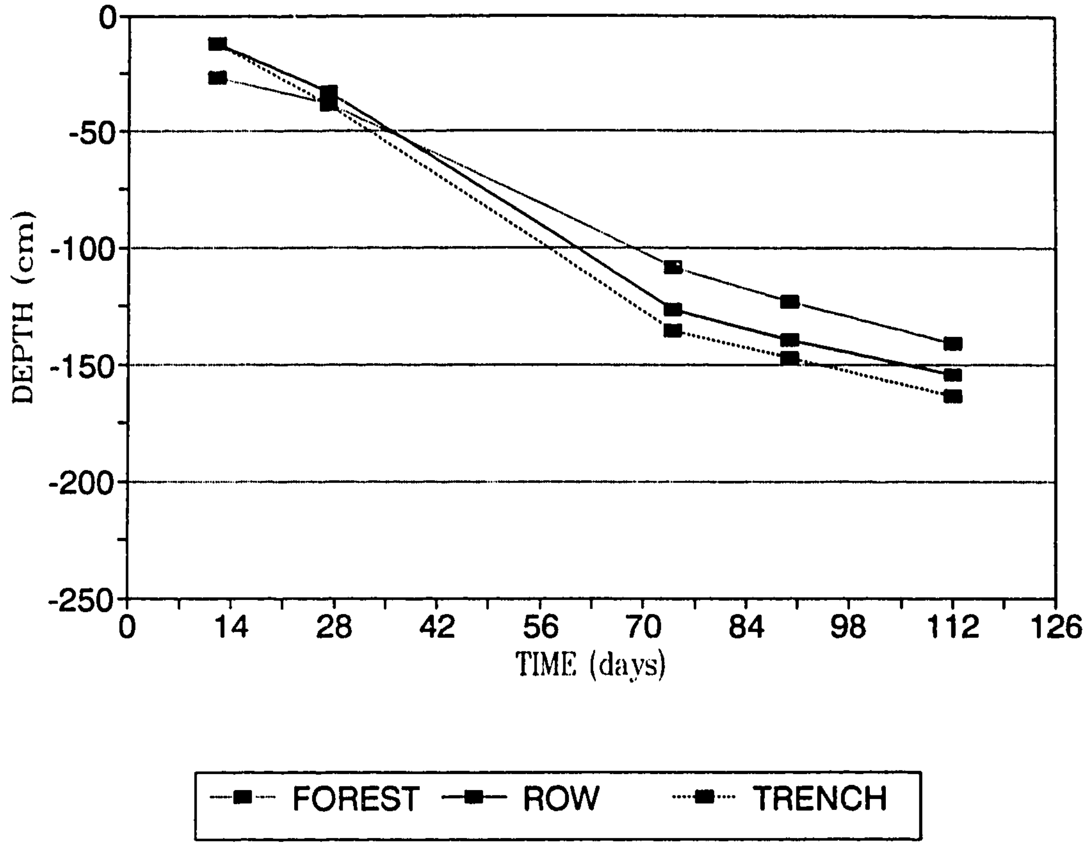

Figure 2-7. Seasonal progression of thaw depths for the oiled Forest, ROW and Trench in 1990. Day 1 = May 1.

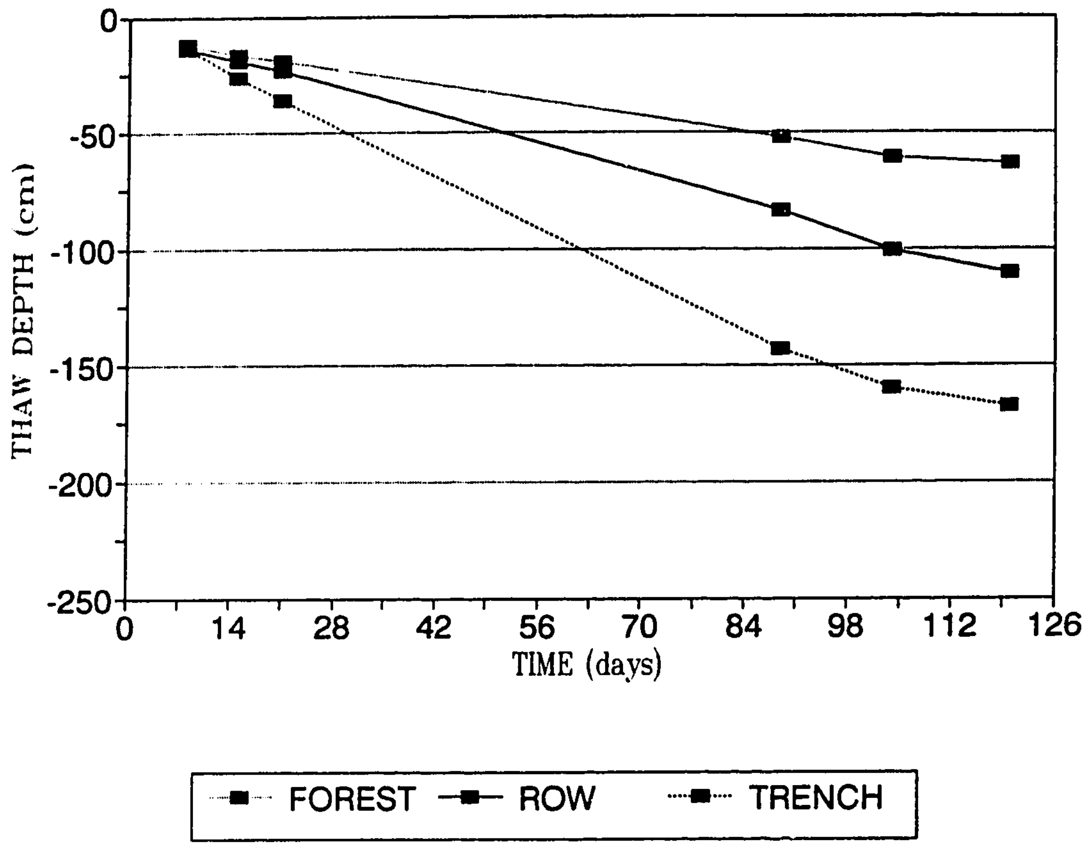

Figure 2-8. Seasonal progression of thaw depths for the unoiled Forest, ROW and Trench in 1991. Day 1 = May 1.

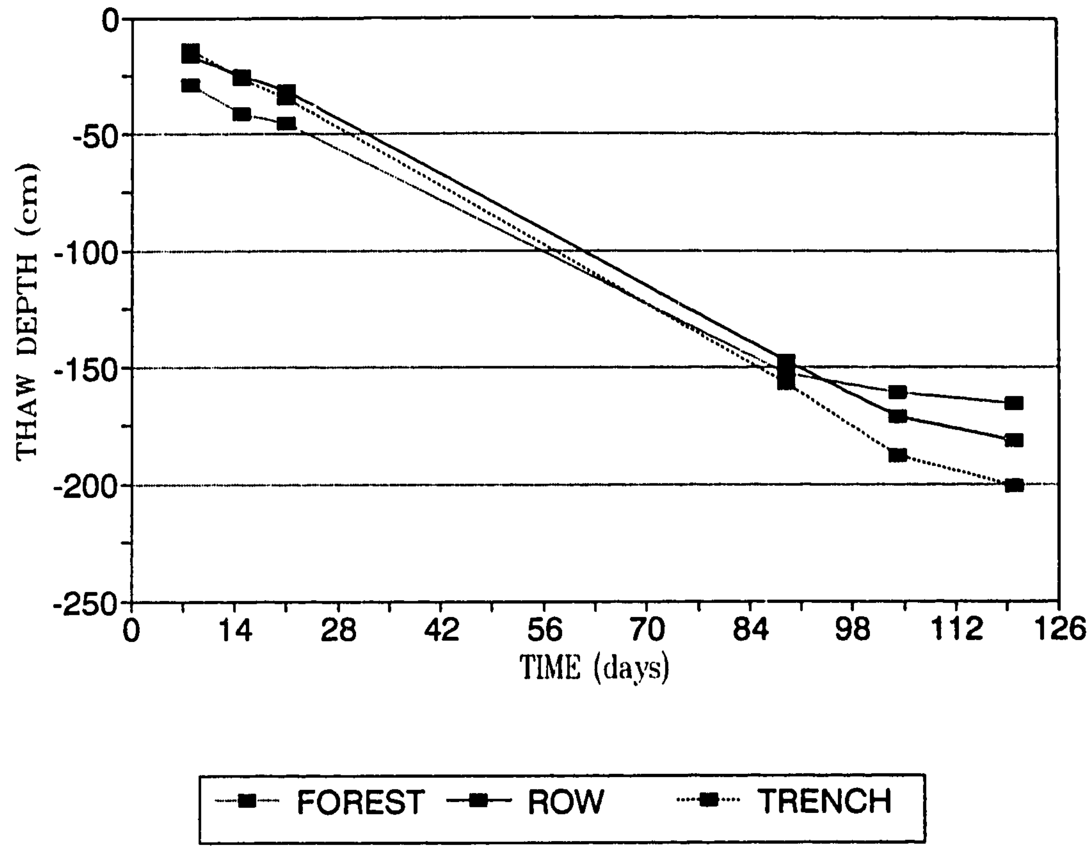

Figure 2-9. Seasonal progression of thaw depths for the oiled Forest, ROW and Trench in 1991. Day 1 = May 1.

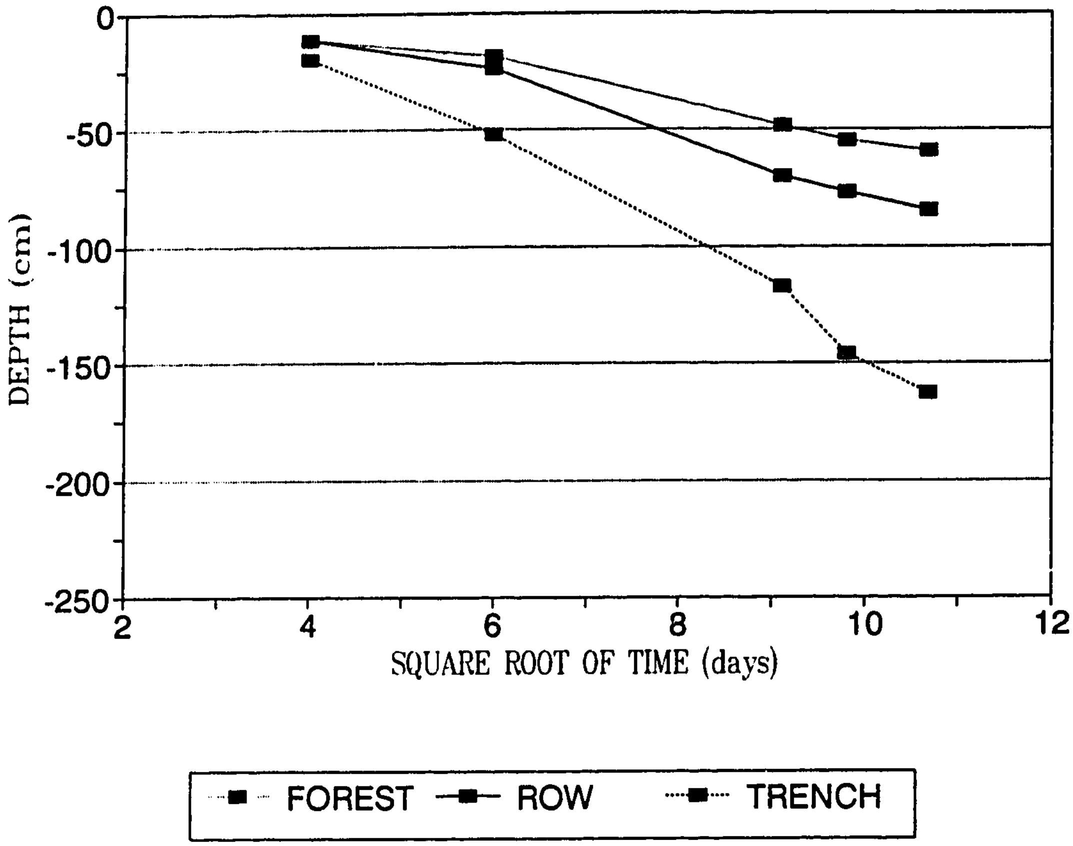

Figure 2-10. Seasonal progression of thaw depths (Z) for the unoiled Forest, ROW and Trench in 1989 against the square root of time (t). Day 1 = May 1.

FOREST	$Z = 7.7\ t^{1/2} - 22.1$	$r^2 = 0.98$
ROW	$Z = 11.8\ t^{1/2} - 39.3$	$r^2 = 0.98$
TRENCH	$Z = 21.8\ t^{1/2} - 72.5$	$r^2 = 0.99$

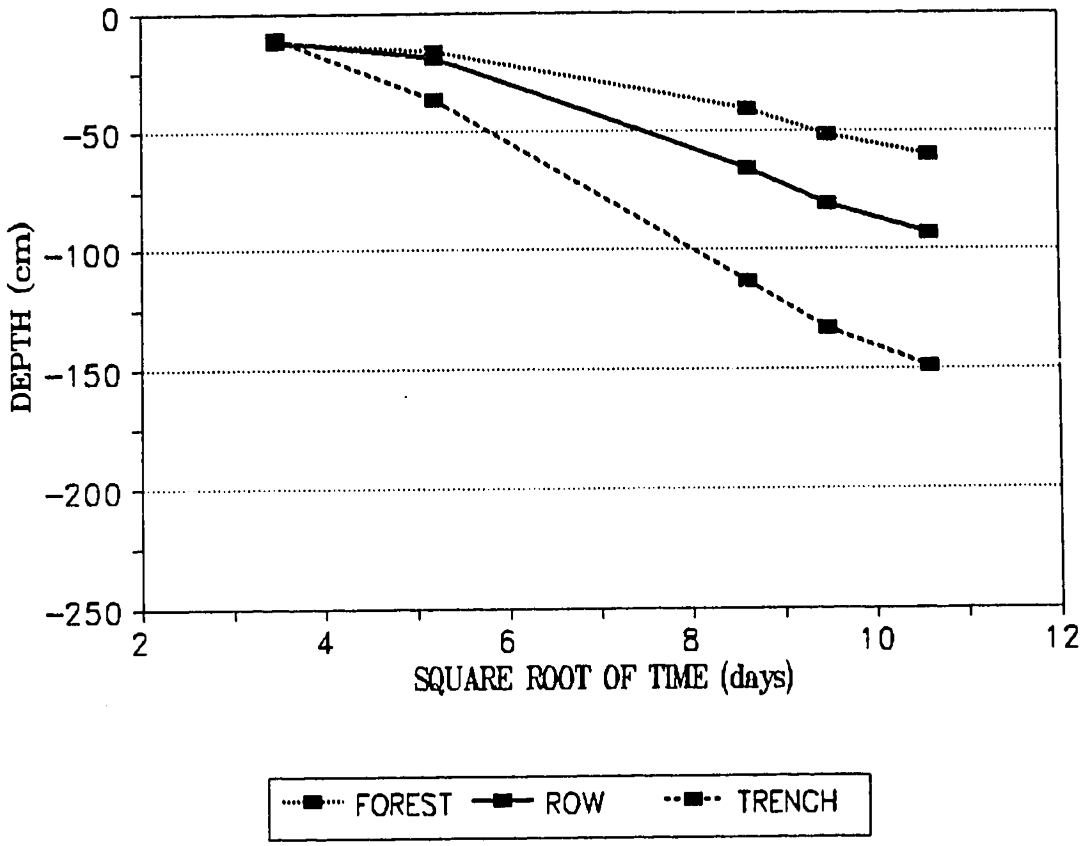

Figure 2-11. Seasonal progression of thaw depths (Z) for the unoiled Forest, ROW and Trench in 1990 against the square root of time (t). Day 1 = May 1.

FOREST	$Z = 6.9\ t^{1/2} - 15.3$	$r^2 = 0.97$
ROW	$Z = 12.1\ t^{1/2} - 35.9$	$r^2 = 0.98$
TRENCH	$Z = 20.3\ t^{1/2} - 62.8$	$r^2 = 0.99$

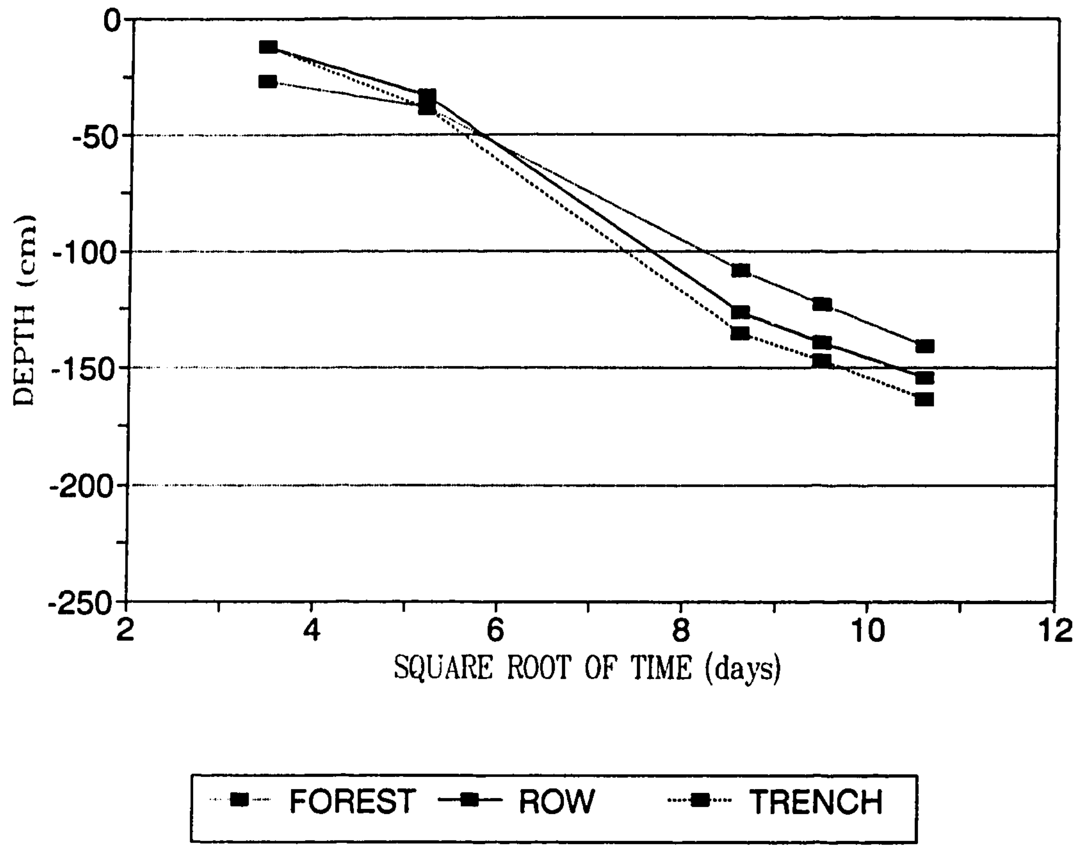

Figure 2-12. Seasonal progression of thaw depths (Z) for the oiled Forest, ROW and Trench in 1990 against the square root of time (t). Day 1 = May 1.

FOREST	$Z = 17.0\ t^{1/2} - 39.5$	$r^2 = 0.98$
ROW	$Z = 21.6\ t^{1/2} - 67.8$	$r^2 = 0.98$
TRENCH	$Z = 22.7\ t^{1/2} - 70.0$	$r^2 = 0.99$

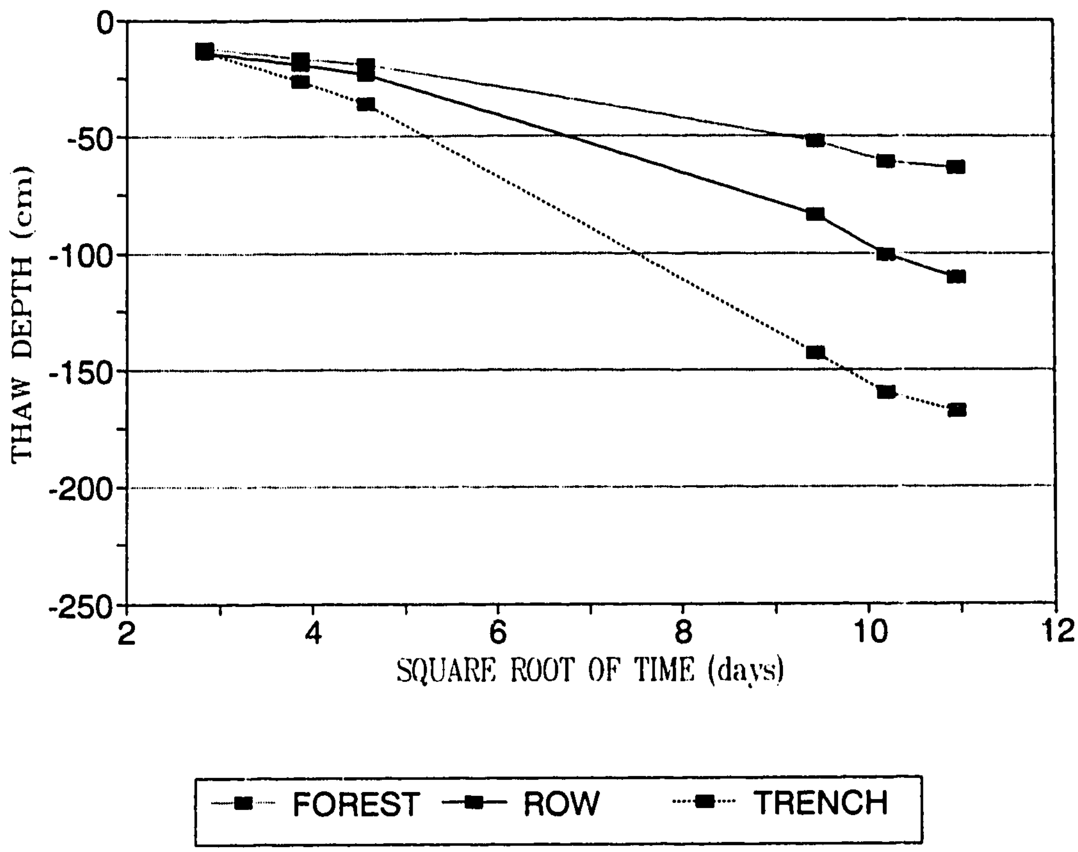

Figure 2-13. Seasonal progression of thaw depths (Z) for the unoiled Forest, ROW and Trench in 1991 against the square root of time (t). Day 1 = May 1.

FOREST	$Z = 6.6\ t^{1/2} - 8.8$	$r^2 = 0.99$
ROW	$Z = 12.2\ t^{1/2} - 26.6$	$r^2 = 0.99$
TRENCH	$Z = 20.2\ t^{1/2} - 49.6$	$r^2 = 0.99$

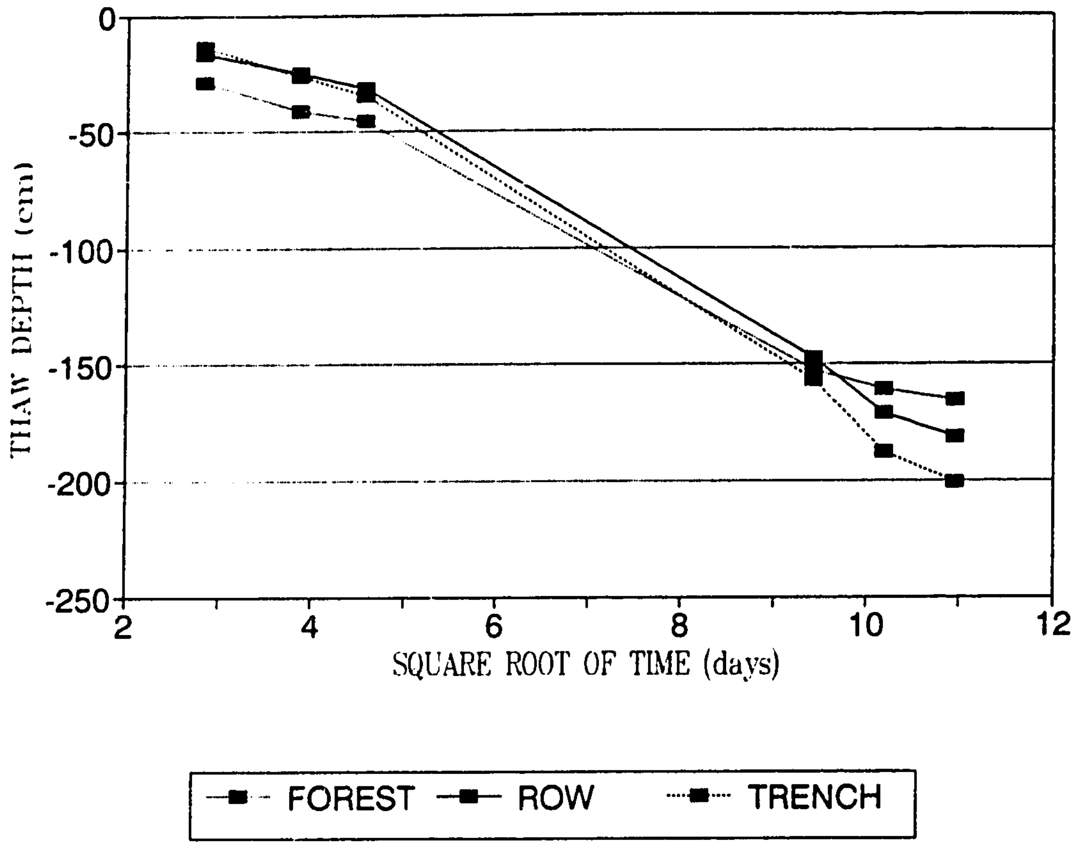

Figure 2-14. Seasonal progression of thaw depths (Z) for the oiled Forest, ROW and Trench in 1991 against the square root of time (t). Day 1 = May 1.

FOREST	$Z = 19.1\ t^{1/2} - 32.4$	$r^2 = 0.99$
ROW	$Z = 21.9\ t^{1/2} - 57.0$	$r^2 = 0.99$
TRENCH	$Z = 24.0\ t^{1/2} - 64.7$	$r^2 = 0.99$

has a thaw rate just slightly lower than the unoiled Trench.

The oiled ROW had very little variation between the two years. It increased from 21.6 to 21.9 cm•day$^{-0.5}$ from 1990 to 1991. This thaw rate was virtually identical to the unoiled Trench's.

The oiled Trench's thaw rate also increased from 1990 (22.7 cm•day$^{-0.5}$) to 1991 (24.0 cm•day$^{-0.5}$). Both these thaw rates are greater than any experienced in the unoiled Trench. Hence the oiled Trench had not only the greatest thaw depths but also the greatest thaw rates.

Microclimatic Data

Frost probing can only provide an indication of the 0° C isotherm in the soil. Microclimatic stations set up at the SEEDS site offer an additional source of information on ground temperatures. While a complete analysis of the microclimatic data is beyond the scope of this paper, some preliminary results have been obtained from the unoiled environments. Of particular concern is whether or not a thaw bulb, or talik, has developed under the Trench. If an unfrozen layer existed under the Trench then subsequent thawing in later years would be facilitated.

Thermistors installed at 0.5 m depth provide an indication of fluctuating ground temperatures in both the unoiled Forest and Trench for the first year of this study, 1989 (Figure 2-15). While the Forest had little variation in temperature at this depth, the Trench had a dramatic fluctuation in temperature. In both the Forest and the Trench ground temperatures were below freezing at the start of the year.

At a depth of approximately 2.0 m, both the Forest and Trench demonstrate remarkable symmetry in their ground temperatures (Figure 2-16). However, without exception, the Trench was warmer than the Forest. Again, in both environments, the ground temperature was below freezing for the first few months of the year.

Using air temperatures at SEEDS, it was possible to construct the cumulative thawing degree-days for 1989 and compare them with the nearest meteorological station, located in Norman Wells (Figure 2-17). Because of an extensive gap in the dataset, the profile ended in mid-August. Despite the distance between SEEDS and Norman Wells, there was virtually no difference between the two sites.

Because of the incomplete microclimatic data from SEEDS and the great similarity between SEEDS and Norman Wells, based on the 1989 cumulative thawing degree-days, the Norman Wells meterological data were used to construct thawing degree-day totals for each year over the course of the entire SEEDS project (Figure 2-18). Thawing degree-day totals increased from 1985 to 1989. In 1990, the lowest thawing degree-day total

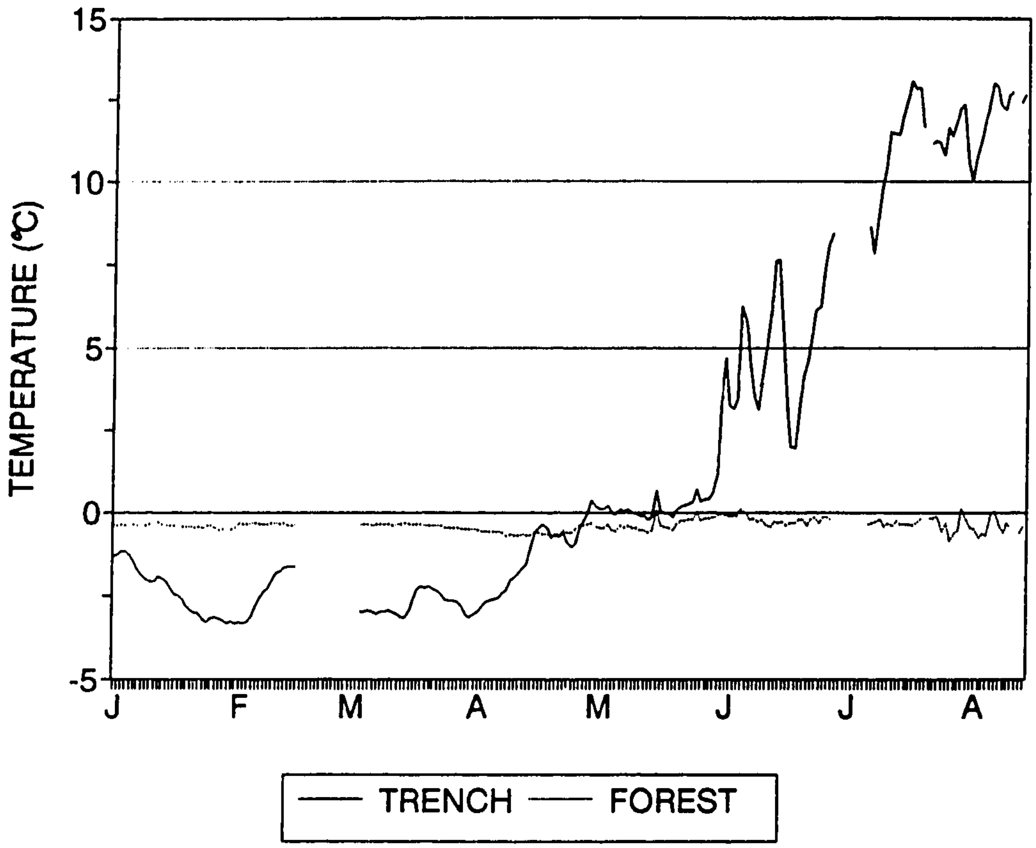

Figure 2-15. Ground temperatures at 0.5 m under the unoiled Trench and Forest in 1989 collected using microclimatic dataloggers. Gaps indicate missing data.

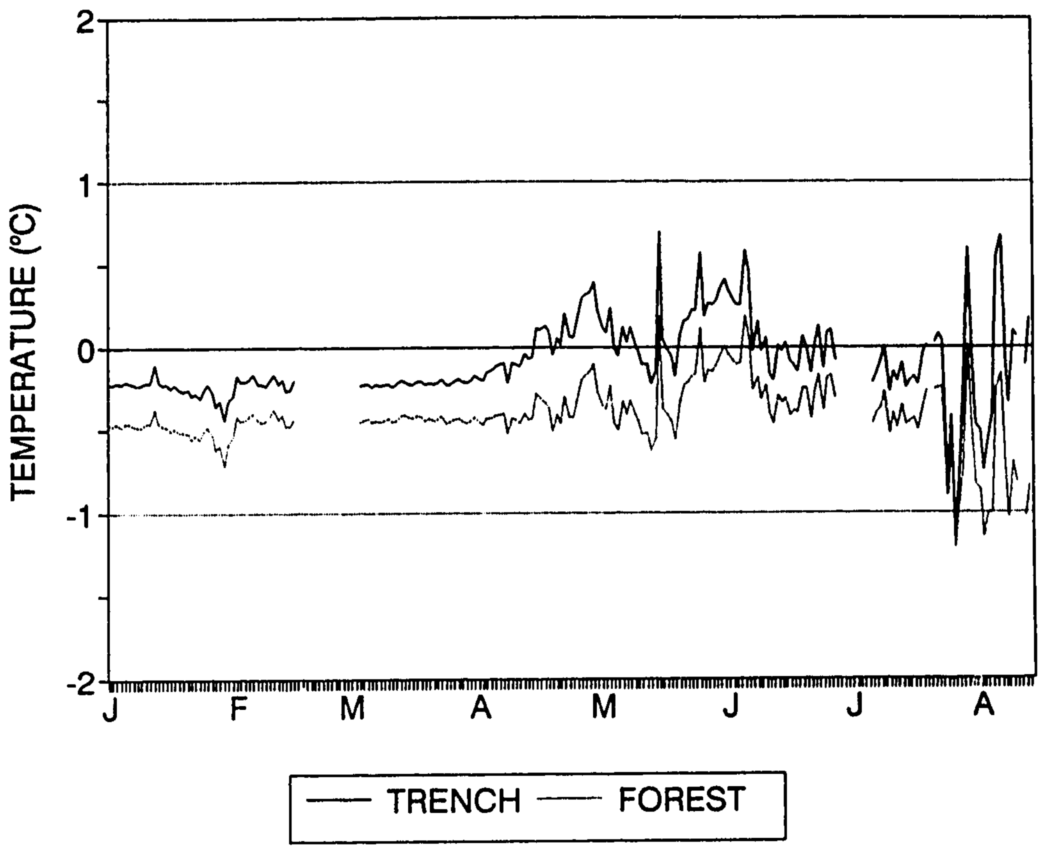

Figure 2-16. Ground temperatures at 2.0 m under the unoiled Trench and Forest in 1989 collected using microclimatic dataloggers. Gaps indicate missing data.

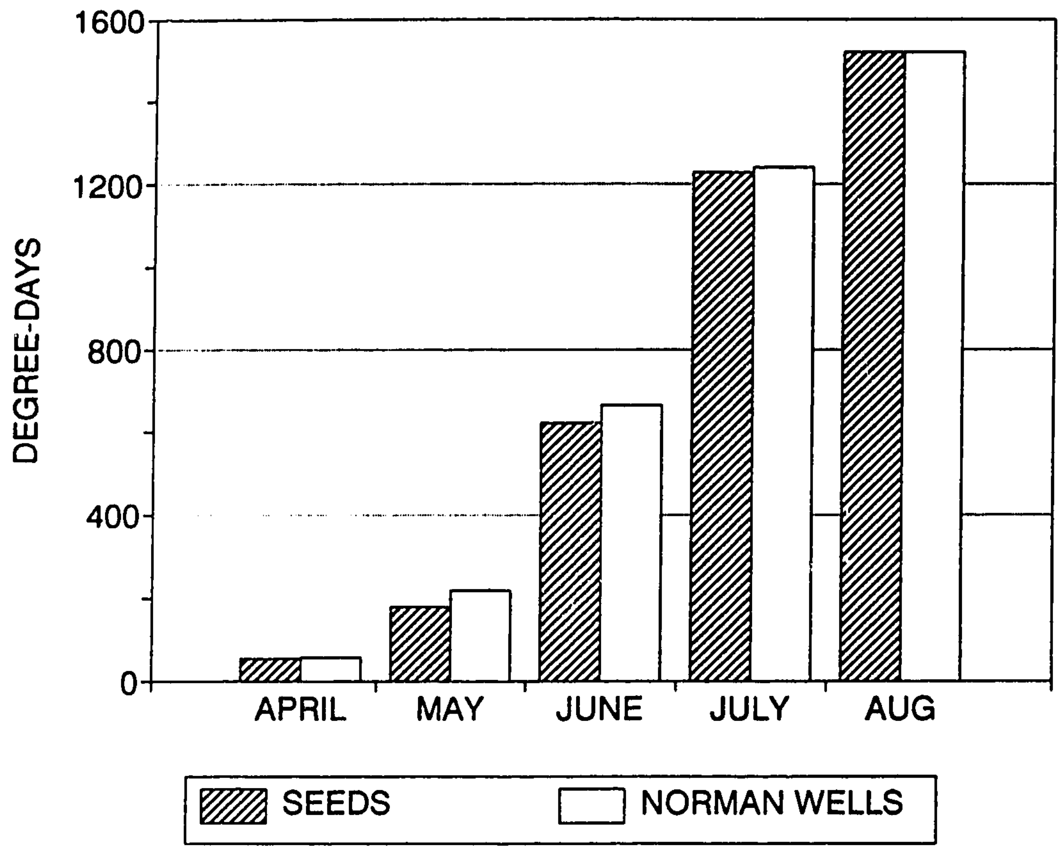

Figure 2-17. Cumulative thawing degree-days at both the SEEDS site and Norman Wells, NWT, from the beginning of April until mid-August, 1989.

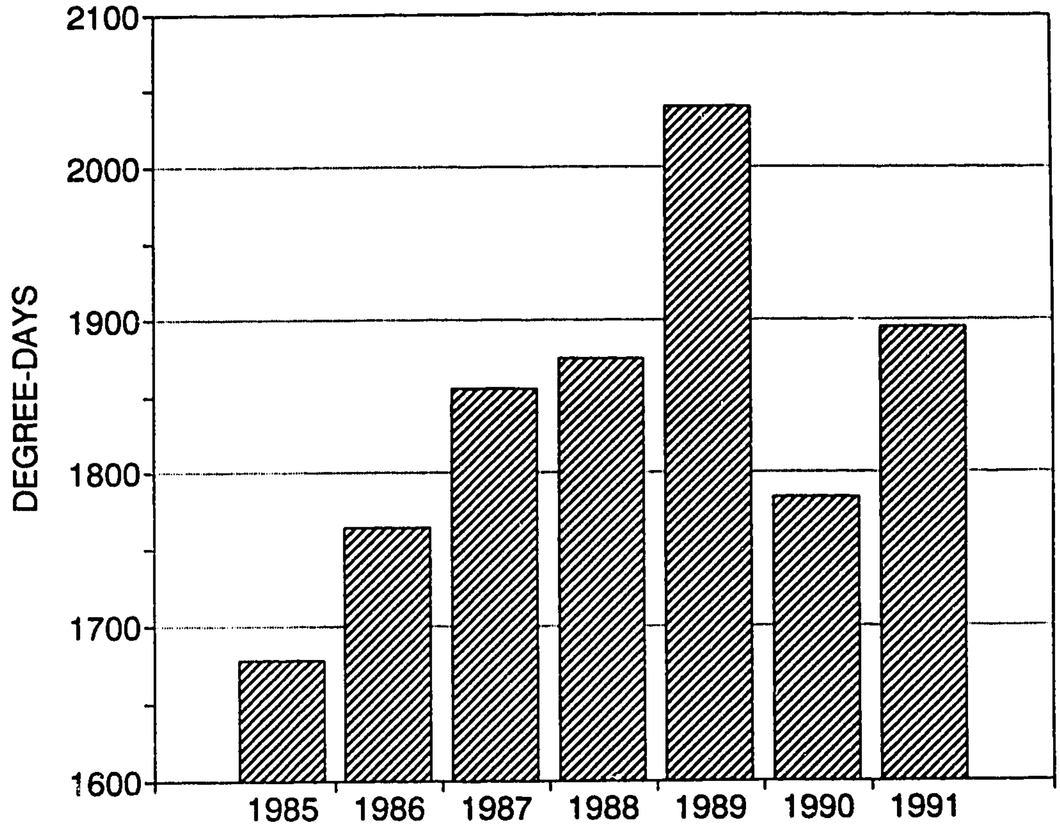

Figure 2-18. Total annual thawing degree-days for Norman Wells, NWT, from 1985 to 1991.

was experienced since 1986.

Cumulative precipitation data for the spring and summer of 1990 were also compared with the 30-year normals for Norman Wells (Figure 2-19). While June of 1990 experienced wetter weather than normal, both July and August were drier than average. In total the spring and summer of 1990 received almost 35 mm of precipitation less than normal.

DISCUSSION

The stable existence of permafrost is associated with the quasi-equilibrium of surface and climate conditions (Brown, 1970; 1973). Aggradation or degradation of permafrost is a function of a positive or negative change in the ground energy balance. Because the ground temperatures in the zone of discontinuous permafrost fluctuate around 0° C, the position of the permafrost table is naturally sensitive to any change in the ground surface energy budget.

Because frost probing was terminated in late August of each year, the measured mean maximum thaw depth can be expected to be somewhat less than the actual depth of the active layer as some post-survey thawing undoubtedly occurred. However, the mean maximum thaw depth should be a close approximation of the actual active layer as the maximum thaw depth would normally be attained between late August and mid-September and the rate of increase declines by late summer (Stearns, 1966; Viereck and Lev, 1983).

The method of frost probing relies upon the probe penetrating to the position of an ice-cemented layer of considerable mechanical strength, which may or may not correspond to the 0° C isotherm (Mackay, 1977; Nelson and Outcalt, 1982). Because of the relatively warm ground temperatures in the discontinous permafrost zone, the zero curtain effect at the permafrost table will result in a margin of error in determining the actual thaw depth regardless of the method selected (Rouse, 1982). The probe data are merely an approximation of the 0° C isotherm, but any bias in the technique should be consistent.

Year-to-year variations in active layer thickness are common. Nicholson (1978b) reported a 25% variation in year-to-year thickness of the active layer near Schefferville, Quebec in an area of discontinuous permafrost. In general, annual variations in active layer thickness are related to meteorological conditions -- for example, an exceptionally warm summer would promote a deeper active layer.

How then can the effects of the disturbance be disentangled from regional climatic effects? It is clear that during the late 1980s, a

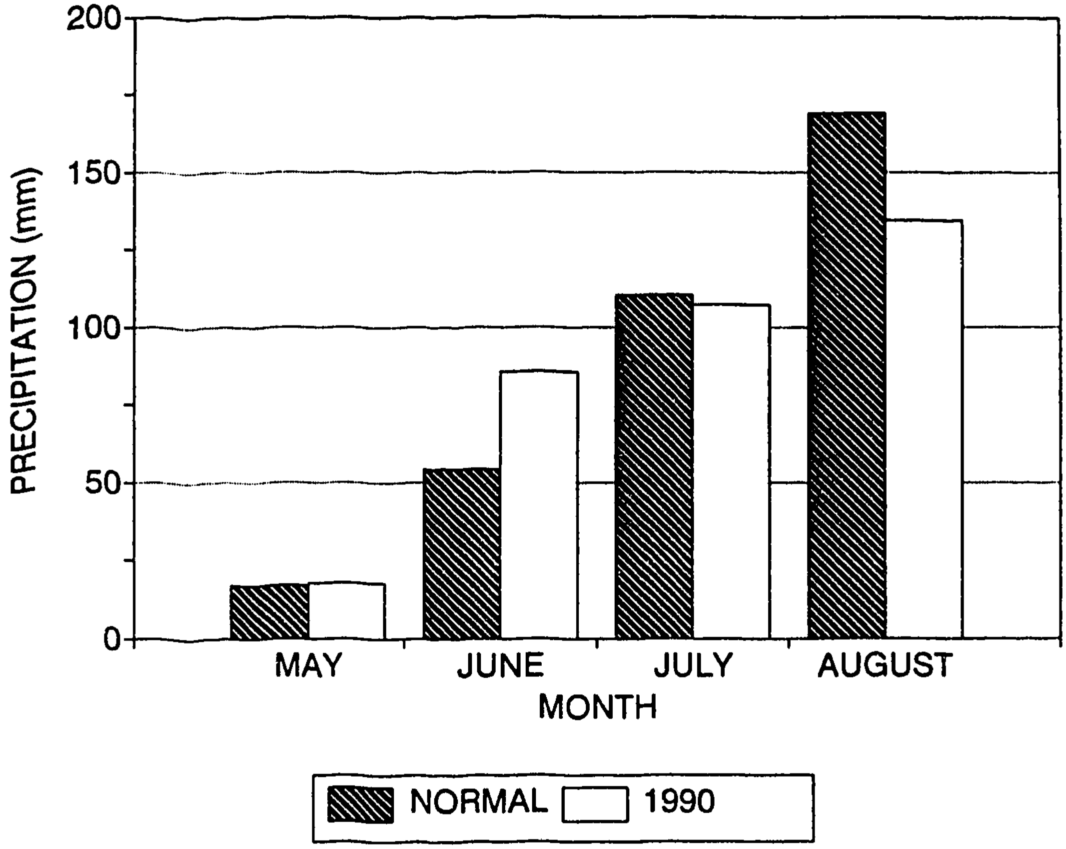

Figure 2-19. Cumulative monthly precipitation data from Norman Wells, NWT for the spring and summer of 1990 and the 30-year normals (1951-1980).

warming trend has been occurring in the Mackenzie region (Figure 2-18) as well as much of the rest of the world (McKay and Hengeveld, 1991). The relatively undisturbed Forest acts as a control for this field experiment and it did not significantly increase its mean maximum thaw depth over the course of the three years of this study. Therefore while the climatic warming experienced during this period may have influenced thaw depths, it likely was not the major influence.

Thaw Depths

All environments, both oiled and unoiled, have experienced ongoing permafrost degradation over the course of this project. In 1986, when the frost probe transects were first established, the mean maximum thaw depth of the forest was 40.4 $\pm$ 10.8 cm (Gallinger, 1991). By 1991, mean maximum thaw depths ranged from 63.7 $\pm$ 17.5 cm for the unoiled Forest to 200.7 $\pm$ 9.4 cm for the oiled Trench.

The lack of significant differences among the individual unoiled ROWs and Trenches in 1989 (Table 2-2) was not particularly surprising, given the age of the disturbance. Gallinger (1991) reported no significant differences among the Trenches in 1986, only one year after Trench 1 and 3 were created and the year that Trench 2 was created. However, in 1987 the youngest, Trench 2, was significantly deeper than the other two Trenches. Even so, this tends to indicate that age alone has little bearing on maximum thaw depth of an individual Trench. By 1989, Trench 2 was still deeper than Trench 1 and 3, although this difference was not significant ($p > 0.1$).

Unlike the Trenches, Gallinger (1991) found ROWs 1 and 3 to be significantly deeper than the one-year-old ROW 2 in 1986. By the next year, however, this difference had vanished. It is not surprising then that by 1989 there would be virtually no difference among ROWs ($p > 0.5$).

Unoiled Forest

Every year since 1986 when the frost probe transects were first established, there have been significant differences among the three unoiled environments (Gallinger, 1991; Table 2-3). By 1989, even the "undisturbed" Forest had attained a mean maximum thaw depth almost 20 cm deeper than pre-disturbance values. Apparantly, mean maximum thaw depths in the Forest have begun to stabilize (Figure 2-2). In fact, the Forest's active layer began to stabilize as early as 1988. During the course of this study (1989-1991) there was no significant change in the mean maximum thaw depth (Table 2-8). The increase in mean maximum thaw depth was focused in the first two years of the disturbance and was likely related to the development of foot-paths, where the insulative mosses and lichens had been compressed. Compressing the organic mat results in an increase in the bulk density and thermal conductivity of the layer (Goodrich, 1983; Lawson, 1986).

The unoiled Forest experienced the least amount of thaw of any unoiled environment because of the relatively undisturbed vegetation which should promote cooler ground temperatures and therefore a thinner active layer (Brown, 1963). Even the open canopy of a subarctic black spruce forest can reflect and absorb over half of the incoming shortwave radiation (Haag and Bliss, 1974; Lafleur and Adams, 1986). In addition, even individual trees can influence the heat exchange at the ground surface to permit the development and maintenance of permafrost (Viereck, 1965; Gill, 1975).

The forest site also contains a thick living and dead organic mat of mosses and lichens. Such a layer is known to insulate the ground from warming and promote the existence of permafrost (Luthin and Guymon, 1974; Zoltai and Tarnocai, 1975; Riseborough and Burn, 1988). The thick organic mat of mosses and lichens is also capable of holding a great deal of moisture. The moisture content of this layer at SEEDS has averaged 350% (Gallinger, 1991). This results in a large portion of the incoming short wave radiation that actually reaches the ground surface being used in evapotranspiration rather than being available for warming the ground.

Snow conditions have also been found to be deepest in the Forest and snow melt is always later in the Forest than in the ROW or Trench (Kershaw, 1991). Hence despite warmer mid-winter conditions in the Forest, the snow-free period is generally a few days shorter than in the other environments.

Unoiled ROW

The hand-cleared ROWs represent an intermediate level of disturbance between the Forest and the Trench. In keeping with this, the thickness of the yearly mean maximum thaw depth was intermediate between the Forest and Trench.

According to Gallinger (1991), the mean maximum thaw depth of the ROW increased from 1986 to 1988. Then, the mean maximum thaw depth apparently decreased slightly from 1988 (88.6 $\pm$ 40.8 cm) to 1989 (84.9 $\pm$ 23.5 cm) when this study began. However, this is likely an artifact of establishing a one-meter buffer adjacent to the Trench to attempt to eliminate edge effects. Gallinger (1991) did not do this because she was interested in the entire profile across the site. Establishing the one-meter buffer zone eliminated the 19 deepest frost probe points from the dataset. Not only did this reduce the mean maximum thaw depth but it also dramatically reduced the standard deviation. The ROW continued to experience a deepening of its mean maximum thaw depths each year during this study (Table 2-1). However, despite the fact that the 1990 mean maximum thaw depth was almost 10 cm deeper than 1989's mean maximum thaw depth, this difference was not significant (Table 2-9). In 1991, the ROW attained its deepest [illegible]imum thaw depth, over 15 cm deeper than 1990, and this was signi[illegible] [illegible]eper ($p < 0.01$) than the 1990 value (Table 2-9). The permafros[illegible] [illegible]ently still degrading five and six years after the ROWs creat[illegible]

It is wel[illegible] do[illegible]ed that forest canopy removal results in an increase in ground temperature (Linell, 1973; Haag and Bliss, 1974; Nicholson, 1978a). With the removal of the trees and tall shrubs, only the organic mat of lichens and mosses separate the air from the soil. The thermal regime of the soil of the boreal forest is influenced by this organic mat (Luthin and Guymon, 1974). The fact that the mean maximum thaw depth of the ROW was substantially lower than the Trench where the organic mat had been removed supports this. In general, the lichens and mosses remained intact, although they became desiccated from the increased radiation, ground temperature and evapotranspiration. Gallinger (1991) reported moisture contents in the ROW of only 170% compared with 350% in the Forest. The reduced moisture content may also be due to infiltration and drainage within the thicker active layer.

Snow depths are shallower and denser on the ROW compared with the Forest because of the enhanced wind (Kershaw, 1991). Thus, the heat transfer coefficient for the cleared ROW is higher than the Forest resulting in colder near-surface temperatures and possible enhanced freezing (Kershaw, 1991). Nicholson and Granberg (1973), working in the Schefferville area discovered an essentially linear relationship between mean ground temperature and snow depth. They argue that areas with very shallow snow cover are also often relatively free of vegetation because of the severity of the conditions. These areas will then have higher summer shallow ground temperatures because of direct solar heating, thus compensating for the very cold winter temperatures, because of the lack of insulative snow.

The ROW has become over 170% deeper than the pre-disturbance values of 1986. This increase is in agreement with the results of Linell (1973) who found the active layer of a 25 year-old ROW to be 300% deeper than the control. However, other studies involving the hand-clearing of a forest canopy have often found only small increases in the mean maximum thaw depth (less than twice the original thaw depth), or even virtually undetectable increases in thaw depths (Heginbottom, 1973; Kurfurst, 1973; Adam and Hernandez, 1977). This is likely a result of most of these studies being located farther north, in the zone of continuous permafrost, where both ground and air temperatures are lower. A lower mean annual air temperature should help to minimize the effect of canopy removal.

Unoiled Trench

The Trench has experienced the greatest increase in mean maximum thaw depth -- almost 400% deeper than the pre-disturbance value. From 1986 to 1989 the mean maximum thaw on the trenches increased by approximately 40 cm annually. The next year, 1990, the Trench actually became significantly shallower (Table 2-9). By 1991 it had regained the mean maximum thaw depth that it had achieved by 1989, and this was significantly deeper than the 1990 value. It is possible that the Trench had begun to stabilize, however, 1990 may simply have been an anomalous year. Since in 1990 Norman Wells experienced a thawing degree-day total lower than the previous three years (Figure 2-18), and it was relatively dry (Figure 2-19), this would likely explain the shallower thaw depths of that year.

Clearly, the removal of the forest canopy in combination with the surface organics has had dramatic effects on the ground thermal regime. Not only does the removal of light-coloured lichens and mosses eliminate an important insulative layer, it also exposes the darker humus or mineral soil, thus reducing the albedo of the surface. Reduced albedo leads to increased ground warming and hence permafrost degradation. This effect has been noted after fires have consumed the organic mat, increasing the number of days the soil remained thawed by over 10% (Viereck, 1982).

The Trench also had the greatest amount of subsidence of the three environments. By 1990, the Trench had subsided over 50 cm on average (Nolte, 1991). This has led to the channelling of meltwater into the Trench and the formation of ponds there. Surface water can be an important source of heat for permafrost degradation (Linell and Tedrow, 1981). The heat stored in surface ponds may lead to a positive feedback effect causing further subsidence and enhanced ponding (Nelson and Outcalt, 1982). Similar effects have been observed on the Norman Wells pipeline where subsided trench areas have become flooded (Wishart, 1988).

The saturated Trench soils may influence the ground temperature year-round. Saturated soil can have a thermal conductivity ten times that of dry soil (Oke, 1978). In the summer this aids warming of the ground and in fall saturated soils can delay freezeback because of the stored latent heat. Wright (1983) found that the active layer of wet areas developed more quickly and often attained a deeper depth than similar drier areas. Wright argued that in saturated areas, the high pore water pressure leads to the suprapermafrost groundwater percolating into still frozen areas thereby transfering latent heat into areas well beyond the zone of conductive heat transfer.

Oiled Transects

In terms of the oil spill mean maximum thaw depths, there was no significant variation among the individual oiled ROWs during the three years of this study (Table 2-5). Among the oiled Trenches, only Trench C in 1991 differed significantly from the other Trenches (Table 2-5). It was over 50 cm shallower than the other two Trenches that year and shallower than it had been the previous two years. An inspection of the entire dataset for Trench C for that year reveals a possible explanation. The mean thaw depth decreased by 37 cm during the last frost probing session. Given the fact that other areas were still increasing this is likely a result of a data collection error in frost probing.

Overall, even though oil concentration rates varied across the site, this apparently had almost no effect on the mean maximum thaw depths. In part, this may be due to the fact that the oil spill transects were purposely located in areas that were heavily oiled.

All oiled environments had the same basic trend. Their mean maximum thaw depths became shallower in 1990 and then in 1991 attained their deepest mean maximum thaw depth. The much deeper mean maximum thaw depths in 1991 were the result of using a three-meter frost probe in that year. Before this time, frost probing was limited to 195 cm.

In 1989 and 1990 the oiled Forest, ROW and Trench did not differ significantly from each other in terms of their mean maximum thaw depths (Table 2-6). And in 1991, only the Trench was significantly deeper than the Forest (Table 2-7). This is in stark contrast to the unoiled environments which were significantly different from each other each year (Table 2-3). However, this is likely a result of being limited to frost probing to a depth of 195 cm in 1989 and 1990.

In 1989, the maximum possible thaw depth was encountered for all three oiled environments (in 1990, the cooler year, no probe point reached 195 cm). The oiled Forest had three maximum probe points (20%), the oiled ROW also had three (12%), and the Trench five (56%). Hence the mean maximum thaw depths for these environments are somewhat conservative. Since the 1991 data, collected using the three meter frost probe, reflect actual mean maximum thaw depths they can be compared with the previous years' data.

There was no significant difference among the three years' data for the oiled Forest (Table 2-8). Therefore, it would seem that although the previous years' mean maximum thaw depths for the oiled Forest may be somewhat low this error is not statistically significant.

In contrast, the oiled ROW did differ significantly ($p < 0.001$) among the three years of study (Table 2-8). While there was no significant difference between 1989 and 1990, the mean maximum thaw depth for 1991 was significantly deeper ($p < 0.01$) than both previous years (Table 2-10). Since we know the 1989 value was low, it is possible that the mean maximum thaw depth for the oiled ROW had essentially stabilized and that the 1990 value was merely reflecting the cooler year's temperatures. However, it cannot be ruled out that the mean maximum thaw depth of the oiled ROW is still increasing.

The oiled Trench also differed significantly ($p < 0.01$) among the three years (Table 2-8). Again, there was no significant difference between the mean maximum thaw depths for 1989 and 1990 (Table 2-10). While the mean maximum thaw depth for the oiled Trench in 1991 was significantly deeper than 1990 ($p < 0.01$), there was no significant difference between the results for 1989 and 1991. This lack of a significant result may be due to the small sample size, since a similar difference (just over 20 cm) between the 1989 and 1991 oiled ROW was significant. However, given the fact that over half of the Trench values in 1989 exceeded 195 cm it would seem likely that there was little difference in actual thaw depths between 1989 and 1991.

Given the fact that the 1989 and 1990 data may be somewhat conservative, especially for the Trench, then the 1991 data become more valuable. In 1991, three years after the oil spill, not only are the three oiled environments significantly deeper than their unoiled counterparts (Table 2-11), they also significantly differ from each other (Table 2-6). Further analysis reveals that only the Trench (the deepest) and the Forest (the shallowest) differ significantly (Table 2-7). Hence, it would seem that not only has the oil increased the mean maximum thaw depth but it also varies with the type of disturbance. Crude oil spilled on a relatively undisturbed surface (the Forest) compared with a moderately disturbed environment (the ROW) produced no significant difference in the resulting mean maximum thaw depths. However, there is a significant difference in the resulting mean maximum thaw depth between crude oil spilled on a relatively undisturbed surface (the Forest) and a highly disturbed environment (the Trench).

Oiled vs. Unoiled

Despite the interesting trends within the mean maximum thaw depths of both the unoiled and oiled environments, the main focus of this study was to examine the effects of crude oil on the active layer of the three disturbance types.

In all three years since the oil spill took place there were dramatic increases in the mean maximum thaw depths of the oiled Forest and ROW compared with their unoiled counterparts (Figure 2-4). Less dramatic differences were also found between the unoiled and oiled Trench.

Forest

The oiled Forest experienced mean maximum thaw depths that were greater than 130% of the unoiled Forest's values in every year (Figure 2-4). This translated into significant differences ($p < 0.0001$) for each year (Table 2-11). Previous research on the effect of crude oil spills on the active layer in forested areas have been somewhat contradictory. Some studies within the taiga had little or no significant increase in active layer after crude oil spills (Mackay et al, 1974; Hutchinson and Freedman, 1978) while some others had great increases (Collins, 1983).

These great discrepancies are likely a result of differing oil concentrations. Both Mackay's group and Hutchinson's group sprayed the oil on the ground with uniform concentration of approximately 9 $l \bullet m^{-2}$. Collins (1983) conducted two point-source spills of 7570 l of crude oil in a black spruce forest in Alaska. Six years after the spills, the summer spill (roughly 25 $l \bullet m^{-2}$) was approximately 50% deeper than the control, and the winter spill (roughly 40 $l \bullet m^{-2}$) was almost 100% deeper than the control. Since the winter spill was at a higher concentration than the summer spill it caused greater blackening of the moss layer resulting in a lower albedo and greater warming. In addition, the oil may coat soil particles and fill pore spaces, increasing the overall thermal conductivity of the soil.

This trend tends to indicate mean maximum thaw depth is proportional to oil concentration rate. However, the average oil concentration rate at the SEEDS spill was only about 5 $l \bullet m^{-2}$ (Kershaw, 1990). This value is misleading because the oil pooled in some areas which would then have much greater concentrations . Many of the areas included in the areal extent of the spill appear completely unoiled, while the high concentration sites are completely blackened. It is possible then, that the frost probe lines, which were set out through the highest concentration areas, are in spots where the oil concentration can be much higher than the site average. This could make the SEEDS concentration values on a localized basis, higher than even those of Collins (1983) and this may account for the very high mean maximum thaw depths experienced at SEEDS.

ROW

The trend in the oiled ROW was repeated with mean maximum thaw depths in excess of 50% of the unoiled ROW (Figure 2-4). This difference in mean maximum thaw depth was significant ($p < 0.001$) for each year (Table 2-11).

In general, the active layer of oil spill sites has been found to be deeper in areas where the forest had been cleared or burned. Hutchinson and Hellebust (1974) suggest this is because of increased incoming solar radiation reaching the ground compared with the forest floor. Longer term studies have indicated that the effect on the active layer can persist and increase. Hutchinson (1984) reported a 30% increase in active layer depth in a black spruce forest and nearly a 50% increase in a burned forest near Norman Wells the eighth summer after the experimental spills.

Trench

By 1989, the unoiled Trench's mean maximum thaw depth was already over 300% deeper than the pre-disturbance mean (Figure 2-3). It is not surprising then that there was only a 10-20% increase in the oiled Trench's mean maximum thaw depth compared with the unoiled Trench (Figure 2-4). The Trench was also the only environment that did not have immediate significant effects of the oil spill on the mean maximum thaw depth. In 1989, while the oiled Trench was deeper on average than the unoiled Trench by approximately 15 cm this difference was not significant (Table 2-11). Ironically, even though the oiled Trench became shallower in 1990 (again, by about 15 cm), it was now significantly ($p < 0.05$) deeper than the unoiled Trench, which had also become about 15 cm shallower (Table 2-11). The significance of this result is likely a function of the decreased variance of the samples for this year. By 1991, both the unoiled and oiled Trenches attained their deepest mean maximum thaw depth, with the oiled Trench some 30 cm deeper on average. This difference was significant ($p < 0.025$) confirming that the oil spill could influence ground temperatures at depths in excess of 1.5 m (Table 2-11).

Other disturbances which have resulted in the exposure of dark mineral soil and hence a similar change in albedo have also resulted in substantial increases in active layer thickness. Mackay (1977) reported the active layer almost doubling within five years after the Inuvik forest fire of 1968. After a forest fire near Fairbanks, Alaska, Viereck (1982) reported thaw depths up to four times the control values in the burned areas and the cleared fireline.

Thaw Rates

The beginning of the thaw period is integrally related to the completion of snowmelt. As long as snow remains on the ground, soil temperatures will remain around 0° C despite air temperatures possibly being well above this. However, once the snow begins to melt in the subarctic region, generally during early to mid-May, it disappears quickly (Kane and Stein, 1983; Slaughter and Benson, 1986).

Thawing of soil generally progresses quickly and then slows down later in the season as the thaw layer increases, with up to 80% of the total thaw occurring by late July, and total thaw by mid-August to mid-September (Stearns, 1966; Viereck and Lev, 1983). The thawed zone, whether because of its thickness alone or the presence of water capable of absorbing latent heat, retards the downward transfer of heat (Jahn, 1985).

The linear thaw rate for each unoiled environment is similar among years (Table 2-12). The thaw rates varied from just under 0.5 cm•day^{-1} for the Forest to almost 1.5 cm•day^{-1} for the Trench. Given the fact that the Trench's mean maximum thaw depth was approximately three times the depth of the Forest's, it is not surprising that the Trench would also have a thaw rate three times that of the Forest.

Just as the oiled mean maximum thaw depths do not vary as much as the unoiled mean maximum thaw depths, the oiled linear thaw rates also show less variation (Table 2-13). The thaw rates vary from approximately 1.2 cm•day^{-1} for the Forest to 1.7 cm•day^{-1} for the Trench.

The thaw rates based upon all the frost probe sessions throughout the thaw season were similar (Figs. 2-7 and 2-9). In both 1990 and 1991 the oiled Forest initially had a deeper thaw depth than either the ROW or Trench, even though ultimately it was the shallowest environment. The thaw rates (slopes) of the oiled environments were also much greater than the unoiled ones.

Jahn and Walker (1983) suggest that the length and the slope of the regression line is an indication of the effect of climate and surface vegetation on the thawing of the soil. Warm summer sites lacking insulative vegetative cover have the longest and steepest lines. This was found to be the case here, with the oiled Trench having the steepest slope of any of the regression lines.

Microclimate Data

Freezeback in the winter can vary dramatically from year to year. Based on a 14-year study in central Alaska, Viereck and Lev (1983) reported that the complete freezeback for the active layer of their forested site occurred between mid-December and late January. Fall freeze-back of the ground occurs both from the ground surface and the surface of the permafrost (Mackay, 1973; 1974). If the active layer is deep enough it is possible that complete freeze-back might not occur and a thaw bulb, or a talik, may develop. If an unfrozen layer existed, then clearly this would aid thawing in the subsequent year.

During the first few months of 1989 ground temperatures were below freezing at both 0.5 and 2.0 m in both the Forest and Trench (Figs. 2-15 and 2-16). This suggests that no thaw bulb existed under either environment. In addition, there is a decrease in temperature in late January at the shallower depth and this decrease also appears in ameliorated form at greater depth. It would seem unlikely that this decrease in temperature would appear at the lower depth unless the layer above it was also frozen.

Microclimatic data from the relatively undisturbed Forest indicates that permafrost temperatures are quite high -- close to 0° C. This has also been noted for the Mackenzie area by a number of authors (Gold and Lachenbruch, 1973; MacInnes et al, 1989; 1990). This reinforces the point that these soils are susceptible to even small changes in ground surface temperatures.

CONCLUSIONS

The oil spill had immediate and dramatic effects on the mean maximum thaw depths of both the relatively undisturbed Forest and the moderately disturbed ROW the first year after the spill. It did not have immediate significant effects on the highly disturbed Trench, although this is likely a result of the frost probing being limited to a depth of only two meters. Significant differences in mean maximum thaw depths were found among types of oiled disturbances when a three meter frost probe was employed.

The SEEDS oil spill has resulted in the greatest increase in mean maximum thaw depths for a crude-oil spill in a subarctic forested environment. This dramatic and persistent increase in mean maximum thaw depths is likely a function of the high oil concentration rates where the oil pooled on the ground. It is unclear whether further degradation of permafrost will occur.

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CHAPTER 3

Experimental revegetation of a crude oil spill on a Subarctic Right-of-Way using willow (*Salix arbusculoides*) cuttings

INTRODUCTION

A spill of crude oil will alter the ecological structure of any ecosystem. Northern ecosystems are especially susceptible because of the low net annual decomposition of the oil as a result of short summers (Hunt et al., 1973) and the potential for thawing of permafrost (Collins, 1983).

One technique to minimize the long-term effects of an oil spill is to plant native oil-adapted plant species in the spill area (Linkins et al., 1984). Native plant species are preferred, because exotic species alter the community composition of the original ecosystem. In addition, exotic species may inhibit reinvasion by other native species (Bliss, 1979; Cargill and Chapin, 1987).

Often, graminoid species are selected for revegetation projects because of the ease of seeding (Alexander and Van Cleve, 1983; Interprovincial Pipelines, Ltd. 1983). However, shrub species may be preferable. The shrub canopy causes increased ground shading which reduces net radiation at the surface (Haag and Bliss, 1974; Rouse, 1976) thus reducing thermal degradation of permafrost. Shrubs also provide preferred forage for ungulates (Viereck and Little, 1972) and if common on rights-of-way they improve habitat for many other animals (Zasada and Epps, 1976; Brusynk and Westworth, 1985).

To facilitate the revegetation of shrubs on disturbed areas, cuttings from shrubs are frequently planted. Shrub cuttings have been used in a number of Subarctic and Boreal revegetation projects (Younkin, 1976; Holloway and Zasada, 1979; Brown and Berg, 1980; Johnson, 1981; Johnson et al., 1981; Interprovincial Pipelines, 1986; Maslen, 1989). The main drawback of such a technique is the intensive labour involved.
With the creation of an experimental crude-oil spill at the SEEDS site (Kershaw, 1990), an opportunity existed to test the revegetation potential of a native shrub species on a variety of oiled substrates in a Subarctic environment. For this experiment, *Salix arbusculoides* was selected as the test species. Willows (*Salix* spp.) have an excellent potential for propagating vegetatively through cuttings (Chmelar, 1974; Densmore and Zasada, 1978; Maslen, 1989) and are a common genus used in revegetation projects (Hardy BBT Ltd, 1989). Willows are also among the first and

dominant shrub colonizers on disturbed sites (Russell, 1985; Kerhaw and Kershaw, 1987; Hardy BBT Ltd, 1989), making their artificial introduction onto oil spill areas merely an aided step in an otherwise natural process. One limitation of cuttings is that they are initially sensitive. If the aboveground portion of the cuttings is too long, it will protrude above the snowpack and this can result in desiccation (Frey, 1983). Hence the portion of the cutting above the ground should be limited to only a few centimeters. This limits the shrubs usefulness as a modifier of the microclimate for the first few years.

S. arbusculoides is a 1-4 m tall shrub, or a 5-6 m tall tree (Argus, 1973). It is found along stream banks, openings in white spruce (*Picea glauca*) forests, and in willow thickets at the tundra's edge (Argus, 1973). Results pertaining to *S. arbusculoides* have broad geographical implications for revegetation projects since it is one of the most common erect deciduous shrubs in upland Boreal and Subarctic ecosystems west of Hudson Bay (Porsild and Cody, 1980). *S. arbusculoides* may also be conspecific with the common Siberian *S. boganidensis*, making it potentially circumpolar in distribution (Argus, 1973). *S. arbusculoides* also has a proven ability to naturally recolonize a variety of disturbances such as roads, borrow pits, bladed slopes, and rights-of-way (Ebersole, 1985; Kershaw and Kershaw, 1987; Farrington, 1988), either through recolonization or vegetatively through surviving root systems (de Grosbois et al., 1991). Several *Salix* spp. including *S. arbusculoides* were found on 35-year-old crude oil spills along the abandoned CANOL Project pipeline (Kershaw and Kershaw, 1987). Furthermore, the genus has a demonstrated ability to seed onto oil spill areas even when absent from adjacent control plant communities (Kershaw and Kershaw, 1987).

S. arbusculoides in particular was selected because it is one of the dominant erect understory shrubs at the SEEDS site (Kershaw et al., 1988). In addition, other work there has established that this species is suitable for planting through cuttings (Maslen, 1989).

The success of a revegetation project may be improved by taking advantage of ecotypic variations exhibited by some shrub species (Van Epps and McKell, 1978; Slauson and Ward, 1982; Good et al., 1985; Maslen, 1989). Maslen (1989) experimented with a number of shrub species, including two different ecotypes of *S. arbusculoides* at the SEEDS site: willows growing on a 14-year-old seismic line, and willows growing within the undisturbed 200 year-old black spruce (*Picea mariana*) forest. She found that cuttings from willows growing on the seismic line fared significantly better than cuttings from the undisturbed forest, during the first growing season. However, no significant differences were found in survivorship or vigour after the initial winter. For this study all cuttings were taken from the seismic line in an attempt to ensure a high early success rate.

While it is clear that *S. arbusculoides* is usually a successful early colonizer, its ability to colonize oiled substrates is poorly understood. The objective of this study was to assess its suitability for oil spill reclamation projects in Boreal and Subarctic environments.

METHODS

Field Methods

Over 900 cuttings from various *S. arbusculoides* shrubs were manually collected from along the 19-year-old north-south seismic line adjacent to the study site. All cuttings were collected before budbreak from 7 to 10 May, 1991. After collection, all cuttings were placed in cold storage until planting, to maintain their dormancy. Before planting, each cutting was examined and any cuttings appearing unhealthy, or which had buds beginning to break dormancy were rejected. Each cutting was then cut to a standard length of 10 cm and any secondary branching was removed.

Planting took place along the North Link on 11 and 12 May, 1991. Cuttings were planted in the three basic environments at SEEDS (Right-of-Way (ROW), Trench, and Forest) to determine if site characteristics would influence shrub performance. A control was established for each of these plots by planting whips in three similar but unoiled locations. To determine if fertilizer would aid survivorship, 6 more plots identical to the first 6 were established with the addition of fertilizer. A 17:25:15 ($N/P_2O_5/K_2O$) commercial fertilizer was applied at a rate of 25 $g \bullet m^{-2}$ (250 $kg \bullet ha^{-1}$). The fertilizer and application rate were the same as those used on the Norman Wells pipeline (Interprovincial Pipelines, Ltd., 1983).

This resulted in a total of 12 plots being established under a variety of treatments and locations (Table 3-1). The 900 cuttings were randomly divided into 12 groups of 75 for planting. Each cutting was inserted to a depth of 7 cm with the remaining 3 cm exposed aboveground, following the technique of Maslen (1989). Plots necessarily reflected the topography of the site but in general were approximately 1 m^2 in size with the cuttings planted approximately 10 cm apart.

Table 3-1. Description of shrub cutting quadrats. No -- indicates treatment not in place; Yes -- indicates treatment applied.

Type of Quadrat	Presence of Oil	Fertilization
Trench	No	No
	No	Yes
	Yes	No
	Yes	Yes
ROW	No	No
	No	Yes
	Yes	No
	Yes	Yes
Forest	No	No
	No	Yes
	Yes	No
	Yes	Yes

Assessment of Vigour

On 8 and 9 August 1991, approximately 13 weeks after planting, the vigour of all shrub cuttings was assessed. Shrub vigour was evaluated using a five-point rating system:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

The effects of winter mortality were evaluated in the spring of 1992 using the same classification system. Because of the late snowmelt in 1992, the spring assessment was not conducted until 31 May.

Assessment of Rooting Success

In the spring of 1992, after the vigour assessment, all live and 20 randomly selected dead cuttings were harvested from each plot. Cuttings were excavated by hand ensuring the root system remained intact. Rooting success was evaluated by examining the number of first order roots (roots originating at the stem) as well as the cumulative length (to the nearest mm) of all roots on each cutting. Any cutting which had its roots broken during excavation was excluded from the calculation of cumulative root length, but was included in the calculation of number of first order roots.

Data Analysis

The shrub vigour data were ordinal in nature and hence a non-parametric statistical test was required. A Kolmogorov-Smirnov Two-Sample Test was selected (Taylor, 1977; Sokal and Rohlf, 1981).

The root data were tested for normality using the Shapiro and Wilk W test (Dunn and Clark, 1987). While the mean cumulative root lengths were normally distributed, the mean number of roots were not. A square root transformation successfully normalized the data. All variances were found to be homogenous when tested using the F-max test (Sokal and Rohlf, 1981). Analysis of variance (ANOVA) was then used to test for differences among treatments (Sokal and Rohlf, 1981).

Potential survivorships are based on rooting success of the sampled dormant cuttings in the spring of 1992 and extrapolated to the population. All statistical tests were performed on the dormant sample.

RESULTS

1991 Shrub Vigour

Each quadrat had 75 shrub cuttings planted in it in May of 1991. By August of that year a number of cuttings were missing, possibly as a result of predation, especially in the unoiled unfertilized Trench (Table 3-2). Percent survivorship varied from 0% in the unoiled fertilized forest to 75% in the oiled fertilized ROW (Figure 3-1).

Within the unoiled plots, there were no significant differences in vigour between fertilized and unfertilized shrub cuttings at the end of the 1991 growing season (Table 3-2). Among the oiled treatments, only the Trench sites had a significant difference between fertilized and unfertilized plots (Table 3-3). In this case, the shrub cuttings in the unfertilized quadrat had greater survivorship and vigour than the cuttings in the fertilized quadrat ($p < 0.01$).

Within the unoiled sample, the fertilized and unfertilized treatments were pooled as their vigour did not differ significantly. Comparisons were then made between environment types. All three environment types differed significantly from each other (Table 3-4). The Trench cuttings had the greatest survivorship (61%), followed by the ROW cuttings (37%), while the Forest cuttings had only 13% surviving. For the oiled sample, pooling of data was not conducted for the Trench quadrats as the fertilized and unfertilized samples differed significantly in their vigour. Hence any comparison involving the fertilized or unfertilized Trench was made with the appropriate other environment. All comparisons were significant except for the ROW versus Trench (Table 3-5). Survivorship of the Trench cuttings varied from 56% (fertilized) to 71% (unfertilized), while the ROW cuttings varied from 68% (unfertilized) to 75% (fertilized). Survivorship of the Forest cuttings was lower than the other two environments, varying from 44% (fertilized) to 46% (unfertilized).

Next, a comparison was made between oiled and unoiled treatments to determine the effects of the oil on shrub vigour. All comparisons differed significantly, except for the oiled and unoiled unfertilized Trench (Table 3-6). In all but one significant case, the oiled treatments had more healthy cuttings than the unoiled treatments. The exception was the unoiled fertilized Trench which had significantly more vigourous cuttings than the oiled fertilized Trench ($p < 0.05$).

1992 Shrub Vigour

The total number of cuttings that could be located declined slightly between the end of 1991 and the spring of 1992. The greatest loss was in the unoiled unfertilized Forest, which declined from 74 to 70 cuttings.

Table 3-2. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips at the end of the 1991 growing season in fertilized and unfertilized quadrats within the unoiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Fertilized Forest	0	0	0	0	64	64		
Unfertilized Forest	5	0	0	13	56	74	0.068	N.S.
Fertilized ROW	3	0	0	25	46	74		
Unfertilized ROW	6	0	0	20	46	72	0.043	N.S.
Fertilized Trench	26	0	0	11	27	64		
Unfertilized Trench	25	0	0	3	15	43	0.175	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;

2) healthy, but with a few (<50%) chlorotic leaves;

3) most (>50%) leaves chlorotic;

4) little development; buds unopened, abnormally-formed leaves,

5) whip has no green tissue, is shrivelled or curled.

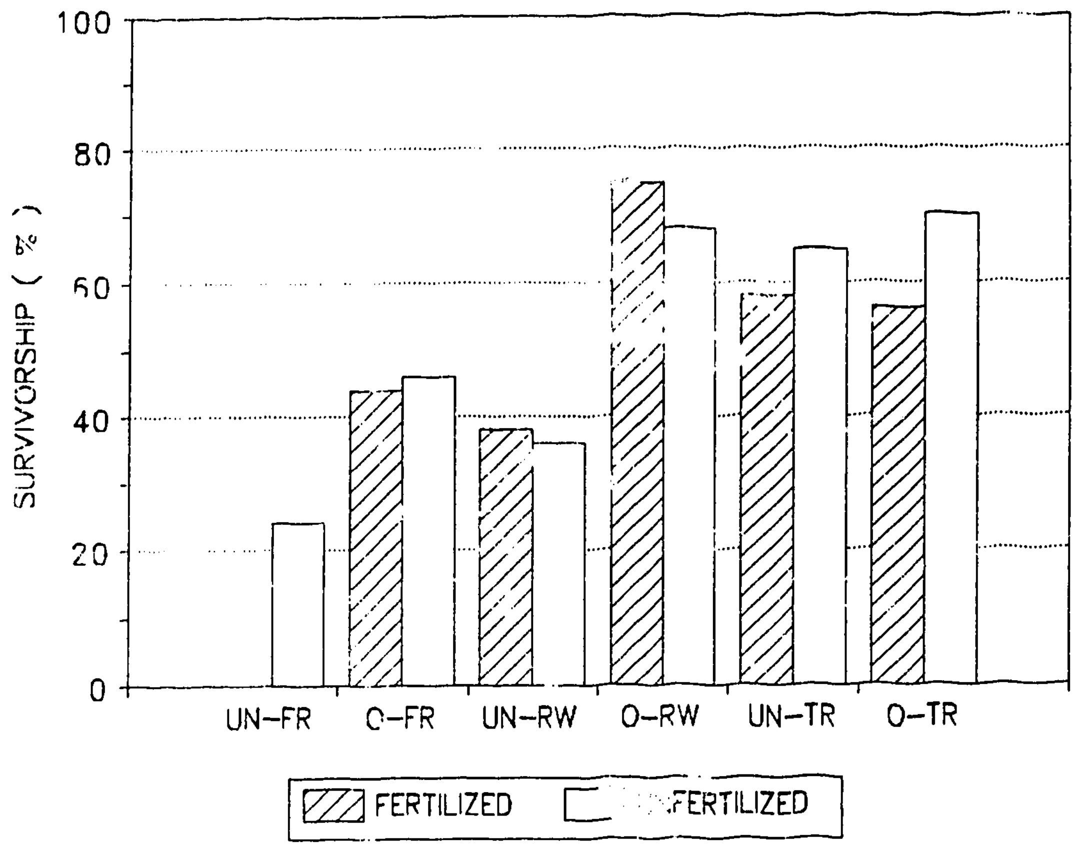

Figure 3-1. Percent survivorship of cuttings growing in the Forest (FR), on the ROW (RW), and the Trench (TR) at the end of the 1991 growing season. UN -- unoiled; O -- oiled.

Table 3-3. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips at the end of the 1991 growing season in fertilized and unfertilized quadrats within the oil spill. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Fertilized Forest	18	0	0	13	40	71		
Unfertilized Forest	28	0	0	3	36	67	0.164	N.S.
Fertilized ROW	18	16	11	3	16	64		
Unfertilized ROW	25	6	5	5	19	60	0.135	N.S.
Fertilized Trench	11	13	12	4	31	71		
Unfertilized Trench	29	3	3	9	18	62	0.313	< 0.01

Table 3-4. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips at the end of the 1991 growing season between types of quadrats within the unoiled sample.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest	5	0	0	13	120	138		
ROW	9	0	0	45	92	146	0.239	< 0.001
Forest	5	0	0	13	120	138		
Trench	51	0	0	14	42	107	0.477	< 0.001
ROW	9	0	0	45	92	146		
Trench	51	0	0	14	42	107	0.415	< 0.001

Vigour Classes:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

Table 3-5. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips at the end of the 1991 growing season between types of quadrats within the oiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest	46	0	0	16	76	138		
ROW	43	22	16	8	35	124	0.320	< 0.001
Fertilized Forest	18	0	0	13	40	71		
Fertilized Trench	11	13	12	4	31	71	0.254	< 0.05
UnfertilizedForest	28	0	0	3	36	67		
Unfertilized Trench	29	3	3	9	18	62	0.247	< 0.05
Fertilized ROW	18	16	11	3	16	64		
Fertilized Trench	11	13	12	4	31	71	0.196	N.S.
Unfertilized ROW	25	6	5	5	19	60		
Unfertilized Trench	29	3	3	9	18	62	0.051	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

Table 3-6. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips at the end of the 1991 growing season between oiled and unoiled quadrats. N.S. - not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Oiled Forest	46	0	0	16	76	138		
Unoiled Forest	5	0	0	13	120	138	0.319	< 0.001
Oiled ROW	43	22	16	8	35	124		
Unoiled ROW	9	0	0	45	92	146	0.592	< 0.001
Oiled Fertilized Trench	11	13	12	4	31	71		
Unoiled Fertilized Trench	26	0	0	11	27	64	0.251	< 0.05
Oiled Unfertilized Trench	29	3	3	9	18	62		
Unoiled Unfertilized Trench	25	0	0	3	15	43	0.114	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

Percent survivorship was quite low in the spring of 1992. It varied from 0% in four of the six unoiled treatments to 13% in both the fertilized and unfertilized oiled Trench (Figure 3-2).

The application of fertilizer resulted in no significant differences between the vigour of cuttings in any of the unoiled (Table 3-7) or oiled (Table 3-8) treatments. Fertilized and unfertilized treatments were then pooled for subsequent analyses.

Next, types of environments were compared among the unoiled samples. None of the three environments differed significantly in terms of the vigour of their shrub cuttings (Table 3-9). Survivorship was 0% for all but the Trench which had 6% of its shrub cuttings still alive, and only 1% healthy and vigorous.

The oiled environments also had no significant differences among them in terms of shrub vigour (Table 3-10). Less than 10% of the cuttings were still deemed healthy and vigorous. Survivorship ranged from 6% (oiled Forest) to 13% (oiled Trench).

Comparing oiled and unoiled environments revealed no significant differences in the vigour of the shrub cuttings (Table 3-11). Survivorship ranged from 0-13%.

1991-1992 Comparisons of shrub Vigour

The winter of 1991/92 had severe effects on the health and vigour of all the shrub cuttings. Within the unoiled sample, cutting vigour declined significantly in almost every environment (Table 3-12). The only exception was the Forest, where only a few cuttings were still alive before the winter.

Within the oiled sample, cutting vigour declined significantly in all environments ($p < 0.001$)(Table 3-13).

Rooting Success

In the spring of 1992, after the shrub cuttings' vigour had been evaluated, all surviving cuttings and a random selection of apparently dead cuttings were harvested for an examination of their roots. No surviving cuttings were found in the unoiled Forest or ROW. The number of primary roots and cumulative root length were recorded for each shrub cutting.

A comparison was made between fertilized and unfertilized treatments. The mean number of roots produced per cutting varied from 2 in the unoiled fertilized Trench to 7.1 in the oiled fertilized Trench (Table 3-14). No significant differences were found between the fertilized and unfertilized treatments.

The mean cumulative root length per cutting varied from 15 mm in the

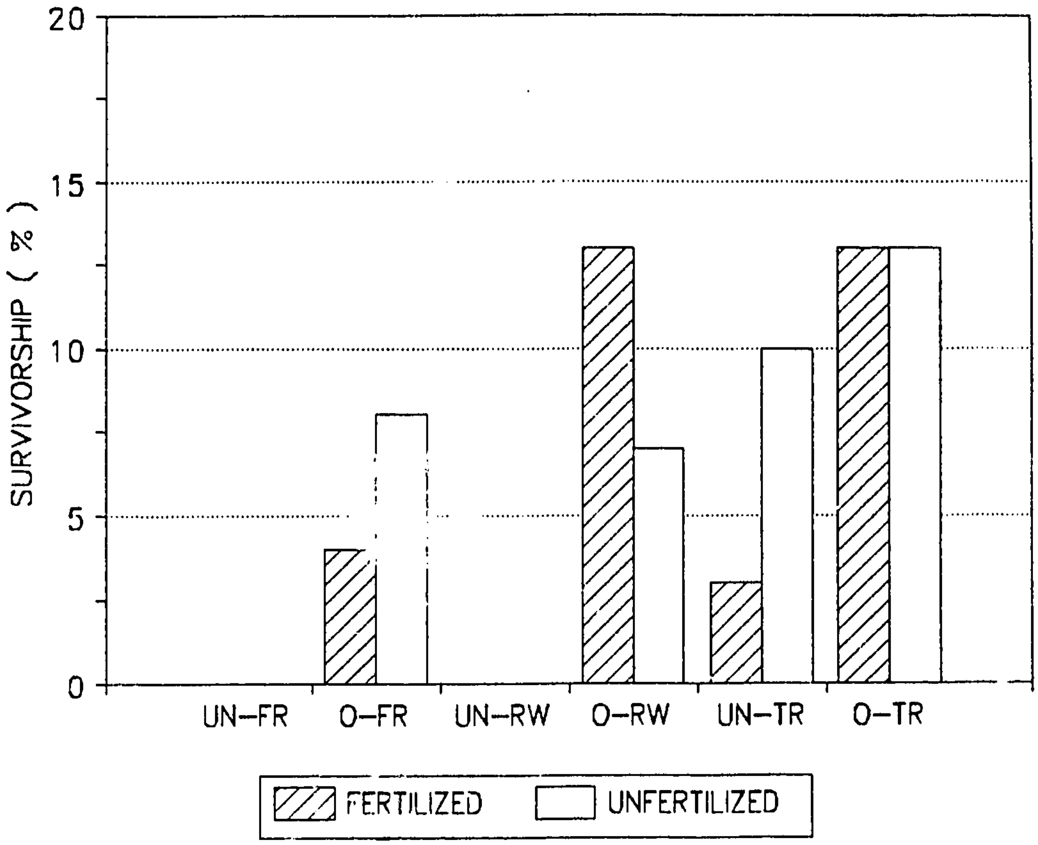

Figure 3-2. Percent survivorship of cuttings growing in the Forest (FR), on the ROW (RW), and the Trench (TR) at the start of the 1992 growing season. UN -- unoiled; O -- oiled.

Table 3-7. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips in the spring of the 1992 growing season in fertilized and unfertilized quadrats within the unoiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Fertilized Forest	0	0	0	0	64	64		
Unfertilized Forest	0	0	0	0	70	70	0	N.S.
Fertilized ROW	0	0	0	0	74	74		
Unfertilized ROW	0	0	0	0	72	72	0	N.S.
Fertilized Trench	1	0	0	1	62	64		
Unfertilized Trench	0	0	0	4	38	42	0.064	N.S.

Table 3-8. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips in the spring of the 1992 growing season in fertilized and unfertilized quadrats within the oiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Fertilized Forest	2	0	0	1	68	71		
Unfertilized Forest	1	1	0	3	61	66	0.034	N.S.
Fertilized ROW	3	1	0	4	54	62		
Unfertilized ROW	2	0	0	2	53	57	0.059	N.S.
Fertilized Trench	4	0	0	5	59	68		
Unfertilized Trench	5	0	0	3	53	61	0.023	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;

2) healthy, but with a few (<50%) chlorotic leaves;

3) most (>50%) leaves chlorotic;

4) little development; buds unopened, abnormally-formed leaves;

5) whip has no green tissue, is shrivelled or curled.

Table 3-9. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips in the spring of the 1992 growing season between types of quadrats within the unoiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest	0	0	0	0	134	134		
ROW	0	0	0	0	146	146	0	N.S.
Forest	0	0	0	0	134	134		
Trench	1	0	0	5	100	106	0.057	N.S.
ROW	0	0	0	0	146	146		
Trench	1	0	0	5	100	106	0.057	N.S.

Table 3-10. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips in the spring of the 1992 growing season between types of quadrats within the oiled sample. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest	3	1	0	4	129	137		
ROW	5	1	0	6	107	119	0.042	N.S.
Forest	3	1	0	4	129	137		
Trench	9	0	0	8	112	129	0.073	N.S.
ROW	5	1	0	6	107	119		
Trench	9	0	0	8	112	129	0.031	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

Table 3-11. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips in the spring of the 1992 growing season between oiled and unoiled quadrats. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Oiled Forest	3	1	0	4	129	137		
Unoiled Forest	0	0	0	0	134	134	0.058	N.S.
Oiled ROW	5	1	0	6	107	119		
Unoiled ROW	0	0	0	0	146	146	0.[illegible]01	N.S.
Oiled Trench	9	0	0	8	112	129		
Unoiled Trench	1	0	0	5	100	106	0.0[illegible]5	N.S.

Vigour Classes:

1) healthy, with normal leaves and/or shoots;

2) healthy, but with a few (<50%) chlorotic leaves;

3) most (>50%) leaves chlorotic;

4) little development; buds unopened, abnormally-formed leaves;

5) whip has no green tissue, is shrivelled or curled.

Table 3-12. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips before and after the winter of 1991/92 for unoiled quadrats. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest (1991)	5	0	0	13	120	138		
Forest (1992)	0	0	0	0	134	134	0.130	N.S.
ROW (1991)	9	0	0	45	92	146		
ROW (1992)	0	0	0	0	146	146	0.308	< 0.001
Fertilized Trench (1991)	26	0	0	11	27	64		
Fertilized Trench (1992)	1	0	0	1	62	64	0.547	< 0.001
Unfertilized Trench (1991)	25	0	0	3	15	43		
Unfertilized Trench (1992)	0	0	0	4	38	42	0.581	< 0.001

Vigour Classes:

1) healthy, with normal leaves and/or shoots;

2) healthy, but with a few (<50%) chlorotic leaves;

3) most (>50%) leaves chlorotic;

4) little development; buds unopened, abnormally-formed leaves;

5) whip has no green tissue, is shrivelled or curled.

Table 3-13. Results of Kolomogorov-Smirnov two-sample tests comparing vigour of shrub whips before and after the winter of 1991/92 for oiled quadrats.

QUADRAT	CUTTING VIGOUR					n	D	p
	1	2	3	4	5			
Forest (1991)	46	0	0	16	76	138		
Forest (1992)	3	1	0	4	129	137	0.391	< 0.001
ROW (1991)	43	22	16	8	35	124		
ROW (1992)	5	1	0	6	107	119	0.617	< 0.001
Fertilized Trench (1991)	11	13	12	4	31	71		
Fertilized Trench (1992)	4	0	0	5	59	68	0.448	< 0.001
Unfertilized Trench (1991)	29	3	3	9	18	62		
Unfertilized Trench (1992)	5	0	0	3	53	61	0.579	< 0.001

Vigour Classes:

1) healthy, with normal leaves and/or shoots;
2) healthy, but with a few (<50%) chlorotic leaves;
3) most (>50%) leaves chlorotic;
4) little development; buds unopened, abnormally-formed leaves;
5) whip has no green tissue, is shrivelled or curled.

Table 3-14. Summary of Analysis of Variance comparing fertilized versus unfertilized quadrats for mean number of roots. All comparisons are based on square root transformed data. Quadrats are oiled unless otherwise specified. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	n	MEAN	STANDARD DEVIATION	F	p
Fertilized Forest	3	5.3	2.5		
Unfertilized Forest	5	3.2	1.3	2.559	N.S.
Fertilized ROW	5	5.8	2.6		
Unfertilized ROW	5	5.6	3.1	0.036	N.S.
Fertilized Trench	9	7.1	4.3		
Unfertilized Trench	8	4.1	2.8	3.796	N.S.
Unoiled Fertilized Trench	2	2	1.4		
Unoiled Unfertilized Trench	3	2.7	1.2	0.429	N.S.

unoiled unfertilized Trench to 206 mm in the oiled fertilized Trench (Table 3-15). Again, no significant differences were found between fertilized and unfertilized treatments.

Next, fertilized and unfertilized quadrats were pooled to compare types of environments. The mean number of roots varied from 2.4 in the unoiled Trench to 5.8 in the oiled ROW (Figure 3-3). However, a one-way ANOVA revealed that there were no significant differences among these samples ($F = 1.897$, $p > 0.1$). The mean number of roots per cutting for the entire sample was 5.2 ($\pm$ 3.2).

The mean cumulative root length per cutting varied from 32 mm in the unoiled Trench to 159 mm in the oiled Trench (Figure 3-4). A one-way ANOVA revealed these differences to be insignificant ($F = 2.118$, $p > 0.1$). Therefore the mean cumulative root length for the entire sample was 114 mm ($\pm$ 102).

Potential Survivorship

A late spring in 1992 necessitated a premature evaluation of the shrub cuttings. A few snow patches persisted and the ground was still quite cold. Even those cuttings that had broken dormancy were in early stages of development: the buds were swollen, or leaves only partially expanded. In all likelihood not all cuttings had yet broken dormancy. This would explain the low survivorships both in the oiled and unoiled plots.

This theory is supported by a plant phenology survey conducted at the SEEDS site at the same time as the shrub cutting evaluation. Of 68 *S. arbusculoides* shrubs monitored for the phenology survey 39 (57%) were either still dormant or were just beginning to have their buds swell. And these were mature shrubs with extensive root systems. It is not surprising then that most of the shrub cuttings were still dormant during the spring evaluation.

To attempt a more thorough evaluation of survivorship, the rooting success of dormant and revived cuttings were examined. Any cuttings without roots were classified as dead, while any with roots were classified as potentially alive.

Potential survivorship was then calculated and it included both those cuttings that were not dormant as well as those that were potentially alive. Potential survivorship varied from 2% in the unoiled ROW to 61% in both the oiled ROW and Trench (Figure 3-5). In all cases the oiled cuttings had higher potential survivorships than the unoiled cuttings. The maximum survivorships at the end of the 1991 growing season were also found in the oiled ROW and Trench, ranging as high as 75% (Figure 3-1). This agrees with the potential survivorship data.

Table 3-15. Summary of Analysis of Variance comparing fertilized versus unfertilized quadrats for mean cumulative root length. Quadrats are oiled unless otherwise specified. N.S. -- not significantly different at $p < 0.05$.

QUADRAT	n	MEAN (mm)	STANDARD DEVIATION	F	p
Fertilized Forest	3	67	46.5		
Unfertilized Forest	5	101	67.7	0.586	N.S.
Fertilized ROW	5	111	108.0		
Unfertilized ROW	5	116	70.7	0.008	N.S.
Fertilized Trench	7	206	148.9		
Unfertilized Trench	7	113	88.1	2.017	N.S.
Unoiled Fertilized Trench	2	50	49.5		
Unoiled Unfertilized Trench	2	15	7.1	0.983	N.S.

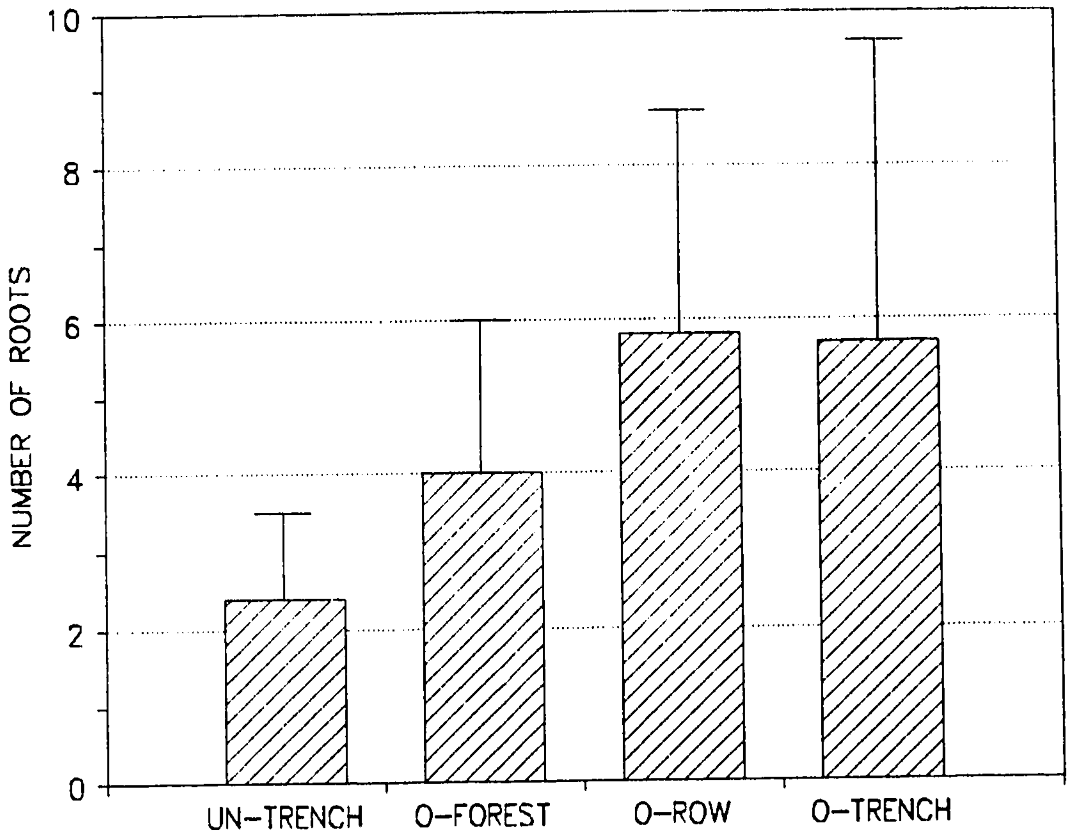

Figure 3-3. Mean number of roots produced by leaf-bearing cuttings at the start of the 1992 growing season. Error bars indicate one standard deviation. Sample sizes: unoiled Trench, n=5; oiled Forest, n=8; oiled ROW, n=10; oiled Trench, n=17. UN -- unoiled; O -- oiled.

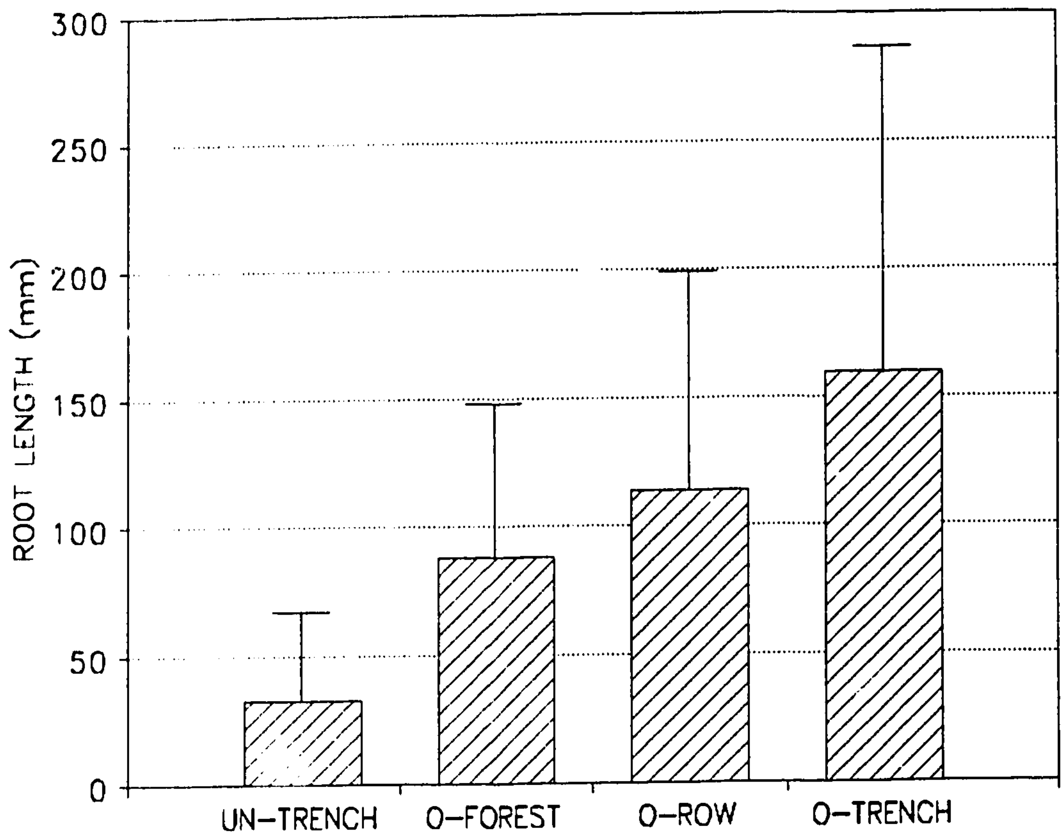

Figure 3-4. Mean cumulative root length of leaf-bearing cuttings at the start of the 1992 growing season. Error bars indicate one standard deviation. Sample sizes: unoiled Trench, n=4; oiled Fcrest, n=8; oiled ROW, n=10; oiled Trench, n=14. UN -- unoiled; O -- oiled.

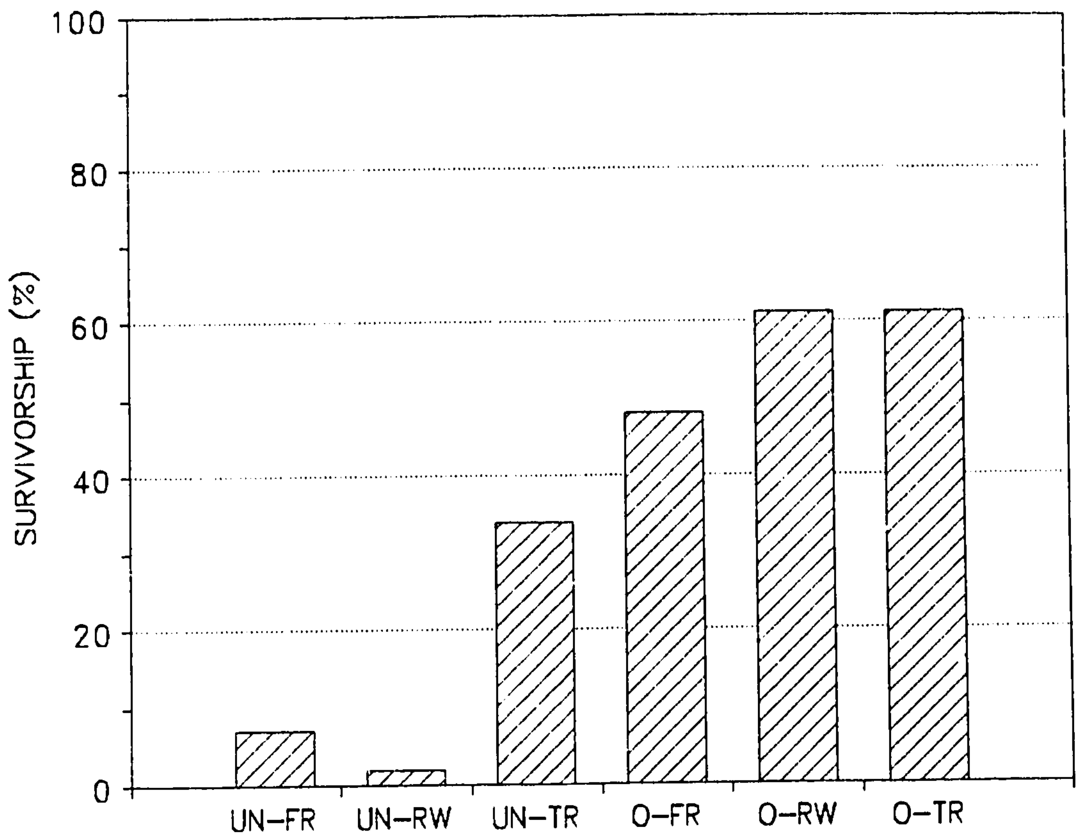

Figure 3-5. Maximum potential survivorship of cuttings growing in the Forest (FR), on the ROW (RW), and the Trench (TR) based on rcot production of dormant cuttings. UN -- unoiled; O -- oiled.

Next, the mean number of roots produced were examined for the dormant, but potentially alive cuttings. The unoiled Forest and ROW were excluded from the analysis because of the low number of potential survivors. Among the oiled cuttings the mean number of roots varied from 3.3 in the Trench to 3.7 in the Forest (Figure 3-6), although this difference was not significant ($F = 0.19$, $p > 0.5$). When pooled, the mean number of roots for all the oiled cuttings was 3.5 ($\pm$ 2.2).

The mean number of roots of the pooled potentially alive oiled cuttings (dormant) were then compared with the revived oiled cuttings (leaf-bearing)(Figure 3-6). The leaf-bearing cuttings had only 1.7 more roots on average, but this difference was significant ($F = 9.22$, $p < 0.005$). The dormant oiled cuttings had 1.5 more roots on average than the dormant unoiled cuttings from the Trench and this difference was also significant ($F = 5.82$, $p < 0.025$).

The mean cumulative root lengths were also compared. Among the oiled cuttings, the mean cumulative root length varied from 59.4 mm in the ROW to 90.9 mm in the Forest (Figure 3-7), although this difference was not significant ($F = 1.26$, $p > 0.25$). When pooled, the mean cumulative root length for the dormant oiled cuttings was 71.7 mm ($\pm$ 64.8).

The mean cumulative root length of the leaf-bearing oiled cuttings was 44.9 mm longer on average than the dormant oiled cuttings, and this difference was significant ($F = 7.97$, $p < 0.01$). In contrast, even though the dormant oiled cuttings were 31.7 mm longer on average than the dormant cuttings of the unoiled Trench this difference was not significant ($F = 2.47$, $p > 0.1$).

DISCUSSION

Shrub Vigour

Although shrub survivorship was relatively high at the end of the 1991 growing season -- up to 75% for some samples -- it declined dramatically by the following spring. One possible explanation is lack of root production. Roots provide plants with moisture and nutrients. Without them, survival is impossible. Many of the shrubs assessed as alive and vigorous at the end of the first growing season likely survived on carbohydrate reserves within the cutting, but failed to put out roots (Trilca, 1977; Maslen, 1989).

This is in contrast to other non-oil spill revegetation projects in the North. Younkin and Friesen (1974) reported 100% survivorship at the end of three growing seasons and Younkin (1976) reported mean survivorship of over 80% after the first winter for cuttings of *S. arbusculoides* in the Mackenzie area of the NWT. Densmore and others (1987) also reported mean

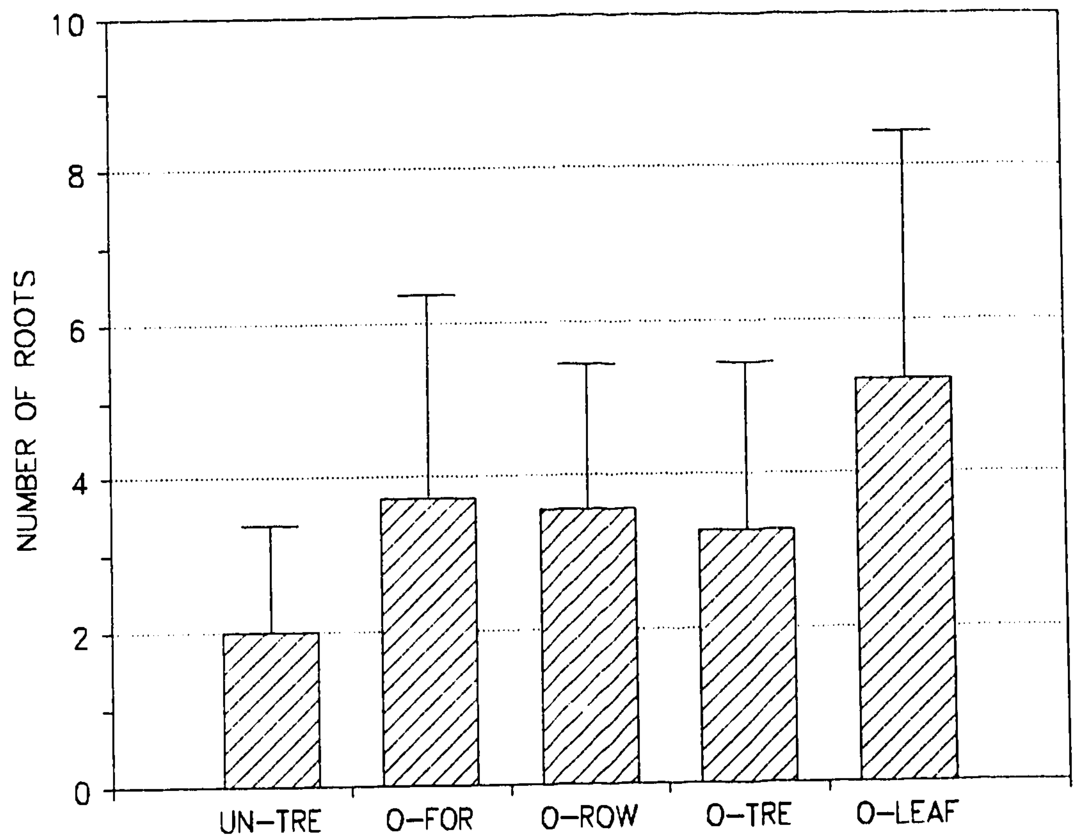

Figure 3-6. Mean number of roots produced by dormant cuttings and leaf-bearing cuttings (LEAF) at the start of the 1992 growing season. Error bars indicate one standard deviation. Sample sizes: unoiled Trench, n=12; oiled Forest, n=18; oiled ROW, n=25; oiled Trench, n=22; oiled leaf-bearing, n=35. UN -- unoiled; O -- oiled.

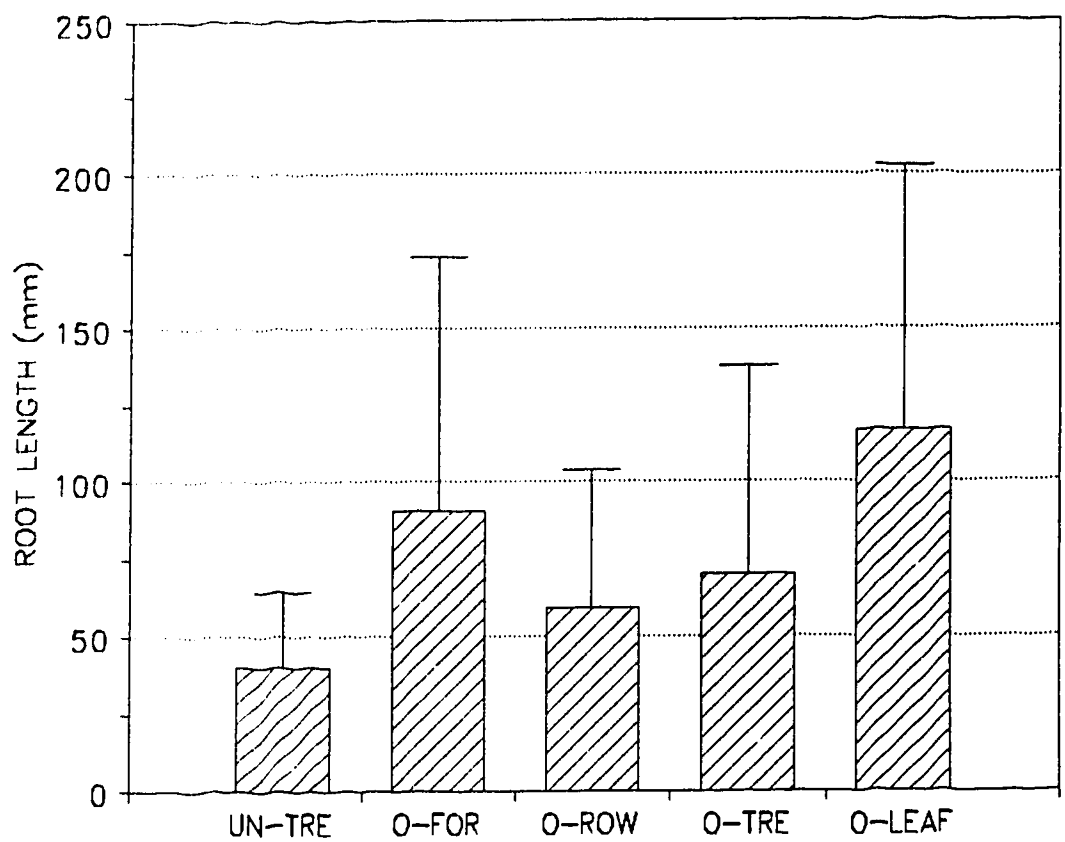

Figure 3-7. Mean cumulative root length of dormant cuttings and leaf-bearing cuttings (LEAF) at the start of the 1992 growing season. Error bars indicate one standard deviation. Sample sizes: unoiled Trench, n=12; oiled Forest, n=18; oiled ROW, n=25; oiled Trench, n=21; oiled leaf-bearing, n=35. UN -- unoiled; O -- oiled.

survivorship over 80% for their cuttings of *S. alaxensis* in Alaska.

Maslen (1989) however reported a large drop in survivorship for *S. arbusculoides* cuttings after the first winter. Despite a similar trend, there is still a dramatic difference between her results and the results of this study. Maslen (1989) reported mean survivorship as being 75% at the end of the first growing season, whereas in this study mean survivorship was only 47%. And while Maslen (1989) reported a mean survivorship of 50% after the first winter, our cuttings had a mean survivorship of only 6% after the first winter.

Since in almost all cases the oiled quadrats had significantly higher survivorships than the unoiled quadrats at the end of the first growing season (Table 3-6), the presence of the oil is unlikely the cause of the discrepancy in the results.

The other difference between Maslen's project and this one is that Maslen only planted cuttings in the Trench. While the overall survivorship for this project was only 47% at the end of the first growing season, the mean survivorships for the unoiled and ciled Trench were 61% and 63% respectively. This is comparable to Maslen's 75%. However, survivorship after the first winter was quite low for the unoiled and oiled Trench: 6% and 13% respectively, compared with Maslen's 50%.

One possible explanation for this discrepancy is the lateness of the spring in 1992. Departure from the field necessitated a spring assessment while the ground was still cold and occasional snow patches persisted. Thus, it is likely that not all spring bud break had occurred by the time of the assessment.

Rooting Success

In terms of rooting success for the pooled oiled cuttings, the mean number of roots was 5.2 ($\pm$ 3.2) with a mean cumulative root length of 130 mm ($\pm$ 81). These results are actually slightly higher than Maslen's (1989) results of 4.9 ($\pm$ 3.0) roots on average with a mean cumulative length of 114 mm ($\pm$ 102). Clearly those cuttings that did survive did not have their root production negatively affected by the crude oil.

The rooting success of oiled potential survivors was also quite high. The mean number of roots was 3.5 ($\pm$ 2.2) with a mean cumulative root length of 71.7 mm ($\pm$ 64.8). Although both of these values were significantly lower than the oiled living values it is clear that root production was not dramatically different for this group (Figure 3-6). This helps to support the theory that many of these cuttings were indeed still alive but merely dormant at the time of the evaluation.

Greater survivorship might be accomplished by the use of longer cuttings and a deeper planting depth, as root production appears to be proportional to the length of the buried cutting (Schiechtl, 1980; Maslen, 1989). This is probably a result of the fact that many willows have preformed dormant root primordia allowing rapid production of adventitious roots (Carlson, 1950; Haissig, 1970). This is likely an adaptation by riparian willows which commonly experience spring flooding and silt deposition of more than 30 cm (Gill, 1973). Hence, riparian species, such as *S. arbusculoides* produce roots along the stem both at and between nodes (diffuse rooting), while non-riparian willows only produce roots at the base of the cutting (basal rooting) (Chmelar, 1974; Densmore and Zasada, 1978). Therefore a longer cutting should result in more roots produced. Densmore and Zasada (1978) working with *S. alaxensis* in Alaska found mean number of roots to be 6.8 only two months after planting when using cuttings 20-25 cm long with only 2-5 cm aboveground.

Increased root production may also result in greater above-ground production. Densmore and others (1987) found that above-ground production was essentially proportional to the length of the cuttings for *S. alaxensis* in Alaska.

Another benefit of longer cuttings is that the stem diameter tends to be greater. Densmore and others (1987) found that cuttings of *S. alaxensis* with a stem diameter greater that 0.6 mm tended to have higher survivorship than cuttings with a stem diameter between 0.3 - 0.6 mm.

The fertilizer had either no effect on the shrubs, or in the case of the oiled Trench, actually decreased survivorship. Other non-oil spill reclamation studies have also reported fertilizer to have no effect on willow cutting survivorship (Densmore et al, 1987; Maslen, 1989). This may be a result of competition with other species for the nutrients, or the cuttings' inability to absorb the added nutrients before root production. However, Densmore and others (1987) found that even during the third growing season fertilizer application did not affect production in *S. alaxensis*. This would tend to support the theory that other species are more able to make use of fertilizer additions.

Potential Survivorships

Potential survivorship values in the spring of 1992 ranged from 34-61% for the unoiled Trench and the oiled environments (Figure 3-5). These values compare favorably with Maslen's results of 50% survivorship. Although it is unlikely that all cuttings that established root systems would survive the winter potential survivorship values are likely more reliable than the actual survivorship values. In support of this, Kershaw (pers. com.) conducted a small pilot experimental planting of *S. arbusculoides* in the oil spill at SEEDS in the spring of 1990, the second growing season after the spill. He observed mean survivorships of 2.8% on oiled ROW and 22.7% on oiled trench 2 winters and 3 growing seasons after planting.

The apparent lack of negative effects of the crude oil are somewhat surprising. In general, the oiled cuttings fared better than the unoiled cuttings. However, there may be several explanations for this trend. While the unoiled Forest and ROW had the highest mortality (Figure 3-1) these sites were also the driest sites and many of the cuttings were brown and shrivelled during the first evaluation at the end of August, 1991. In contrast, the oiled Forest and ROW sites were much moister. This was inherently the case, as the oil naturally concentrated in low lying areas. Hence the results are perhaps best interpreted as the unoiled quadrats suffering from a lack of water, rather than the oiled quadrats benefitting from the oil. This hypothesis appears to be validated by the results from the oiled and unoiled Trench. The unoiled Trench was a moist environment (because of ground subsidence) and the cuttings planted there either did better than their oiled counterparts or did not differ significantly from the oiled cuttings (Table 3-6).

Nonetheless, even if the oil was not truly beneficial to the cuttings, it did not appear to be very toxic to the cuttings. Only the cuttings planted in the unoiled fertilized Trench fared better than their oiled counterparts (41% and 15%, respectively were vigorous)(Table 3-6). While the difference in vigour was significant, survivorship in the oiled and unoiled fertilized Trench did not differ greatly (56% and 58%, respectively). It is possible then that the oil had only slight effects on mortality, but greater effects on vigour. However, the results from the unfertilized Trench do not support this. Both the oiled and unoiled cuttings had high numbers of healthy cuttings (47% and 58%, respectively). These values are comparable to the results of Maslen (1989) who reported that 50% of her cuttings were vigorous after the first growing season.

The fact that the cuttings were planted the third growing season after the oil spill likely influenced their success. Many of the phytotoxic elements of the oil may have degraded by the time of the study even though large quantities of oil residue were found in all soil samples taken adjacent to oiled study plots. Oil-degrading microorganisms are present in northern soils, but since they are temperature-dependent they are limited by the brief summer (Cook and Westlake, 1974). While the number of oil-degrading microorganisms may increase within days or even hours of a spill in temperate regions (Atlas and Bronner, 1981), the increase may take months or even years in the north (Haines and Atlas, 1982).

In addition, the cuttings may have benefitted from the water-saturated soil in the Trench. The high water levels would reduce oil penetration into the soil. Phytotoxic effects of oil are generally believed to be inversely related to water uptake and a result of a disruption of the plant-soil-water relationship (Schwedinger, 1968). A high water to oil ratio may minimize such a disruption.

Regardless of the amount of oil decomposition that may or may not have taken place, there may be another reason to explain the apparent lack of toxic effects of the oil on the shrub cuttings. It is well known that applying crude oil to an area will result in the death of virtually all growing plant tissue (e.g. Currier and Peoples, 1954; Overbeek and Blondeau, 1954; Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). However, resprouting of some species can occur within a few weeks after an oil spill (Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). The shrub cuttings thus mimic the initial sprouting after an oil spill.

CONCLUSIONS

The potential of *Salix arbusculoides* as a revegetation species for northern oil spills remains uncertain. While initial survivorship values were as high as 75% at the end of the first growing season, by the start of the next growing season survivorship values were less than 15% for all plots. However, this may have been due to the lateness of the spring in 1992. By examining rooting success, it was found that potential survivorships were as high as 61% at this time. If this is indeed the case then this shrub could be a valuable revegetation species for subarctic oil spills. Given the fact that cuttings planted in oiled areas fared better or no worse than cuttings planted in unoiled areas, it appears that in the third growing season after the oil spill, the crude oil apparently had little or no effect on the shrub cuttings. If the potential survivorships are an accurate reflection of true survivorships then *S. arbusculoides* could be just as effective as a revegetation species for crude oil spills on moist sites as it is for any other kind of disturbance in the north.

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CHAPTER 4

Plant community responses to an experimental crude oil spill on a Subarctic Right-of-Way

INTRODUCTION

A great deal of research has been conducted on the effects of petroleum products on plant communities, dating back to the early part of this century (Carr, 1919; Baldwin, 1922). Much of the early work derives from research on herbicides (e.g. Crafts and Reiber, 1948; Currier, 1951; Ennis et al., 1952) or insecticides (e.g. DeOng et al., 1927; Knight et al., 1929; Rohrbaugh, 1941).

The effects of oil pollution on plants are dependent upon a number of factors: the type and quantity of oil, the degree of its weathering, the time of year, and the species and age of plants involved (Baker, 1970). In general, the smaller the hydrocarbon molecule the more phytotoxic the oil (Van Overbeek and Blondeau, 1954).

Crude oil can have a number of effects on plant tissue. Plants with thick cuticles and few stomata are relatively resistant to oil penetration through their leaves, however, once into the leaf, oil moves into the intercellular spaces (Knight et al., 1929; Minshall and Helson, 1949). Cell membranes are then damaged by penetration of oil molecules, causing leakage of cell contents (Currier, 1951; Van Overbeek and Blondeau, 1954). Oil contamination also leads to reduced transpiration because of blocked stomata (Knight et al., 1929; Riehl et al., 1958). Plant wilting can result from oil within plant tissue interfering with translocation of water and nutrients (Wedding and Riehl, 1958; Schwedinger, 1968).

The effects of oil spills in Arctic and Subarctic regions are thought to persist for longer periods of time because net annual decomposition of oil is low as a result of cool temperatures and brief summers (Hunt et al., 1973). This is a result of the fact that oil-degrading microorganisms are temperature dependent and hence limited to activity during the brief thaw season (Cook and Westlake, 1974). While the number of oil-degrading microorganisms may rise within hours or days of oil application in temperate regions (Atlas and Bronner, 1981), the increase may take months or even years in northern ecosystems (Haines and Atlas, 1982).

Research on oil spills in northern environments did not begin until the early 1970s, but there was a large amount of work conducted on the subject in that decade (e.g. Wein and Bliss, 1973; Greene et al., 1975; Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978; Jenkins et al., 1978; Linkins et al., 1978; Mckendrick and Mitchell, 1978; Walker et al., 1978).

Most of this research was conducted in either tundra or taiga ecosystems to determine the sensitivity of northern species to potential oil spills. The preferred application method of most of these experiments was a spray application, to ensure uniform coverage on all vegetation. While such a technique may successfully mimic an aboveground pipeline rupture where pressurized oil is sprayed from the pipe, it may not mimic a belowground pipeline rupture where the oil would be concentrated in the soil. A spray application tends to create a thin coat of oil which would enhance weathering of the oil (Jenkins et al., 1978). In addition, such a method results in high surface area contact for plants, thus killing most green tissue. A belowground spill may have more long-term effects on the rooting systems of plants but less immediate effect on aboveground plant tissue. This may be especially significant for non-vascular species. Indeed, in a study of actual oil spills along the CANOL pipeline in the NWT, Kershaw and Kershaw (1986) found non-vascular species thriving on slightly elevated sites within oil spill areas where vascular species had been killed.

In addition, as most of the experimental work was conducted in either undisturbed tundra or taiga ecosystems it does not provide information on the effects of such a spill on the actual operating environment of a pipeline. Currently, there is only one major oil pipeline in northern Canada, the Interprovincial Pipeline project, stretching from Norman Wells, NWT to Zama, Alberta. A pipeline corridor consists of two distinct environments: the trench area, where the soil has been excavated for the pipeline and then backfilled, and the right-of-way where the trees and shrubs have been removed, but the organic layer is relatively undisturbed.

Changes in the plant cover on such areas can have wide implications. Reduction in plant cover can reduce forage for a number of animals. In addition, the removal of vegetation and the blackening of the soil surface can reduce the albedo of the surface and result in warming of the soil leading to permafrost degradation (Collins, 1983).

The current study was undertaken at the SEEDS site, near Fort Norman, NWT. A spill of 3273 L (or 20 imperial barrels) of Norman Wells crude oil was initiated in August of 1988 (Kershaw, 1990). This resulted in an area of contamination of 673 m^2 with an average concentration of 5 $L \bullet m^2$. The goal of this study was to establish the effects of a small-scale crude-oil spill on the plant communities found within what would be the actual operating environment of an oil pipeline within 3 to 4 growing seasons after construction. Because of the relative homogeneity of understory vegetation across much of the Subarctic, the results of this study should have broad management implications for the reclamation of future oil pipelines in the north.

METHODS

Field Methods

In 1988, prior to the oil spill, 288 permanent 25 x 25 cm quadrats were established on a 1 x 1 m grid system over the proposed oil spill area along ROW 2 and the North Link. The number of species present and the percent cover of each species were visually assessed annually, at the end of each growing season. Taxonomy follows Porsild and Cody (1980) for vascular plants, Steere (1978) for mosses and Thomson (1979) for lichens. Any species present at a cover value of less than 1% (for example, one individual orchid) were arbitrarily assigned a value of 0.1% for statistical purposes. In addition, a qualitative assessment of the oil present (heavy, light, or apparently absent) was noted. The number of quadrats varied from year to year, primarily in response to fluctuating water levels.

Species Assemblages

For the purpose of these analyses, a number of related species were grouped together to form a species assemblage (Table 4-1). This was done because identification of some species (especially some mosses and lichens) can be difficult in the field, and some species were otherwise too rare to include (e.g. some of the grasses).

Data Analysis

In order to control for natural interannual variations among quadrats, no quadrat was included in the final dataset unless data had been recorded on it for all four years of the study. This reduced the total dataset from 288 to 210 quadrats. Next, the quadrats were assigned to one of two major categories: ROW or Trench, depending upon their location. Each of these two categories were then split into three subdivisions based on the apparent oil concentration they experienced: heavy, light, or apparently unoiled. Because of the subsidence in the Trench there were no quadrats there that appeared to be unoiled.

The effects of the oil on the plant species were assessed in three ways. First, changes in the number of species (or floristic diversity) were calculated. The distribution of the number of species per quadrat

Table 4-1. Species list for SEEDS oil spill quadrats. Indented species have been pooled under species assemblage name for all analysis.

Non-Vascular Species

Cetraria spp.
- *C. cucullata*
- *C. nivalis*
- *C. tilesii*

Cladonia spp.
- *C. amaurocraea*
- *C. chlorophaea* group
- *C. coccifera*
- *C. cornuta*
- *C. fimbriata*
- *C. gracilis*
- *C. rangeriferina*
- *C. stellaris*
- *C.* spp.

Moss spp.
- *Aulacomnium palustre*
- *Dicranum* spp.
- *Hylocomium splendens*
- *Orthodicranum flagellare*
- *Ptilidium pulchellum*
- *Tomenthypnum nitens*
- Misc. moss spp.

Peltigera spp.
- *P. aphthosa*
- *P. canina*

Vascular Species

Andromeda polifolia
Anemone richardsonii
Arctagrostis latifolia
Arctostaphylos rubra
Betula glandulosa
Betula pumila
Calamagrostis canadensis

Carex spp.
- *C. gynocrates*
- *C. media*
- *C. membranacea*
- *C. vaginata*

Empetrum nigrum
Epilobium angustifolium
Equisetum arvense
Equisetum scirpoides

Eriophorum spp.
- *E.* spp.

Festuca spp.
- *F. ovina*
- *F. rubra*

Larix laricina
Ledum groenlandicum

Miscellaneous graminoids
- *Alopecurus arundinacea*
- *Phleum pratense*
- *Poa glauca*
- *Poa pratensis*

Orchis rotundifolia
Picea mariana
Potentilla fruticosa
Pyrola secunda
Rosa acicularis
Rubus chamaemorus
Salix arbusculoides
Salix myrtillifolia
Saussurea angustifolia
Senecio atropurpureus
Spiranthes romanzoffiana
Stellaria longipes
Vaccinium uliginosum
Vaccinium vitis-idaea

was found to be normal using the Shapiro and Wilk's W Test (Dunn and Clark, 1987). Analysis of Variance was then used to test for differences among years (Sokal and Rohlf, 1981). When required, multiple comparison tests were performed using the Tukey-Kramer method because sample sizes were the same (Sokal and Rohlf, 1981).

Next, changes in total percentage plant cover were assessed. These data were not normal, however, a logarithmic transformation successfully corrected for this. Analysis of Variance was then used to test for differences (Sokal and Rohlf, 1981). When required, multiple comparison tests were performed using the Tukey-Kramer method when sample sizes were the same or the GT2-Method when substantial differences in sample size existed (Sokal and Rohlf, 1981).

Finally, changes in the percentage cover of individual species were assessed. These data were found not to be normal with the Shapiro and Wilk's W Test (Dunn and Clark, 1987) and no transformation successfully corrected for this. Hence a non-parametric test was required and the Kruskal-Wallis test was selected (Sokal and Rohlf, 1981). When the overall Kruskal-Wallis test was significant, pairwise comparisons were conducted using an experimentwise error rate calculated using the Dunn-Sidak method (Sokal and Rohlf, 1981).

RESULTS

Because the oil spill simulated an actual pipeline rupture, not all areas received equal quantities of oil. The oil flowed over the area, concentrating in low lying micro-sites and missing or only lightly coating higher areas. In order to take these differences into account three levels of disturbance were identified: heavily oiled areas, lightly oiled areas, and apparently unoiled areas.

Floristic Diversity

The ROW and Trench were distinct environments. Since the Trench had the organic layer removed it was lacking many of the species found on the ROW. The two environments were therefore dealt with separately.

ROW

Before the oil spill, the number of species or species assemblages per quadrat on the ROW varied from 7.4 ($\pm$ 2.1) on the quadrats that remained apparently unoiled to 8.3 ($\pm$ 2.2) on the quadrats that became heavily oiled (Figure 4-1 to 4-3). This difference in the number of species present among the three types of ROW quadrats before the oil spill was not statistically significant ($F = 2.8$, $p > 0.05$).

After the oil spill, the heavily oiled ROW experienced a dramatic and sustained decrease in the number of species present (Figure 4-1).

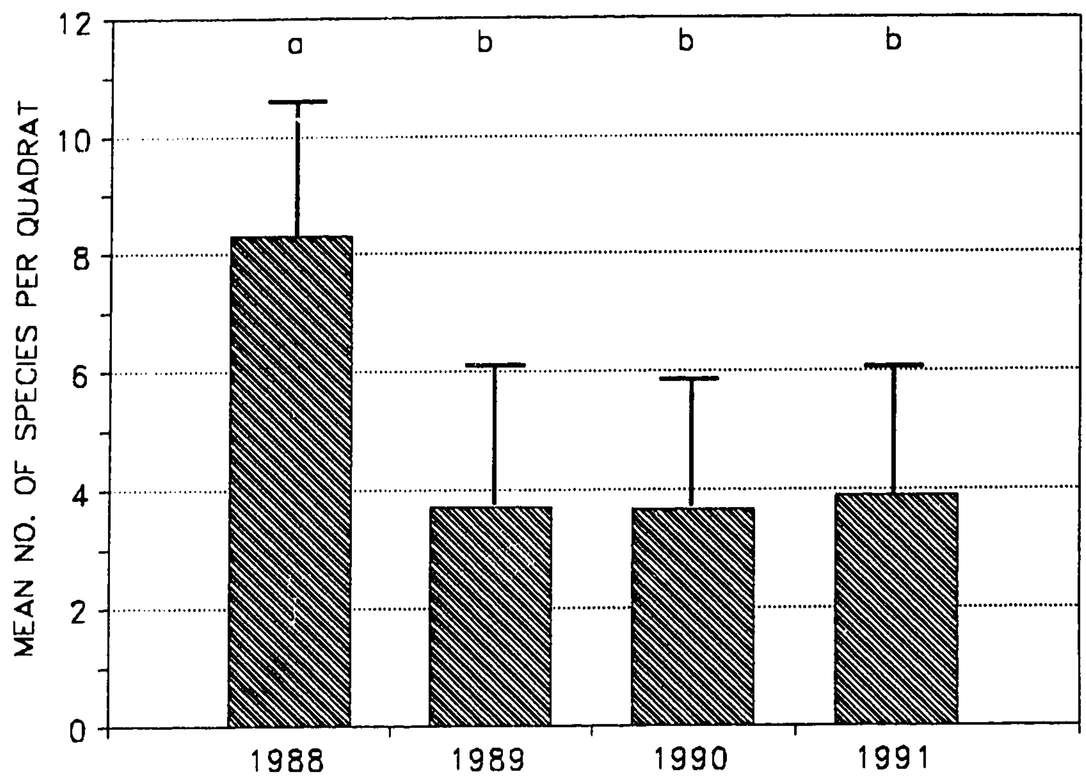

Fig. 4-1. Mean number of species or species assemblages present on the heavily oiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

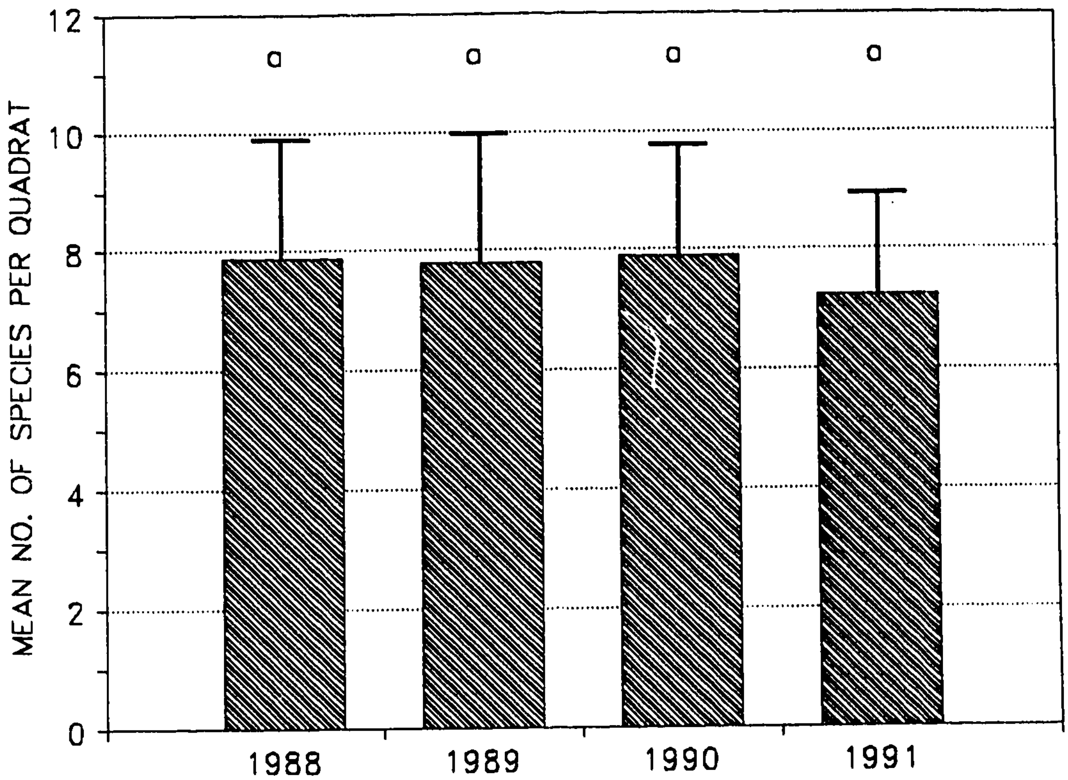

Fig. 4-2. Mean number of species or species assemblages present on the lightly oiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

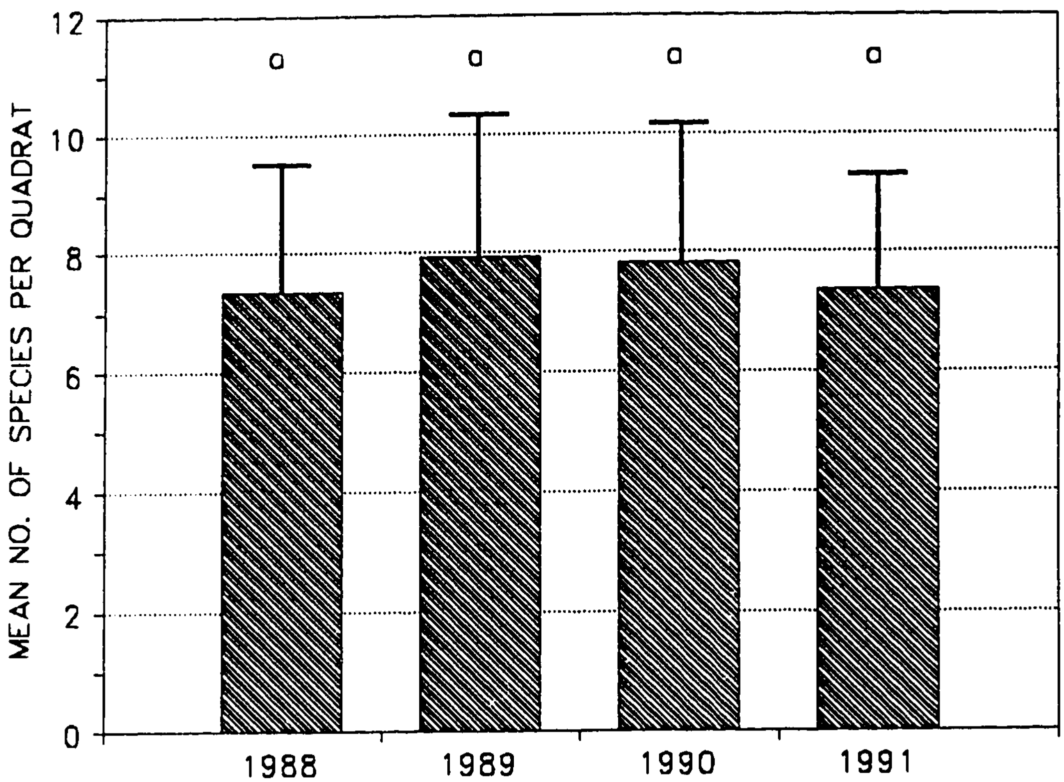

Fig. 4-3. Mean number of species or species assemblages present on the apparently unoiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly (p > 0.05).

This decrease was significant ($F = 52.9$, $p < 0.0001$). A multiple comparison test revealed that the number of species present before the oil spill in 1988 was significantly greater than the number of species present in 1989 ($Q = 14.7$, $p < 0.001$), 1990 ($Q = 14.8$, $p < 0.001$), and 1991 ($Q = 14.1$, $p < 0.001$).

The lightly oiled ROW experienced virtually no change in the number of species present after the oil spill until 1991 when the number of species did decline slightly (Figure 4-2). This difference was not significant ($F = 1.0$, $p > 0.25$).

The apparently unoiled ROW actually had a slight increase in the number of species present the first two years after the spill (Figure 4-3), however these differences were not significant ($F = 1.3$, $p > 0.25$).

Trench

The number of species present on the Trench before the oil spill varied from 4.0 ($\pm$ 1.5) on the quadrats that became heavily oiled to 4.9 ($\pm$ 1.7) on the quadrats that became lightly oiled (Figure 4-4 to 4-5). This difference was significant ($F = 4.2$, $p < 0.05$).

The heavily oiled Trench slightly decreased and then increased in terms of the number of species present compared with the pre-spill value (Figure 4-4). This change was not significant ($F = 1.8$, $p > 0.1$).

The lightly oiled Trench actually had a slight increase in the number of species present after the spill (Figure 4-5). This difference was not significant ($F = 0.4$, $p > 0.75$).

Total Plant Cover

Even if a species was not completely eliminated by the oil spill it may still have been affected by the oil, either positively or negatively. By examining the total percentage cover of all species both before the oil spill (1988) and in the following three years it was possible to determine the immediate- and medium-term effects of the oil. Just as with the floristic diversity analysis, the quadrats were divided into ROW and Trench and subdivided by oil concentration.

ROW

Before the oil spill, the total percentage plant cover ranged from 40.4% ($\pm$ 29.6) on the quadrats that would remain apparently unoiled to 74.0% ($\pm$ 33.1) on the quadrats that would become heavily oiled (Figure 4-6 to 4-8). This difference was significant ($F = 14.9$ $p < 0.0001$). There was no significant difference between the quadrats that would become heavily or lightly oiled ($m = 1.1$, $p > 0.1$), while the quadrats which remained unoiled had a significantly lower mean plant cover value than either the quadrats that would become lightly ($m = 3.3$,

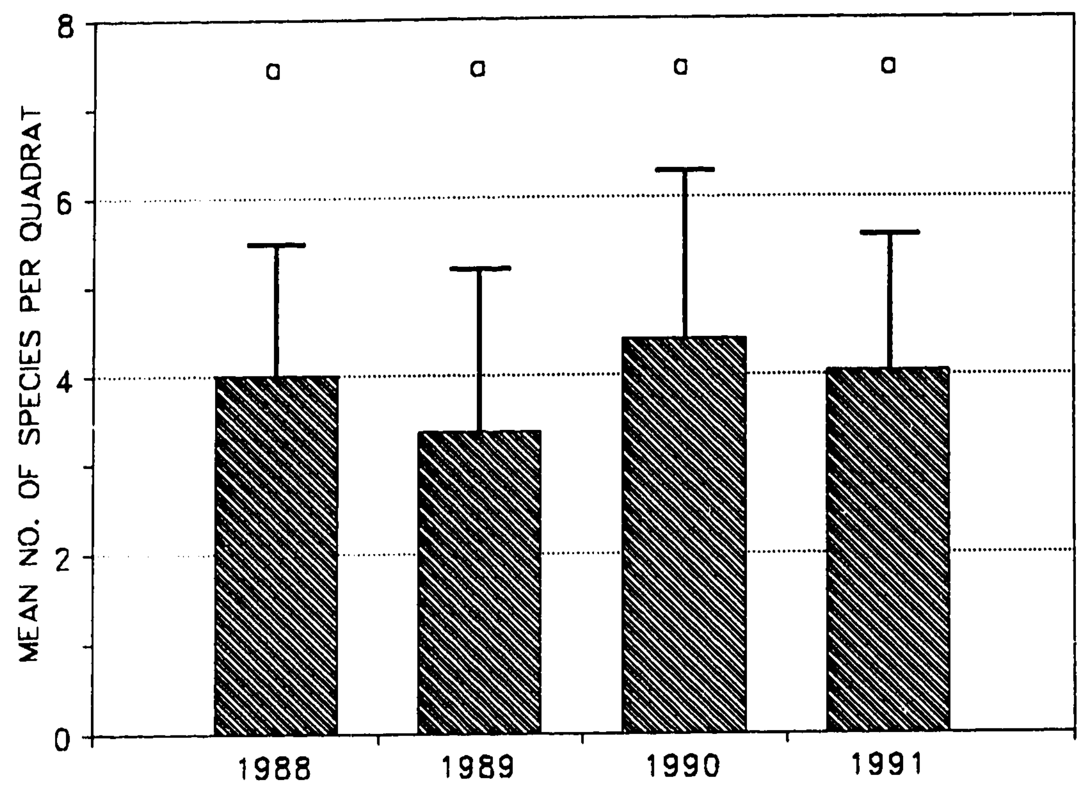

Fig. 4-4. Mean number of species or species assemblages present on the heavily oiled Trench before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

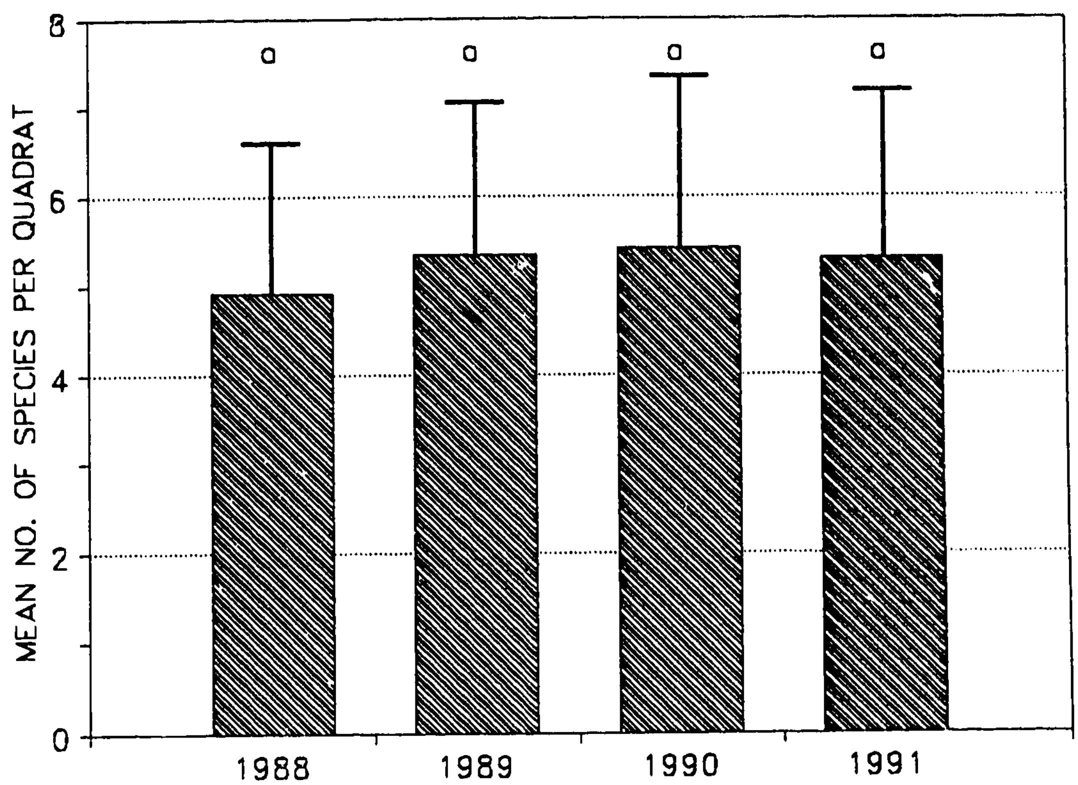

Fig. 4-5. Mean number of species or species assemblages present on the lightly oiled Trench before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

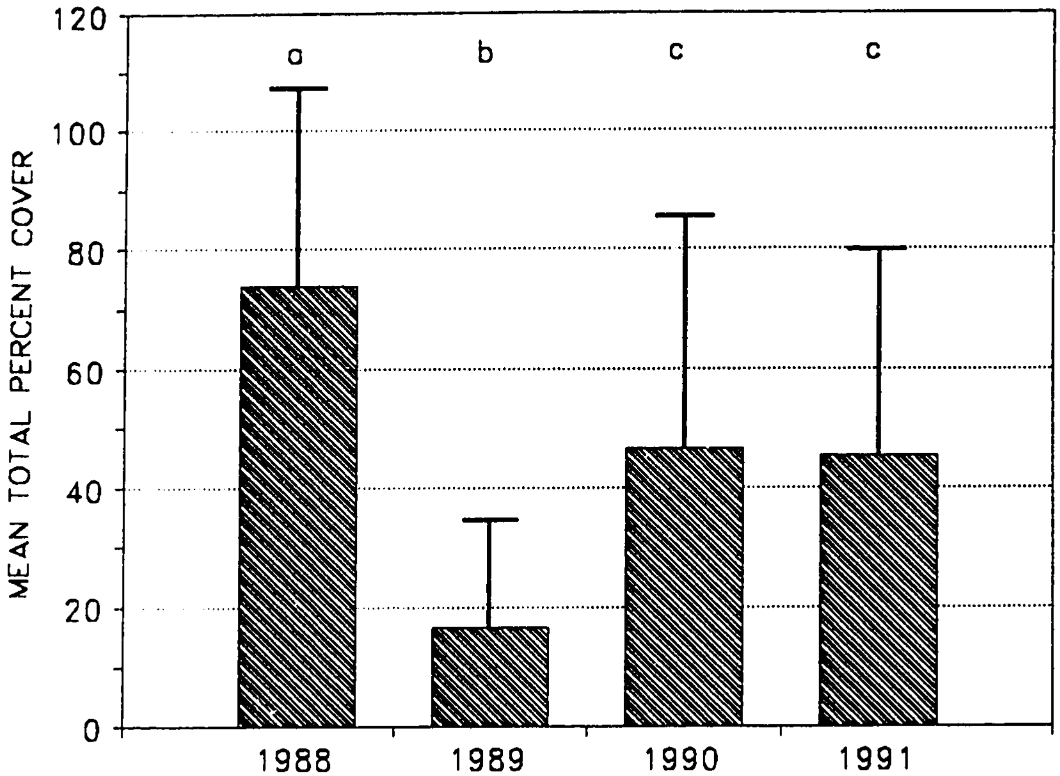

Fig. 4-6. Mean total percentage plant cover present on the heavily oiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

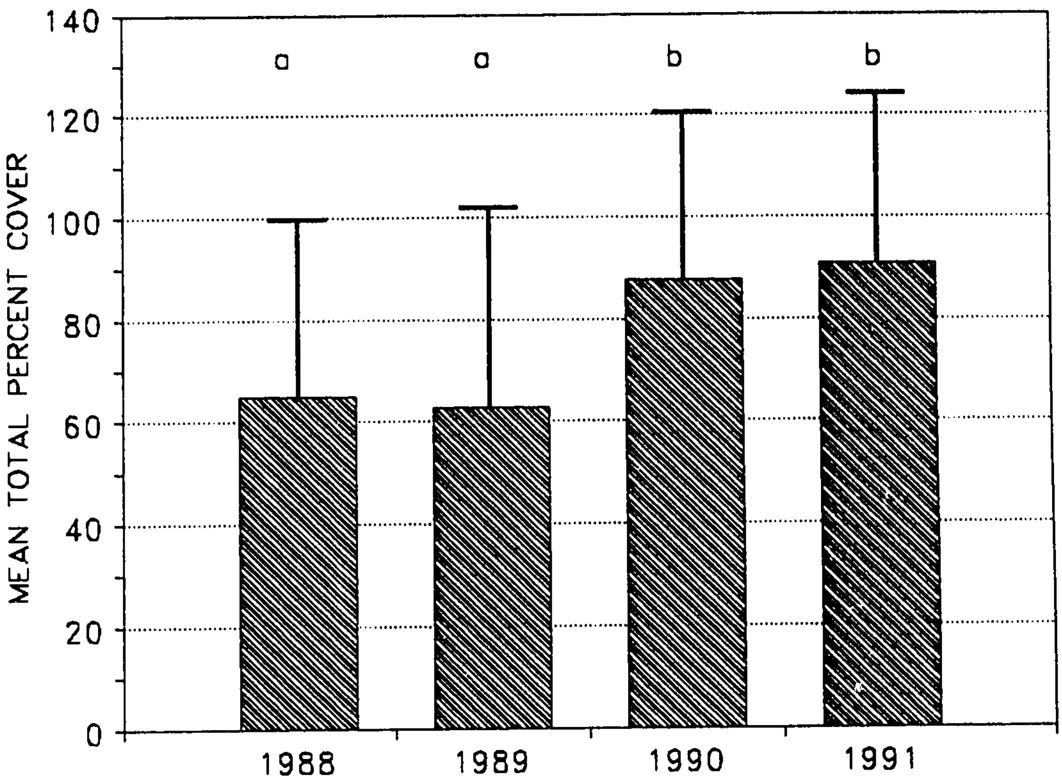

Fig. 4-7. Mean total percentage plant cover present on the lightly oiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

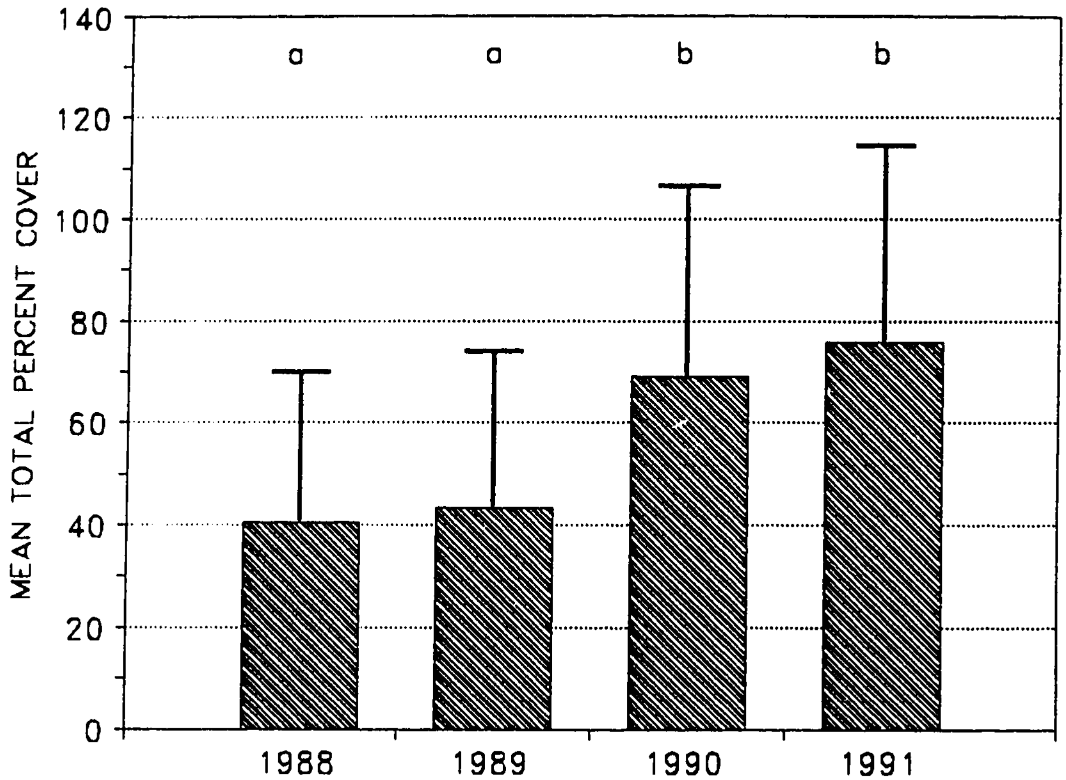

Fig. 4-8. Mean total percentage plant cover present on the apparently unoiled ROW before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

$p < 0.01$) or heavily ($m = 4.9$, $p < 0.01$) oiled.

The heavily oiled quadrats experienced the most dramatic change in mean total plant cover, going from almost 75% before the oil spill to less than 20% the year after the spill (Figure 4-6). Over the four years, the change in total cover was significant ($F = 22.4$, $p < 0.0001$). The pre-spill mean plant cover was significantly greater than the 1989 ($Q = 12.6$, $p < 0.0001$), the 1990 ($Q = 6.0$, $p < 0.001$), and the 1991 ($Q = 6.2$, $p < 0.001$) values.

The lightly oiled quadrats had little change in plant cover immediately after the spill and then increased above the pre-spill level (Figure 4-7). This difference was significant ($F = 7.0$, $p < 0.001$). The slight decrease in 1989 from the pre-spill value was not significant ($Q = 0.4$, $p > 0.5$), however in both 1990 ($Q = 3.9$, $p < 0.05$) and 1991 ($Q = 4.5$, $p < 0.01$) the mean total plant cover was significantly greater than the pre-spill value.

The apparently unoiled quadrats also experienced little change in mean plant cover immediately after the spill and then increased above the pre-spill value (Figure 4-8). This change in plant cover was significant ($F = 14.0$, $p < 0.0001$). The slight increase in 1989 from the pre-spill value was not significant ($Q = 0.8$, $p > 0.25$), however in both 1990 ($Q = 7.1$, $p < 0.001$) and 1991 ($Q = 8.7$, $p < 0.001$) the mean total plant cover was significantly greater than the pre-spill value.

Trench

Before the oil spill, the total mean plant cover ranged from 43.2% ($\pm$ 27.6) on the quadrats that would become heavily oiled to 66.9% ($\pm$ 27.1) on the quadrats that would become lightly oiled (Figure 4-9 to 4-10). This difference was significant ($F = 7.2$, $p < 0.025$).

The heavily oiled Trench had its plant cover value decrease immediately after the oil spill and then increase above the pre-spill value (Figure 4-9). This change in plant cover was significant ($F = 8.8$, $p < 0.001$). While the 1989 decrease from the pre-spill value was not significant ($Q = 2.7$, $p > 0.05$), the 1990 increase above the pre-spill value was significant ($Q = 4.8$, $p < 0.01$), although the 1991 value was not significantly different from the pre-spill value ($Q = 3.2$, $p > 0.05$).

The lightly oiled Trench increased in mean plant cover after the oil spill (Figure 4-10). This change was significant ($F = 3.4$, $p < 0.025$). 6Neither the 1989 ($Q = 0.3$, $p > 0.5$) or 1991 ($Q = 1.7$, $p > 0.01$) increase above the pre-spill value were significant, however the 1990 value was significantly greater than the pre-spill value ($Q = 3.7$, $p < 0.05$).

Species Abundance

While net changes in total plant cover provide an indication of the relative health and vigour of an ecosystem they do not provide any

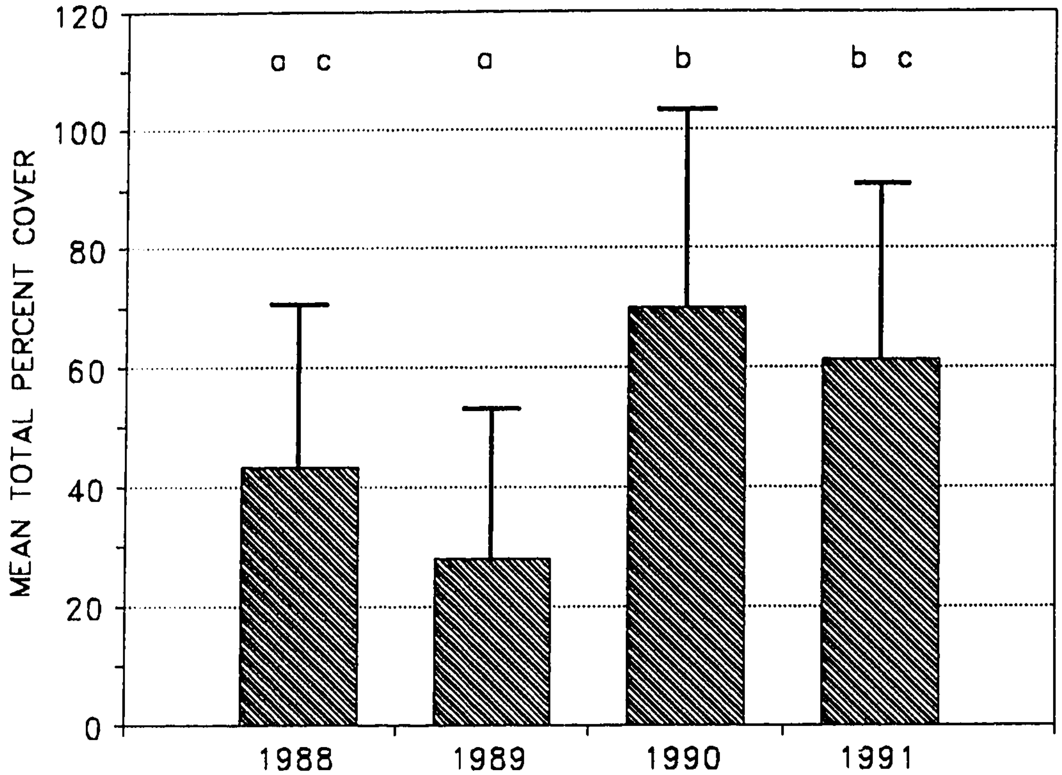

Fig. 4-9. Mean total percentage plant cover present on the heavily oiled Trench before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

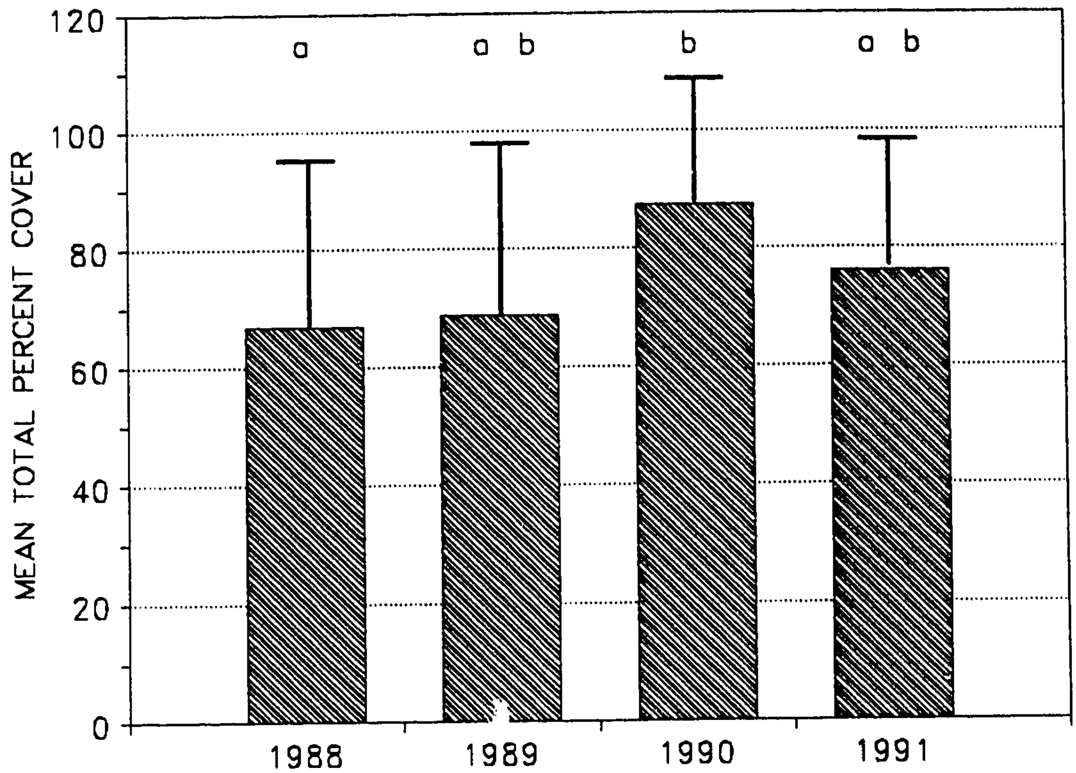

Fig. 4-10. Mean total percentage plant cover present on the lightly oiled Trench before (1988) and after (1989-1991) the crude oil spill. Error bars indicate one standard deviation. Bars with the same letter above them do not differ significantly ($p > 0.05$).

information on which species are particularly susceptible or resistant to the effects of the crude oil. By examining the percentage cover of each species both before the oil spill (1988) and the subsequent three years it is possible to determine which species are most sensitive and which are most adapted to crude oil exposure. Just as with the floristic diversity analysis, the quadrats were divided into ROW and Trench and subdivided by oil concentration.

ROW

The percentage cover for each species before the oil spill was compared among the three types of ROW quadrats: those that became heavily oiled, lightly oiled, and apparently unoiled (Table 4-2). Only seven of the 34 species or species assemblages significantly differed among the three types of quadrats. Most of these species were more abundant on those quadrats that became heavily or lightly oiled than on those that remained apparently unoiled.

Next, each subdivision of the ROW quadrats was analyzed separately over time. After the oil spill, the heavily oiled ROW had 19 of 30 species significantly change from their pre-spill value (Table 4-3). All but two of these species were either eliminated from the study plots or were significantly less abundant at some point after the spill. The exceptions were all grasses and sedges: *Eriophorum*, and the miscellaneous graminoids. While they experienced small, but insignificant decreases the year after the spill, in the third year significant increases above pre-spill levels were achieved.

The lightly oiled ROW had six species or assemblages of 34 species significantly change in terms of their percentage cover after the oil spill (Table 4-4). Only two species significantly declined in abundance from their pre-spill value and they only did so in the third year after the spill: *Equisetum arvense*, and *Saussurea angustifolia* which was eliminated. Three of the groups significantly increased in abundance from their pre-spill value, but not until either the second or third growing season after the spill: the moss spp., *Carex* spp., and *Eriophorum*. The miscellaneous graminoid species were the sixth group to show a significant overall change. Pairwise comparisons revealed no significant increase or decrease from the pre-spill value. Only the 1990 and 1991 values differed significantly ($p < 0.05$).

The apparently unoiled ROW had seven species or assemblages of the 31 present significantly change in terms of their percentage cover after the oil spill (Table 4-5). Two of these species were eliminated by the third growing season after the spill (*Anemone richardsonii* and *Saussurea angustifolia*). *Equisetum arvense* increased significantly in 1990 and then decreased significantly in 1991, both in comparison with the pre-spill value. The other four species or assemblages significantly increased in

Table 4-2. Mean percent cover values for each species or species assemblage with standard deviations below them for the three types of ROW quadrats (heavily oiled, lightly oiled, and apparently unoiled) before the oil spill (1988). Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size: heavily oiled, n = 49; lightly oiled, n = 38; apparently unoiled, n = 72. N.S. -- not significantly different at $p < 0.05$. Where a significant difference was found multiple comparison tests were performed. In a given row, means with the same superscript do not differ significantly at an experimentwise level of $p < 0.05$.

Species	Heavily oiled	Lightly oiled	Unoiled	H	p
Moss spp.	47.633^{a} (27.775)	37.371^{a} (28.666)	16.121^{b} (22.247)	41.0	<0.001
Cetraria spp.	0	0.003 (0.016)	0.226 (1.770)	0.8	N.S.
Cladonia spp.	2.445 (8.787)	2.932 (8.204)	3.679 (8.700)	1.9	N.S.
Peltigera spp.	0.214 (0.733)	0.189 (0.865)	0.114 (0.640)	3.7	N.S.
Andromeda polifolia	0.002 (0.014)	0.026 (0.162)	0	3.1	N.S.
Anemone richardsonii	0.043 (0.286)	0.026 (0.162)	0.226 (1.235)	3.6	N.S.
Arctagrostis latifolia	1.165^{a} (1.630)	0.721^{b} (1.898)	0.265^{b} (0.682)	21.3	<0.001
Arctostaphylos rubra	3.449 (6.384)	5.868 (10.089)	2.893 (5.862)	2.1	N.S.
Betula glandulosa	0.494 (2.255)	0.661 (3.257)	0.725 (3.145)	0.2	N.S.
Betula pumila	0.612 (3.168)	0.105 (0.649)	0.210 (1.310)	0.2	N.S.
Carex spp.	1.114 (2.068)	1.600 (3.250)	0.564 (1.036)	1.5	N.S.
Empetrum nigrum	1.927^{a} (3.995)	0.324^{b} (1.628)	1.360^{b} (0.328)	12.8	< 0.01
Epilobium angustifolium	0	0.026 (0.162)	0	2.6	N.S.
Equisetum arvense	0.516 (1.207)	1.768 (5.743)	0.381 (1.033)	1.0	N.S.
Equisetum scirpoides	0.404 (0.846)	0.608 (1.649)	0.386 (0.794)	2.9	N.S.
Eriophorum spp.	0.518^{a} (1.695)	0.087^{ab} (0.486)	0.142^{b} (1.178)	10.0	< 0.01
Festuca spp.	0.002 (0.014)	0.082 (0.486)	0.003 (0.017)	0.8	N.S.
Larix laricina	0.249^{a} (0.854)	0.003^{ab} (0.016)	0.097^{b} (0.632)	9.5	< 0.01

Table 4-2 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the three types of ROW quadrats (heavily oiled, lightly oiled, and apparently unoiled) before the oil spill (1988). Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size: heavily oiled, n = 49; lightly oiled, n = 38; apparently unoiled, n = 72. N.S. -- not significantly different at $p < 0.05$. Where a significant difference was found multiple comparison tests were performed. In a given row, means with the same superscript do not differ significantly at an experimentwise level of $p < 0.05$.

Species	Heavily oiled	Lightly oiled	Unoiled	H	p
Ledum groenlandicum	4.722 (6.407)	5.005 (6.990)	4.547 (5.567)	0.4	N.S.
miscellaneous graminoid spp.	0.255 (1.728)	0.121 (0.386)	0.044 (0.262)	6.2	< 0.05
Orchis rotundifolia	0.020 (0.143)	0.003 (0.016)	0	1.1	N.S.
Picea mariana	0.165 (0.898)	0.403 (2.432)	0.058 (0.471)	1.7	N.S.
Potentilla fruticosa	0.063 (0.242)	0.426 (1.794)	1.960 (5.337)	6.5	< 0.05
Pyrola secunda	0.082 (0.344)	0.003 (0.016)	0.003 (0.017)	0.7	N.S.
Rosa acicularis	0	0.003 (0.016)	0.058 (0.471)	0.9	N.S.
Rubus chamaemorus	0.716 (2.020)	1.345 (2.997)	0.835 (2.109)	3.3	N.S.
Salix arbusculoides	0.429 (2.291)	1.368 (5.772)	0.319 (1.372)	0.6	N.S.
Salix myrtillifolia	3.286 (7.397)	0.845 (2.583)	3.778 (9.184)	2.8	N.S.
Saussurea angustifolia	0.094 (0.448)	0.345 (1.168)	0.322 (1.018)	0.5	N.S.
Senecio atropurpureus	0	0.005 (0.023)	0.015 (0.118)	0.6	N.S.
Spiranthes romanzoffiana	0.002 (0.014)	0.026 (0.162)	0	0.6	N.S.
Stellaria longipes	0.002 (0.014)	0.003 (0.016)	0.003 (0.017)	0.2	N.S.
Vaccinium uliginosum	2.563 (4.621)	2.245 (2.576)	1.614 (3.331)	4.1	N.S.
Vaccinium vitis-idaea	0.824 (1.606)	0.611 (1.375)	0.476 (1.348)	0.5	N.S.

Table 4-3. Mean percent cover values for each species or species assemblage with standard deviations below them for the heavily oiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant ($n = 49$). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Moss spp.	47.633 (27.775)	12.155[c] (16.226)	36.306 (30.346)	33.755 (26.444)	43.9	0.0001
Cladonia spp.	2.445 (8.787)	0.002[c] (0.014)	0.002[c] (0.014)	0.041[c] (0.286)	42.8	0.0001
Peltigera spp.	0.214 (0.733)	0[b]	0[b]	0.002[b] (0.014)	24.0	0.0001
Andromeda polifolia	0.002 (0.014)	0	0	0	3.0	N.S.
Anemone richardsonii	0.043 (0.286)	0	0	0.002 (0.014)	3.7	N.S.
Arctagrostis latifolia	1.165 (1.630)	0.127[c] (0.857)	0.063[c] (0.200)	0.153[c] (0.538)	55.3	0.0001
Arctostaphylos rubra	3.449 (6.384)	0.186[c] (0.808)	0.041[c] (0.286)	0.041[c] (0.286)	36.5	0.0001
Betula glandulosa	0.494 (2.255)	0.194 (0.832)	0.045 (0.200)	0.020 (0.143)	6.6	N.S.
Betula pumila	0.612 (3.168)	0.204 (1.429)	0.510 (3.571)	0.306 (2.143)	0.6	N.S.
Carex spp.	1.114 (2.068)	0.412[b] (1.152)	3.067 (9.763)	2.908 (8.874)	8.9	N.S.
Empetrum nigrum	1.927 (3.995)	0.249[b] (0.829)	0.331[c] (1.736)	0.451[c] (1.671)	18.8	0.001
Equisetum arvense	0.516 (1.207)	0.249[b] (1.216)	0.047[b] (0.200)	0[c]	23.6	0.0001
Equisetum scirpoides	0.404 (0.846)	0.118[c] (0.423)	0.229[b] (0.425)	0.135[c] (0.265)	22.2	0.0001
Eriophorum spp.	0.518 (1.695)	0.088 (0.343)	3.024 (6.667)	4.027[b] (7.798)	16.6	0.001
Festuca spp.	0.002 (0.014)	0.002 (0.014)	0.027 (0.144)	0.084 (0.449)	3.2	N.S.
Larix laricina	0.249 (0.854)	0.043* (0.286)	0.063* (0.429)	0.061[a] (0.429)	10.0	0.05

Table 4-3 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the heavily oiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 49). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Ledum groenlandicum	4.722 (6.407)	1.204[b] (3.079)	1.153[c] (3.250)	1.657[c] (4.278)	21.2	0.0001
miscellaneous graminoid spp.	0.255 (1.728)	0.102 (0.467)	0.122 (0.526)	1.349[a] (3.418)	13.9	0.01
Orchis rotundifolia	0.020 (0.143)	0	0	0	3.0	N.S.
Picea mariana	0.165 (0.898)	0.002 (0.014)	0.002 (0.014)	0.041 (0.286)	2.1	N.S.
Potentilla fruticosa	0.063 (0.242)	0.002 (0.014)	0	0.002 (0.014)	6.3	N.S.
Pyrola secunda	0.082 (0.344)	0	0	0	9.1	0.05
Rubus chamaemorus	0.716 (2.020)	0.143 (1.000)	0.245 (1.714)	0.082[b] (0.571)	16.4	0.001
Salix arbusculoides	0.429 (2.291)	0	0	0	6.0	N.S.
Salix myrtillifolia	3.286 (7.397)	0.353 (1.547)	0.796[a] (5.000)	0.124[c] (0.857)	13.4	0.01
Saussurea angustifolia	0.094 (0.448)	0[b]	0[b]	0[b]	24.9	0.0001
Spiranthes romanzoffiana	0.002 (0.014)	0	0	0	3.0	N.S.
Stellaria longipes	0.002 (0.014)	0	0.041 (0.286)	0	2.0	N.S.
Vaccinium uliginosum	2.563 (4.621)	0.490[b] (1.202)	0.543[c] (1.934)	0.153[c] (0.538)	33.6	0.0001
Vaccinium vitis-idaea	0.824 (1.606)	0.029[c] (0.144)	0.033[c] (0.145)	0.073[c] (0.316)	45.4	0.0001

Table 4-4. Mean percent cover values for each species or species assemblage with standard deviations below them for the lightly oiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 38). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Moss spp.	37.371 (28.666)	36.979 (30.016)	54.237 (30.702)	58.158[b] (29.715)	14.8	0.01
Cetraria spp.	0.003 (0.016)	0	0	0	1.7	N.S.
Cladonia spp.	2.932 (8.204)	2.637 (9.566)	2.637 (10.248)	2.634 (10.826)	7.7	N.S.
Peltigera spp.	0.189 (0.865)	0.026 (0.162)	0.026 (0.162)	0	6.2	N.S.
Andromeda polifolia	0.026 (0.162)	0.026 (0.162)	0.079 (0.487)	0	1.0	N.S.
Anemone richardsonii	0.026 (0.162)	0.082 (0.486)	0.029 (0.163)	0	2.2	N.S.
Arctagrostis latifolia	0.721 (1.898)	0.513 (2.466)	0.592 (1.343)	0.229 (0.840)	1.9	N.S.
Arctostaphylos rubra	5.868 (10.089)	3.745 (9.170)	2.900 (6.041)	2.558 (5.458)	2.6	N.S.
Betula glandulosa	0.661 (3.257)	0.211 (0.664)	0.532 (2.262)	0.661 (2.373)	0.2	N.S.
Betula pumila	0.105 (0.649)	0.079 (0.487)	0.105 (0.649)	0.105 (0.649)	0.1	N.S
Carex spp.	1.600 (3.250)	2.432 (5.001)	6.300 (11.553)	6.513[c] (10.315)	14.0	0.01
Empetrum nigrum	0.324 (1.628)	0.539 (3.242)	0.716 (4.059)	0.716 (4.059)	0.8	N.S.
Epilobium angustifolium	0.026 (0.162)	0	0	0	3.0	N.S.
Equisetum arvense	1.768 (5.743)	1.803 (5.758)	1.582 (3.255)	0.005[c] (0.023)	24.6	0.0001
Equisetum scirpoides	0.600 (1.649)	0.808 (1.969)	2.753 (6.599)	1.284 (2.897)	6.8	N.S.
Eriophorum spp.	0.087 (0.486)	0.192 (0.690)	2.087[a] (7.195)	4.053[a] (8.832)	9.2	0.05
Festuca spp.	0.082 (0.486)	0.026 (0.162)	0.058 (0.226)	0.605 (2.261)	3.7	N.S.

Table 4-4 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the lightly oiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 38). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Larix laricina	0.003 (0.016)	0.005 (0.023)	0	0	3.7	N.S.
Ledum groenlandicum	5.005 (6.990)	3.597 (6.347)	5.403 (8.690)	5.458 (8.660)	0.4	N.S.
miscellaneous graminoid spp.	0.121 (0.386)	0.089 (0.272)	0.058 (0.227)	1.134 (1.918)	8.9	0.05
Orchis rotundifolia	0.003 (0.016)	1.579 (9.733)	0.132 (0.811)	0	1.0	N.S.
Picea mariana	0.403 (2.432)	0.403 (2.432)	0.537 (3.243)	0.589 (3.242)	1.5	N.S.
Potentilla fruticosa	0.426 (1.794)	0.458 (2.444)	0.282 (1.175)	0.358 (1.508)	2.1	N.S.
Pyrola secunda	0.003 (0.016)	0	0	0	1.7	N.S.
Rosa acicularis	0.003 (0.016)	0.003 (0.016)	0.003 (0.016)	0.026 (0.162)	0.1	N.S.
Rubus chamaemorus	1.345 (2.997)	0.508 (1.106)	0.818 (1.842)	0.371 (0.818)	1.9	N.S.
Salix arbusculoides	1.368 (5.772)	1.713 (7.907)	0.795 (3.587)	0.526 (2.263)	0.7	N.S.
Salix myrtillifolia	0.845 (2.583)	1.555 (4.929)	1.534 (5.439)	0.871 (2.895)	0.4	N.S.
Saussurea angustifolia	0.345 (1.168)	0.687 (2.337)	0.003 (0.016)	0*	8.2	0.05
Senecio atropurpureus	0.005 (0.023)	0.008 (0.027)	0.003 (0.016)	0	3.4	N.S.
Spiranthes romanzoffiana	0.026 (0.162)	0.003 (0.016)	0	0	2.0	N.S.
Stellaria longipes	0.003 (0.016)	0.003 (0.016)	0.026 (0.162)	0	1.0	N.S.
Vaccinium uliginosum	2.245 (2.576)	1.774 (1.827)	2.882 (3.600)	3.400 (3.889)	1.2	N.S.
Vaccinium vitis-idaea	0.611 (1.375)	0.239 (0.568)	0.516 (1.328)	0.518 (1.364)	1.7	N.S.

Table 4-5. Mean percent cover values for each species or species assemblage with standard deviations below them for the apparently unoiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 72). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Moss spp.	16.121 (22.247)	19.621 (25.332)	33.088[c] (30.034)	40.889[c] (30.287)	33.9	0.0001
Cetraria spp.	0.226 (1.770)	0.128 (0.648)	0.090 (0.599)	0.153 (0.725)	0.8	N.S.
Cladonia spp.	3.679 (8.700)	3.624 (8.085)	3.596 (7.975)	3.331 (10.175)	1.1	N.S.
Peltigera spp.	0.114 (0.640)	0.007 (0.026)	0.031 (0.236)	0.088 (0.365)	1.8	N.S.
Anemone richardsonii	0.226 (1.235)	0.090 (0.402)	0.050 (0.201)	0[b]	9.5	0.05
Arctagrostis latifolia	0.265 (0.682)	0.413 (0.895)	0.572 (1.916)	0.257 (0.735)	1.0	N.S.
Arctostaphylos rubra	2.893 (5.862)	3.614 (7.340)	5.143 (10.192)	5.211 (8.157)	1.6	N.S.
Betula glandulosa	0.725 (3.145)	0.463 (1.668)	0.585 (2.459)	0.778 (3.212)	1.9	N.S.
Betula pumila	0.210 (1.310)	0.194 (1.229)	0.153 (1.002)	0.278 (1.855)	0.4	N.S.
Carex spp.	0.564 (1.036)	0.625 (1.120)	0.749 (1.727)	1.667[c] (2.236)	17.6	0.001
Empetrum nigrum	0.328 (1.360)	0.381 (1.190)	1.071 (3.828)	0.833 (3.306)	0.7	N.S.
Equisetum arvense	0.381 (1.033)	0.618 (1.078)	1.229[a] (2.571)	0.022[c] (0.120)	30.8	0.0001
Equisetum scirpoides	0.386 (0.794)	0.579 (0.951)	1.963[c] (3.749)	2.249[c] (4.860)	15.9	0.01
Eriophorum spp.	0.142 (1.178)	0.075 (0.589)	0.308 (1.534)	0.488 (2.397)	0.7	N.S.
Festuca spp.	0.003 (0.017)	0	0.006 (0.023)	0.100 (0.508)	5.6	N.S.
Larix laricina	0.097 (0.632)	0	0	0.139 (1.179)	3.7	N.S.
Ledum groenlandicum	4.547 (5.567)	3.603 (5.119)	5.894 (8.262)	6.654 (9.020)	3.4	N.S.

Table 4-5 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the apparantly unoiled ROW before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 72). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
miscellaneous graminoid spp.	0.044 (0.262)	0.083 (0.496)	0.029 (0.236)	0.543[a] (1.500)	18.2	0.001
Picea mariana	0.058 (0.471)	0.015 (0.118)	0.069 (0.484)	0.228 (1.769)	3.4	N.S.
Potentilla fruticosa	1.960 (5.337)	2.017 (5.834)	2.656 (6.773)	2.074 (5.065)	0.1	N.S.
Pyrola secunda	0.003 (0.017)	0.004 (0.020)	0.004 (0.020)	0	3.1	N.S.
Rosa acicularis	0.058 (0.471)	0.056 (0.285)	0.032 (0.236)	0.014 (0.118)	1.8	N.S.
Rubus chamaemorus	0.835 (2.109)	0.546 (1.254)	1.242 (3.403)	0.242 (0.910)	3.9	N.S.
Salix arbusculoides	0.319 (1.372)	0.126 (0.626)	0.031 (0.236)	0.278 (1.366)	0.3	N.S.
Salix myrtillifolia	3.778 (9.184)	4.336 (10.786)	7.014 (16.977)	5.056 (12.511)	0.3	N.S.
Saussurea angustifolia	0.322 (1.018)	0.404 (1.109)	0.160 (0.663)	0[c]	14.4	0.01
Senecio atropurpureus	0.015 (0.118)	0.015 (0.118)	0.003 (0.017)	0	2.0	N.S.
Spiranthes romanzoffiana	0	0.004 (0.020)	0.018 (0.119)	0.003 (0.017)	4.0	N.S.
Stellaria longipes	0.003 (0.017)	0.001 (0.012)	0	0	3.7	N.S.
Vaccinium uliginosum	1.614 (3.331)	1.404 (2.579)	2.638 (4.798)	3.551 (5.661)	3.7	N.S.
Vaccinium vitis-idaea	0.476 (1.348)	0.418 (1.066)	0.538 (1.160)	0.638 (1.204)	2.1	N.S.

abundance in either the second or third year after the spill compared with the pre-spill value: the moss spp., *Carex* spp., *Equisetum scirpoides*, and the miscellaneous graminoids.

Trench

Before examining the effects of the oil on the plant community, a comparison was made between the two pre-spill groupings of quadrats: heavily and lightly oiled. Only two of the species or assemblages significantly differed before the spill in terms of mean percentage cover: moss spp. and *Festuca* spp. (Table 4-6). Both were more abundant on the quadrats that became lightly oiled.

The heavily oiled Trench had only 4 species or assemblages of 21 species significantly change in abundance after the oil spill (Table 4-7). Two of these groups, *Equisetum arvense* and the miscellaneous graminoids, significantly decreased in abundance after the spill compared with the pre-spill value, although *E. arvense* did not do so until the third year of the study. The other two groups, the moss spp. and *Carex* spp. both significantly increased in abundance in the second and third years after the spill compared with the pre-spill value.

The lightly oiled Trench also had a total of 21 species or assemblages present, but only three of them significantly changed in their abundance after the oil spill (Table 4-8). Both *Equisetum arvense* and the miscellaneous graminoids significantly declined in abundance after the spill, although *E. arvense* did not do so until the third year after the spill. In contrast, the moss species significantly increased in abundance both the second and third years after the spill compared with the pre-spill value.

DISCUSSION

Floristic Diversity

ROW

Only the heavily oiled ROW experienced a significant decrease in the number of species present after the spill and this decrease was dramatic: from over 8 species per quadrat to less than 4. Since there was no significant difference in the number of species per quadrat in the types of ROW quadrats before the spill only the variation in oil concentration can explain the post-spill differences. The heavily oiled quadrats tended to be low-lying areas where the oil pooled and therefore the quadrats were blackened by oil. It is perhaps more remarkable that almost half the species survived rather than over half were eliminated.

The fact that there was no significant difference between the lightly oiled and apparently unoiled ROW quadrats implies that a small quantity of crude oil will have little or no effect on the number of

Table 4-6. Mean percent cover values for each species or species assemblage with standard deviations below them for the two types of Trench quadrats (heavily and lightly oiled) before the oil spill (1988). Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size: heavily oiled Trench, n = 27; lightly oiled Trench, n = 24. N.S. -- not significantly different at $p < 0.05$.

Species	Heavily oiled	Lightly oiled	H	p
Moss spp.	27.370 (21.855)	50.083 (23.093)	12.1	< 0.001
Arctagrostis latifolia	0.752 (1.341)	1.333 (3.371)	2.0	N.S.
Arctostaphylos rubra	0.074 (0.385)	0.083 (0.408)	0.1	N.S.
Betula glandulosa	0	0.625 (3.062)	3.7	N.S.
Carex spp.	0.189 (0.556)	0.088 (0.282)	0.1	N.S.
Empetrum nigrum	0	0.042 (0.204)	1.3	N.S.
Epilobium angustifolium	0.037 (0.192)	0.008 (0.028)	0.4	N.S.
Equisetum arvense	2.659 (7.756)	1.500 (3.330)	0.1	N.S.
Equisetum scirpoides	0.089 (0.265)	0.083 (0.201)	2.4	N.S.
Eriophorum spp.	0.685 (1.633)	0.213 (0.832)	3.8	N.S.
Festuca spp.	0.278 (0.808)	1.521 (1.850)	9.3	< 0.01
Ledum groenlandicum	0.185 (0.681)	0.504 (1.718)	0.4	N.S.
miscellaneous graminoid spp.	8.804 (9.087)	10.283 (7.751)	1.0	N.S.
Rubus chamaemorus	0.004 (0.019)	0	0.9	N.S.
Salix arbusculoides	0.007 (0.027)	0.013 (0.034)	0.4	N.S.

Table 4-6 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the two types of Trench quadrats (heavily and lightly oiled) before the oil spill (1988). Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size: heavily oiled Trench, n = 27; lightly oiled Trench, n = 24. N.S. -- not significantly different at $p < 0.05$.

Species	Heavily Oiled	Lightly Oiled	H	p
Salix myrtillifolia	2.037 (10.585)	0.167 (0.565)	0.4	N.S.
Saussurea angustifolia	0	0.042 (0.204)	2.1	N.S.
Vaccinium uliginosum	0.004 (0.019)	0.175 (0.635)	2.5	N.S.
Vaccinium vitis-idaea	0.041 (0.193)	0.088 (0.408)	0.1	N.S.

Table 4-7. Mean percent cover values for each species or species assemblage with standard deviations below them for the heavily oiled Trench before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 27). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Moss spp.	27.370 (21.855)	22.896 (24.413)	57.778[c] (31.638)	47.037[a] (27.219)	23.2	0.0001
Peltigera spp.	0	0	0	0.148 (0.602)	6.1	N.S.
Anemone richardsonii	0	0.004 (0.019)	0.004 (0.019)	0	2.0	N.S.
Arctagrostis latifolia	0.752 (1.341)	0.374 (1.547)	0.093 (0.264)	0.430 (1.922)	5.3	N.S.
Arctostaphylos rubra	0.074 (0.385)	0	0	0	3.0	N.S.
Carex spp.	0.189 (0.556)	0.193 (0.621)	2.322[a] (6.916)	2.563[a] (7.795)	9.6	0.05
Epilobium angustifolium	0.037 (0.192)	0	0	0.011 (0.032)	6.1	N.S.
Equisetum arvense	2.659 (7.756)	1.541 (2.361)	2.478 (6.640)	0.052[c] (0.193)	23.0	0.0001
Equisetum scirpoides	0.089 (0.265)	0.056 (0.193)	0.030 (0.047)	0.111 (0.261)	4.0	N.S.
Eriophorum spp.	0.685 (1.633)	0.967 (1.889)	5.111 (8.586)	6.852 (8.896)	5.9	N.S.
Festuca spp.	0.278 (0.808)	0.052 (0.193)	0.093 (0.264)	0.604 (1.596)	1.2	N.S.
Ledum groenlandicum	0.185 (0.681)	0.037 (0.192)	0.004 (0.019)	0	2.1	N.S.
miscellaneous graminoid spp.	8.804 (9.087)	1.985[b] (5.120)	2.052[a] (3.690)	3.374 (3.998)	11.7	0.01
Potentilla fruticosa	0	0	0	0.004	3.0	N.S.
Rosa acicularis	0	0.004 (0.019)	0	0	3.0	N.S.
Rubus chamaemorus	0.004 (0.019)	0.004 (0.019)	0.004 (0.019)	0.004 (0.019)	0	N.S.
Salix arbusculoides	0.007 (0.027)	0.007 (0.027)	0.052 (0.193)	0.004 (0.019)	4.1	N.S.

Table 4-7 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the heavily oiled Trench before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 27). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Salix myrtillifolia	2.037 (10.585)	0.007 (0.027)	0	0	3.7	N.S.
Stellaria longipes	0	0.004 (0.019)	0	0	3.0	N.S.
Vaccinium uliginosum	0.004 (0.019)	0	0.011 (0.032)	0.004 (0.019)	3.9	N.S.
Vaccinium vitis-idaea	0.041 (0.193)	0.004 (0.019)	0.007 (0.027)	0.004 (0.019)	0.7	N.S.

Table 4-8. Mean percent cover values for each species or species assemblage with standard deviations below them for the lightly oiled Trench before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 24). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Moss spp.	50.083 (23.093)	57.667 (25.274)	73.583[c] (16.730)	64.375[a] (18.493)	12.9	0.01
Cladonia spp.	0	0	0	0.004 (0.204)	3.0	N.S.
Peltigera spp.	0	0	0	0.046 (0.204)	6.1	N.S.
Arctagrostis latifolia	1.333 (3.371)	0.708 (1.944)	1.171 (3.251)	0.513 (1.281)	0.9	N.S.
Arctostaphylos rubra	0.083 (0.408)	0.046 (0.204)	0.125 (0.612)	0	2.0	N.S.
Betula glandulosa	0.625 (3.062)	0.425 (2.040)	0.417 (2.041)	0.417 (2.041)	1.9	N.S.
Carex spp.	0.088 (0.282)	0.542 (1.318)	0.383 (1.277)	0.792 (1.351)	4.0	N.S.
Empetrum nigrum	0.042 (0.204)	0.004 (0.020)	0.042 (0.204)	0.042 (0.204)	0.1	N.S.
Epilobium angustifolium	0.008 (0.028)	0.013 (0.034)	0.088 (0.282)	0.083 (0.282)	0.4	N.S.
Equisetum arvense	1.500 (3.330)	2.688 (6.010)	1.967 (6.183)	0.188[b] (0.373)	19.1	0.001
Equisetum scirpoides	0.083 (0.201)	0.113 (0.405)	0.271 (0.600)	0.246 (0.398)	3.8	N.S.
Eriophorum spp.	0.213 (0.832)	0.467 (1.282)	1.063 (2.766)	0.875 (3.125)	4.6	N.S.
Festuca spp.	1.521 (1.850)	0.658 (1.228)	1.575 (2.809)	2.463 (3.047)	3.0	N.S.
Ledum groenlandicum	0.504 (1.718)	0.463 (1.718)	0.463 (1.718)	0.379 (1.171)	0.2	N.S.
miscellaneous graminoid spp.	10.283 (7.751)	3.308[b] (5.012)	4.904[a] (5.656)	4.500[a] (4.075)	11.9	0.01
Orchis rotundifolia	0	0.833 (4.082)	0	0	3.0	N.S.
Potentilla fruticosa	0	0	0.004 (0.020)	0.004 (0.020)	2.0	N.S.

Table 4-8 continued. Mean percent cover values for each species or species assemblage with standard deviations below them for the lightly oiled Trench before the oil spill (1988) and the following three years. Because the distributions were not normal, a Kruskal-Wallis test was performed (H). Sample size for each year is constant (n = 24). N.S. -- not significantly different at $p < 0.05$. Where significant differences were found, pairwise comparisons were then conducted between the pre-spill values and each post-spill growing season value. The experimentwise significance level is indicated next to the post-spill value. a -- $p < 0.1$; b -- $p < 0.05$; c -- $p < 0.01$.

Species	1988	1989	1990	1991	H	p <
Rubus chamaemorus	0	0.083 (0.408)	0.083 (0.408)	0.083 (0.408)	1.0	N.S.
Salix arbusculoides	0.013 (0.034)	0.025 (0.044)	0.050 (0.204)	0.058 (0.204)	1.8	N.S.
Salix myrtillifolia	0.167 (0.565)	0.208 (0.721)	0.625 (2.242)	0.546 (2.104)	0.4	N.S.
Saussurea angustifolia	0.042 (0.204)	0.125 (0.612)	0	0	2.0	N.S.
Vaccinium uliginosum	0.175 (0.635)	0.213 (0.657)	0.321 (0.880)	0.375 (1.173)	0.5	N.S.
Vaccinium vitis-idaea	0.088 (0.408)	0.046 (0.204)	0.042 (0.204)	0.088 (0.408)	0.4	N.S.

species present in such an ecosystem. However, the pooling of "sensitive" species, such as the lichens and mosses, may be masking the real decrease in diversity.

Trench

Before the oil spill the quadrats that became heavily oiled had significantly fewer species than the quadrats that became lightly oiled. Part of this variation may be related to the differential seeding of the agronomic species along the Trench. This may be the result of subsidence in the Trench. The heavily oiled quadrats tended to be the lowest ones and hence the wettest. Standing water could be present in these quadrats for much of the growing season and hence exclude some species.

After the oil spill neither the heavily nor lightly oiled quadrats had any significant change in the number of species present. This may have been a result of the high water conditions in the Trench ameliorating the effects of the oil, or the fact that fewer species were present on the Trench than the ROW and these were hardier species. In fact, the Trench had fewer native species present and it was dominated by grasses and sedges. Other research has indicated that natural oil seeps have few adverse effects on sedge communities (McCown et al., 1973).

Total Plant Cover

ROW

Before the oil spill the total percentage plant cover significantly varied among the three types of ROW quadrats. Both the quadrats that became heavily and lightly oiled had greater total plant cover than the quadrats that remained apparently unoiled. The unoiled quadrats were generally the highest and driest quadrats and often lacked the moss species, thus reducing the total plant cover (see Table 4-2).

After the oil spill, only the heavily oiled ROW experienced a significant drop in total plant cover, decreasing about 75% from the pre-spill value. Other researchers have reported decreases of 95% or more one year after a spray application oil spill (Wein and Bliss, 1973; Freedman and Hutchinson, 1978).

Such reductions in plant cover also have implications for the thermal budget of the soil. Removal of surface vegetation can result in an increase in the active layer depth (Linell, 1973; Haag and Bliss, 1974) which can lead to subsidence as a result of thawing of ice-rich soils (Brown, 1970). At the SEEDS site canopy clearing has resulted in more than a doubling of the depth of the active layer on the ROW, and removal of the organic layer on the Trench has resulted in more than a tripling of the active layer depth compared with the pre-disturbance depth of the active layer in the Forest (see chapter 2).

Both the lightly and apparently unoiled ROW showed virtually no change in mean total plant cover the growing season after the spill, however the plant cover on both significantly increased by the following growing season. Given the fact that no significant increase in plant cover was experienced on either the lightly oiled or apparently unoiled ROW the following year, it is possible that the surge in plant cover was a result of the small quantities of the crude oil present decomposing through microbial action and adding nutrients to the soil (Ellis and Adams, 1961).

The increase in total plant cover might also be a resumption of natural plant community changes on the ROW. Before the oil spill, the apparently unoiled ROW had a mean total plant cover of only 40%. Given the fact that the canopy had only been removed two years prior to the oil spill, it is quite likely that the plants were still responding to the altered microclimate.

Trench

Before the oil spill the total percentage plant cover was significantly higher on the quadrats that became lightly oiled than on those that became heavily oiled. This difference agrees with the difference found with the number of species. Because the quadrats that became heavily oiled were often flooded this would reduce the number of species that could grow there and create patches where little or no vegetation was present.

After the oil spill neither the heavily nor lightly oiled Trench experienced a significant decrease in plant cover, although eventually they both had significant increases in plant cover. This is in agreement with the lack of changes in floristic abundance and may indicate that high water levels had ameliorated the effects of the oil. The delayed surge in plant cover after the oil spill is also in agreement with the results on the ROW.

Species Abundance

The ROW and Trench were only two years old when the oil spill occurred in 1988. While the ROW had an intact organic mat, the Trench substrate began with a bare mineral soil surface. Hence the plants were still responding to the new conditions. Hernandez (1973) reported on the natural recolonization of a bare soil surface (a seismic line) in a white spruce (*Picea glauca*) forest near Tuktoyaktuk, NWT. Three years after the creation of the seismic line the total plant cover was still increasing.

If the apparently unoiled ROW was not affected by the crude oil then it could still be adapting to the change in the conditions. The native species that were more abundant after the oil spill than before (the mosses, *Carex* spp., and *Equisetum scirpoides*) were all species that Hernandez (1973) reported as increasing in his study. Kershaw and Kershaw (1987) also reported the genus *Carex* and *Equisetum* as successful colonizers on disturbances in tundra areas of the western NWT. However, they reported only one species of *Equisetum* increasing and that was *E. arvense*, the one species that declined on the apparently unoiled ROW.

In addition, natural annual variation can account for some changes in abundance in a given species, as no single variable (e.g. soil temperature, precipitation) is critical in limiting growth in all species (Chapin and Shaver, 1985).

Pre-spill Differences

ROW

Of the 34 species assemblages found on the three types of ROW quadrat only seven differed significantly in terms of their percentage cover values prior to the oil spill. With the exception of *Potentilla fruticosa* they all were more abundant on the quadrats that became heavily or lightly oiled.

Since the oil tended to pool in low-lying areas, the heavily oiled quadrats also tended to be relatively wet. One would therefore expect the abundant species on the low-lying quadrats to be hydrophillic. Indeed, three of these groups (*Arctagrostis latifolia*, *Eriophorum* spp., and miscellaneous graminoid spp.) were monocotyledons and a fourth was the moss species assemblage. All these species prefer moist environments. The other two species (*Empetrum nigrum* and *Larix laricina*) are also common in muskegs (Porsild and Cody, 1980).

In contrast, the shrub *Potentilla fruticosa* is common on both moist and dry soils (Porsild and Cody, 1980). Its slightly greater abundance on the quadrats that remained unoiled may be a function of more rapid growth on the elevated areas that are warmer.

Trench

Before the oil spill, both the moss species and *Festuca* species were more abundant on the quadrats that were to become lightly oiled. It may seem somewhat counter-intuitive that these species assemblages were more abundant on the higher and drier quadrats, however, because of subsidence, the low-lying areas of the Trench were often submerged under water, hence colonization could not occur.

Post-spill Differences

The effects of the oil on the various types of quadrats differed dramatically (Table 4-9). On the heavily oiled ROW almost two-thirds of the species or species assemblages significantly changed in abundance and all but two declined in abundance. No species with a pre-spill abundance of more than 1% was unaffected by the oil. In contrast, less than 25% of the species changed in their mean cover value on the heavily oiled Trench and half of those species increased in abundance.

Table 4-9. Summary of changes in individual species abundance. - -- less common at the end of the study than before the spill; + -- more common at the end of the study than before the spill; N.S.-- no significant change in cover value; 0 -- absent from this group.

Species	ROW Heavily Oiled	ROW Lightly Oiled	ROW Unoiled	Trench Heavily Oiled	Trench Lightly Oiled
Moss spp.	-	+	+	+	+
Cladonia spp.	-	N.S.	N.S.	0	N.S.
Peltigera spp.	-	N.S.	N.S.	N.S.	N.S.
Anemone richardsonii	N.S.	N.S.	-	N.S.	0
Arctagrostis latifolia	-	N.S.	N.S.	N.S.	N.S.
Arctostaphylos rubra	-	N.S.	N.S.	N.S.	N.S.
Carex spp.	-	+	+	+	N.S.
Empetrum nigrum	-	N.S.	N.S.	0	N.S.
Equisetum arvense	-	-	+/-	-	-
Equisetum scirpoides	-	N.S.	+	N.S.	N.S.
Eriophorum spp.	+	+	N.S.	N.S.	N.S.
Larix laricina	-	N.S.	N.S.	N.S.	N.S.
Ledum groenlandicum	-	N.S.	N.S.	N.S.	N.S.
Miscellaneous graminoid spp.	+	N.S.	+	-	-
Pyrola secunda	-	N.S.	N.S.	0	0
Rubus chamaemorus	-	N.S.	N.S.	N.S.	N.S.
Salix myrtillifolia	-	N.S.	N.S.	N.S.	N.S.
Saussurea angustifolia	-	-	-	0	N.S.
Vaccinium uliginosum	-	N.S.	N.S.	N.S.	N.S.
Vaccinium vitis-idaea	-	N.S.	N.S.	N.S.	N.S.

No species responded completely consistently on all types of treatments. However, *Equisetum arvense* did significantly decline on all types of environments, but it also significantly increased on the apparently unoiled ROW before declining. Aside from the heavily oiled ROW, it never significantly declined until the third year after the spill. *Equisetum scirpoides* significantly declined in abundance on the heavily oiled ROW, yet it increased in abundance on the apparently unoiled ROW. *E. scirpoides* is not merely replacing *E. arvense* as the latter was also increasing in abundance until 1991 when it was almost eliminated. This genus appears to be susceptible to the effects of crude oil. Hutchinson and Hellebust (1978) found that both *E. pratense* and *E. scirpoides* were virtually eliminated from their oiled plots near Norman Wells, NWT, even three years after the spray application of the oil. However, eight years after the spill, Hutchinson (1984) reported that *E. pratense* was 200% more abundant on the oiled plots than on the similar unoiled plots. *E. scirpoides* was not mentioned at this time and so presumably it had been eliminated from the study plots. Hutchinson and Freedman (1978) reported that *Equisetum* spp. virtually vanished after their spray application of oil in a forested area near Norman Wells, NWT for two years after the spill, before reappearing in the third year from surviving belowground rhizomes.

A number of other species responded consistently if they changed significantly. *Eriophorum* spp. became significantly more abundant on both the heavily and lightly oiled ROW. On the other types of quadrats it also increased, although not significantly. *Eriophorum* spp. have also been noted for their resistance to crude oil. McCown and others (1973) found *E. scheuchzerii* growing in or near natural oil seeps along with *Carex aquatilis*. *E. scheuchzerii* was growing in oil and yet exhibited no negative side effects. In addition it is one of the few genera that clearly survive most spray application experiments (Wein and Bliss, 1973; Freedman and Hutchinson, 1978). Part of the success of this genus is likely due to its rooting structure. Unlike many northern species, *Eriophorum* spp. send down entirely new root systems each year, which follow the thawing of the soil (Billings et al., 1978). Establishing new root systems each year should help prevent the disruption of the translocation of water and nutrients up into the plant.

Saussurea angustifolia vanished from all types of ROW quadrats. It was absent entirely from the heavily oiled Trench quadrats (both before and after the oil spill) and it vanished from the lightly oiled Trench quadrats (although it was rare before the oil spill). Wein and Bliss (1973) reported that this species had some signs of regrowth on one of their spills.

Some species responded differently on different types of quadrats. For example, on all but the heavily oiled ROW, the moss species assemblage became significantly more abundant in mean cover value by the second or third growing season after the spill. This is in stark contrast to other studies. Most spray application experiments have reported that the death of mosses and lichens was rapid and complete (Wein and Bliss, 1973; Freedman and Hutchinson 1976; Hutchinson and Freedman, 1978). However, Kershaw and Kershaw (1986) found many mosses and lichens growing on 35-year-old crude oil spills in the Mackenzie Mountains, NWT. They theorized that while non-vascular plants are sensitive to direct contact with oil, if they remained even slightly elevated above the flow of the oil, they can survive. In the case of the SEEDS spill, the mosses and lichens on the heavily oiled ROW became coated with oil, whereas on less contaminated sites the non-vasculars did not and hence continued to thrive.

Carex spp. significantly decreased on the heavily oiled ROW only the year after the spill. On both the other kinds of ROW quadrats and the heavily oiled Trench it significantly increased in abundance during the second or third year after the spill. It also increased in abundance on the heavily oiled ROW after the first year after the spill and on the lightly oiled Trench, although not significantly. Other researchers have also noted *Carex*'s resistance to crude oil. McCown and others (1973) found *C. aquatilis* growing in or near natural oil seeps. It had active underground rhizomes imbedded in the oil and yet the plants displayed no obvious signs of injury. Wein and Bliss (1973) noted that *Carex* was one of the genera to most quickly recover from their spray application of crude oil. Within one year of application, *Carex* spp. had recovered to over 55% of control values. In contrast, Hutchinson and Hellebust (1978) reported a decline in *Carex* spp. even three years after their oil spill, however by the eighth year *Carex* spp. had increased above pre-spill levels (Hutchinson, 1984).

The miscellaneous graminoid species became significantly more abundant on both the heavily oiled and apparently unoiled ROW quadrats, yet it became significantly less abundant on the Trench quadrats the first year after the spill. These graminoid species represent three different genera (*Alopecurus*, *Phleum*, and *Poa*) of agronomic species that have been sown on the SEEDS site after the creation of the disturbance. This seed mix was used by Interprovincial Pipelines on the Norman Wells pipeline. The conflicting results between the Trench and the ROW are a function of the different initial state of the two kinds of environments. The ROW had very little grass cover initially (less than 1%) and therefore it could quickly surpass the pre-spill value. In contrast, the Trench experienced a large decrease before rebounding. Hence it seems these agronomic species may quickly recover from an oil spill, but they can be dramatically affected initially. Kershaw and Kershaw (1986) found two species of *Poa* growing on their 35-year-old oil spill, even though these species were absent from the surrounding unoiled areas. In a laboratory study, Klokk (1984) working with a species of *Poa* and *Phleum* found they were resilient to the effects of small quantities of oil, compared with some other genera of grasses. However, as the current study has demonstrated, these species may suffer a dramatic decline immediately after an oil spill and this could be important in areas where these species have been sown to make up the majority of the plant community (e.g. on a pipeline corridor).

Anemone richardsonii is the only species that significantly changed only on the apparently unoiled ROW, where it vanished completely. It also vanished from the heavily and lightly oiled ROW (at least for one year), however it was rare there before the spill. Ironically, it was absent from the heavily oiled Trench before the oil spill, but was present (in very small quantities) after the spill. It seems that this species has been affected by the oil, but because it was relatively rare, its decline was not statistically significant in most cases. Hutchinson and Hellebust (1978) reported on the related *A. parviflora* and observed that it was slightly more common on their oil spill plots than on the control plots three years after the spill, however it is unclear whether this difference was statistically significant. Kershaw and Kershaw found similar values of *A. parviflora* on 35-year-old oil spill sites and on the control sites.

A number of other species significantly changed only on the heavily oiled ROW. All these species significantly declined after the spill. The grass *Arctagrostis latifolia* significantly declined the first year after the spill and exhibited little recovery. Kershaw and Kershaw (1986) noted that *A. latifolia* was present on their 35-year-old oil spills in about the same abundance as on the surrounding unoiled areas, indicating that recovery does occur after a certain number of years.

Four members of the heath family (Ericaceae) significantly declined on the heavily oiled ROW after the oil spill: *Arctostaphylos rubra*, *Ledum groenlandicum*, *Vaccinium uliginosum*, and *Vaccinium vitis-idea*. *Arctostaphylos rubra* was reduced to less than one-tenth of its pre-spill abundance the first year after the spill and it demonstrated little recovery. Even though *A. rubra* did not significantly decline on the lightly oiled ROW, its abundance did drop to less than one-half of its pre-spill value. In contrast it almost doubled in abundance on the apparently unoiled ROW, yet this difference was not significant. On the Trench, *A. rubra* was rare before the spill and absent by the end of the study. *A. rubra* appears to be highly susceptible to summer oil spills. Not only do its leaves tend to develop large brown necrotic patches after exposure to oil (Hutchinson and Freedman, 1978), but it is generally dramatically reduced in abundance (Wein and Bliss, 1973; Hutchinson and Hellebust, 1978).

Ledum groenlandicum significantly declined in abundance on the heavily oiled ROW the first year after the spill and it had little recovery over the next two years. On the other kinds of ROW areas and the lightly oiled Trench it experienced little change in abundance. It was eliminated from the heavily oiled Trench, however it was rare there to begin with. While Freedman and Hutchinson (1976) noted that ericaceous shrubs such as the similar *L. palustre* experienced the greatest relative decrease in cover after their spill, Wein and Bliss (1973) observed that it had some regrowth within one year of a spill. In addition, Hutchinson and Freedman (1978) noted that *L. groenlandicum* demonstrated one of the greatest abilities to recover from an oil spill within only a few years. While regrowth of individuals exposed to oil appears possible such plants are often described as unhealthy looking and the leaves are abnormally large with thin cuticles (Freedman and Hutchinson, 1976).

The two *Vaccinium* spp., *V. uliginosum* and *V. vitis-idea*, both significantly declined in abundance the first year after the spill on the heavily oiled ROW. While they experienced a slight decline on the other ROW areas, this was not significant. On the Trench, they were rare before and after the spill. Wein and Bliss (1973) noted that both species exhibited signs of regrowth after their spill and *V. vitis-idea* in particular, likely because of its waxy evergreen leaves, was much slower to turn brown than many other species. However, Hutchinson and Freedman (1978) indicated that *V. vitis-idea* developed new seedlings on their oiled plots after four years. In contrast, Kershaw and Kershaw found *V. vitis-idea* to be slightly less common on their 35-year-old oil spills than on the surrounding unoiled communities, indicating that recovery for this species may be quite slow, despite some short term regeneration. This is likely a function of the fact that *V. vitis-idea* tends to have its roots concentrated in the upper 10 cm of the organic layer (Limbach et al., 1982) and hence its roots would experience high contact with the oil in this layer.

Empetrum nigrum significantly declined the first year after the spill and showed little sign of recovery in subsequent years. On both the other types of ROW areas it increased slightly in abundance, but not significantly. On the Trench, it was absent or very rare. *E. nigrum* like *V. vitis-idea* possesses waxy evergreen leaves and hence demonstrates some initial resistance to oil (Wein and Bliss, 1973). However, this resistance is short-lived and the species is one of the hardest hit by crude oil likely because of its low growth form (Wein and Bliss, 1973; Freedman and Hutchinson, 1976).

All mature larches (*Larix laricina*) were removed from the site to create the clearing, hence all individuals present during the oil spill were young saplings. *L. laricina* significantly declined in abundance the first year after the spill and showed little sign of recovery in subsequent years. It also declined on the other types of ROW areas, however not significantly. It was entirely absent from the Trench. *L.*

laricina is known to be sensitive to crude oil. Hutchinson and Freedman (1978) observed that *L. laricina* quickly dropped its needles regardless of whether or not each branch was sprayed with oil. This is in contrast to black spruce (*Picea mariana*) which did not show such dramatic effects until the next growing season.

Pyrola secunda was eliminated the first year after the oil spill and did not reappear on the heavily oiled ROW. It also vanished from the other types of ROW quadrats but this change was not significant. It was completely absent from the Trench before and after the spill. Because its leaves are mainly at the base of the plant, this species is apparently quite susceptible to crude oil (Hutchinson et al., 1974; Hutchinson and Hellebust, 1978). However, it appeared to have recovered to surrounding values on 35-year-old spills along the CANOL (Kershaw and Kershaw, 1986).

Rubus chamaemorus is rarely abundant. It declined significantly on the heavily oiled ROW the third year after the spill and it also declined to less than half its pre-spill abundance on the lightly oiled ROW, however, this was not significant. It was virtually absent from the Trench. Because of its low growth form and shallow creeping rootstock it is not surprising that it would be highly susceptible to crude oil.

Despite the fact that *Salix arbusculoides* was eliminated from the heavily oiled ROW, only *S. myrtillifolia* significantly declined and then not until the second year after the oil spill. On the other ROW quadrats it increased in abundance slightly (though not significantly) while on the heavily oiled Trench it was totally eliminated. In contrast, on the lightly oiled Trench it more than doubled in abundance but this was not significant. Willows have shown some resistance to crude oil, especially at the end of the growing season (Wein and Bliss, 1973; Freedman and Hutchinson, 1976; Holt, 1987). They may also be capable of rooting in oiled substrates (chapter 3).

Having half of the species or assemblages decline in abundance as a result of such a small spill is dramatic evidence of the phytotoxicity of crude oil. However, this effect was concentrated in only the low lying areas of the ROW where the plants experienced very high levels of crude oil. Excluding the heavily oiled ROW only 4 species or assemblages declined in abundance and one of them (the miscellaneous graminoids) only did so on the Trench and they were recovering by the end of the third post-spill growing season.

From a landscape point of view the decline of the three other species is not particularly important. Cumulatively, these three species made up a cover value of less than 5% before the spill. Overwhelmingly, the moss species comprise the most abundant group, with a mean cover value ranging from 16-50% before the spill. Since the mosses increased everywhere except on the heavily oiled ROW then the oil, in low concentrations, cannot have had a great negative effect on them.

CONCLUSIONS

The number of species or species assemblages present significantly declined on only the heavily oiled ROW, where it dropped to less than half of the pre-spill number. The species richness was low but comparable to other upland Subarctic regions in Northwestern North America.

The total plant cover decreased dramatically in some areas -- especially on the heavily oiled ROW. Even on the heavily oiled ROW the total plant cover increased to just over half of the pre-spill value in the subsequent two growing seasons. In other, less oil contaminated areas, the total plant cover significantly increased above pre-spill values. This may indicate that the effects of the oil were of short term duration and the natural vegetative recovery process may be once again underway.

A total of 19 species or species assemblages out of a possible 34 significantly declined in abundance at some point after the oil spill. Most of the other species were relatively rare before the oil spill. In comparison only six species or species assemblages increased in abundance as a result of the oil spill. Two of these species (the *Equisetum* spp.) did so only on the apparently unoiled ROW. Three of the four other groups were monocotyledons (grasses and sedges) and the fourth was the moss species.

While it is clear that most species, particularly on lightly oiled sites, were starting to recover by the end of the study, areas where the oil had concentrated were blackened and oil was still present in the soil. Fumes from the oil were also still discernible, especially on warm summer days.

In conclusion, it is recommended given a small (approximately 20 barrel) crude oil spill in early autumn that no clean-up operation be undertaken, given the possibility of causing greater damage to the organic layer.

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CHAPTER 5
CONCLUSIONS

Overview

The SEEDS oil spill experiment is part of a much larger ongoing ecological research project. Detailed pre-spill information exists on a variety of factors including the soils, permafrost conditions, microclimate, and vegetation. Data presented here on the first three post-spill growing seasons provide valuable information on the immediate effects of crude oil on a Subarctic system. The potential exists for more information to be collected over longer periods of time on the ongoing effects of the oil and the rate of recovery of both the plant communities and the active layer. A brief summary is presented here of the results obtained in this study.

Effects on the Active Layer

Previous studies on the effects of crude oil on the active layer are somewhat conflicting. While some researchers have reported large increases in the active layer (e.g. Lawson et al., 1978; Collins, 1983) others had small or negligible increases (Freedman and Hutchinson, 1976; Hutchinson and Freedman, 1978). One year after the SEEDS oil spill there were dramatic effects on the mean maximum thaw depths of both the relatively undisturbed Forest (which more than doubled) and the moderately disturbed ROW (which almost doubled). The highly disturbed Trench did not significantly increase in terms of its mean maximum thaw depth. Only the mean maximum thaw depth of the ROW continued to become significantly deeper over time. By the end of the study, mean maximum thaw depths on the unoiled environments ranged from 64-168 cm while they ranged from 166-201 cm on the oiled environments.

The SEEDS oil spill has resulted in the greatest increase in ·ean maximum thaw depths for a crude-oil spill in a Subarctic forested environment. This dramatic and persistent increase in mean maximum thaw depths is likely a function of the high oil concentration rates where the oil pooled on the ground. It is unclear whether further degradation of permafrost will occur.

Revegetation using *Salix arbusculoides*

The seeding of native oil-adapted plant species after a spill is a common reclamation practice (Linkins et al., 1984). In northern areas, this can help minimize the effects of the spill on the permafrost. The shrub canopy causes increased ground shading which reduces net radiation at the surface (Haag and Bliss, 1974; Rouse, 1976) thus reducing thermal degradation of permafrost.

Willows are proven recolonizers on a wide range of disturbances (Ebersole, 1985; Kershaw and Kershaw, 1987; de Grosbois et al., 1991). They have also been the focus of revegetation research on a variety of disturbances (Densmore et al., 1987; Maslen, 1989). While many of these studies have identified *Salix arbusculoides* as a natural recolonizer, its ability as a revegetation species for northern oil spills was uncertain.

Results from this experimental planting of cuttings are somewhat ambiguous. While initial survivorship values were as high as 75% at the end of the first growing season, by the start of the next growing season survivorship values were less than 15% for all plots. However, this may have been due to the lateness of the spring in 1992. By examining rooting success, it was found that potential survivorship was as high as 61% at this time.

Given the fact that cuttings planted in oiled areas fared better or no worse than cuttings planted in unoiled areas, it appears that in the third growing season after the oil spill, the crude oil apparently had little or no effect on the shrub cuttings. If the potential survivorships are an accurate reflection of true survivorships then *S. arbusculoides* could be just as effective as a revegetation species for crude oil spills on moist sites as it is for any other kind of disturbance in the north.

Changes in the Plant Communities

It has long been known that crude oil can be highly toxic to many plant species (Van Overbeek and Blondeau, 1954; Baker, 1970). The effects on northern ecosystems have been observed by many researchers (e.g. Wein and Bliss, 1973; Freedman and Hutchinson, 1978). The SEEDS oil spill was an experimental attempt to accurately mimic a belowground pipeline rupture and observe its effects on the existing plant communities.

The number of species or species assemblages present significantly declined on only the heavily oiled ROW, where it dropped to less than half of the pre-spill number.

The total plant cover decreased dramatically in some areas -- especially on the heavily oiled ROW. In other areas, the total plant cover significantly increased above pre-spill values. This is in stark contrast to many other studies where decreases of 95% or more have been reported one year after a spray application oil spill (Wein and Bliss, 1973; Freedman and Hutchinson, 1978).

A total of 19 species or species assemblages out of a possible 34 significantly declined after the oil spill on at least one of the types of environments. These were the moss assemblage, the *Cladonia* spp., the *Peltigera* spp., *Anemone richardsonii*, *Arctagrostis latifolia*, *Arctostaphylos rubra*, *Carex* spp., *Empetrum nigrum*, *Equisetum arvense*, *E. scirpoides*, *Larix laricina*, *Ledum groenlandicum*, the miscellaneous graminoid spp. (*Alopecurus arundinacea*, *Phleum pratense*, *Poa glauca*, and *P. pratensis*), *Pyrola secunda*, *Rubus chamaemorus*, *Salix myrtillifolia*, *Saussurea angustifolia*, *Vaccinium uliginosum*, and *V. vitis-idaea*. Most of these species only significantly declined on the heavily oiled ROW. A majority of the other species were relatively rare before the oil spill.

In comparison only six species or species assemblages increased in abundance as a result of the oil spill on at least one type of environment. These were the moss assemblage, *Carex* spp., *Equisetum arvense*, *E. scirpoides*, *Eriophorum* spp., and the miscellaneous graminoid spp (*Alopecurus arundinacea*, *Phleum pratense*, *Poa glauca*, and *P. pratensis*). Both *Equisetum arvense* and *E. scirpoides* only significantly increased on the apparently unoiled ROW.

Of particular interest are the *Eriophorum* species and the miscellaneous graminoids which increased even on the heavily oiled ROW. Although the genus *Carex* significantly declined on the heavily oiled ROW, it returned to pre-spill levels the second year after the spill. These grass and sedge species may prove valuable in reclamation work on future northern oil spills.

While many species were starting to recover by the third year after the spill, areas where the oil had concentrated were blackened and oil was still present in the soil. Fumes from the oil were also still discernible, especially on warm summer days.

Summation

No matter how many precautions are taken, no engineering scheme is foolproof. A buried pipeline such as the Interprovincial Pipeline (IPL), stretching almost 900 km from Norman Wells, NWT to Zama, AB, is destined to have oil leaks. In fact, in the spring of 1992, IPL reported their first leak. The decision of whether or not to initiate immediate clean-up operations must be based on as much information as possible. The effects of the oil spill on the vegetation, the organic layer, and the active layer must be balanced with the potential for additional site disturbances resulting from mounting a clean-up operation.

The results of this study on a small (approximately 3000 L or 20 imperial barrels) crude oil spill in early autumn indicate that increases in the active layer of the Trench were small but significant, and quite large on both the ROW and the Forest. Such alterations and the resulting subsidence could have important effects on pipeline integrity.

Changes in the plant communities and particularly in total plant cover indicate that the effects of the spill were highly localized and not as dramatic as many other studies would have predicted.

The primary concern after such a spill would be attempting to prevent the degradation of permafrost and subsidence of the soil surface. If this could be prevented, either through an oil clean-up operation, or a revegetation programme. ... likely that effects of this size of a spill would be minimal an ... term duration.

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