Effects of Experimental spills of Crude and Diesel oil on Arctic Vegetation

A long-term study on high arctic terrestrial plant communities in Jameson Land, central East Greenland

NERI Technical Report, no. 205

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Ministry of Environment and Energy
National Environmental Research Institute
September 1997

Data sheet

Title:	Effects of experimental spills of crude and diesel oil on arctic vegetation. A long-term study on high arctic terrestrial plant communities in Jameson Land, central East Greenland
Author:	Christian Bay, Botanical Museum, University of Copenhagen
Department:	Department of Arctic Environment
Serial title and number:	NERI Techical Report, no. 205
Publisher:	Ministry of Environment and Energy National Environmental Research Institute ©
URL:	http://www.dmu.dk
Year of publication:	September 1997
Referee:	Peter Aastrup
Please quote:	Bay, C. (1997): Effects of experimental spills of crude and diesel oil on arctic vegetation. A long-term study on high arctic terrestrial plant communities in Jameson Land, central East Greenland. National Environmental Research Institute, Denmark. 44 pp. - NERI Technical Report, no. 205
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Abstract:	Crude and diesel oils were applied to five major plant communities at Mesters Vig, East Greenland. The spills were seen to have an immediate effect and eleven years after the spills, the recovery of woody species, herbs, and graminoids was less than 1%. The recovery of mosses was faster, especially in soils with high water content.
Keywords:	Arctic plant communities, oil spill, revegetation
ISBN:	87-7772-345-7
ISSN:	0905-815X
Printed by:	Scanprint
Paper quality:	MultiArt Silk 100g (TCF)
Impression:	200
Number of pages:	44
Price:	DKK 100,- (incl. 25% VAT, excl. freight)
For sale at:	National Environmental Research Institute P.O.Box 358, Frederiksborgvej 399 DK-4000 Roskilde, Denmark Tel: +45 46 30 11 00 Fax: +45 46 30 12 14
	Miljøbutikken Information & Books Læderstræde 1 1201 Copenhagen K Tel: +45 33 92 76 92 (info) Fax: +45 33 37 92 92 (Books)

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Summary

Biological studies were carried out in Jameson Land (70-71°N.) and at Mesters Vig (72°N.), central East Greenland, in 1982 prior to oil exploration. The objective was to anticipate and take precautions for possible environmental impacts on vegetation and wildlife that might be caused by oil exploration activities.

North Sea crude oil and arctic diesel oil were applied to the five major plant communities at Mesters Vig in order to determine the vulnerability of plant species and to follow the recovery of plant cover in each community. The experimental spills had an intensity of 10 l m^{-2}, and were carried out in three types of dwarf shrub heath: 1) dry *Dryas-Cassiope* heath, 2) dry *Cassiope* heath, 3) moist, mossy *Vaccinium uliginosum* heath, and in moist, mossy grassland and wet graminoid fen. Vegetation analyses comprising recording of species composition, frequency, and cover of vascular plants, mosses, and lichens were carried out before the spills, the following year, and six times during the period 1984-1993. The reactions of the species were recorded on each occasion.

The spills were seen to have an immediate effect. After one year, there was a significant decline in the number of vascular species recorded, and a reduction in the total plant cover of all groups to a few percent or less in all plant communities. A delay in the reduction of moss cover was only recorded in three plots treated with diesel oil. The effects of crude oil spills seem to be more severe than the effects of diesel oil spills.

Eleven years after the spills, the recovery of woody species, herbs, and graminoids was less than 1%. Mosses growing in soils with a high water content showed substantial recovery from the toxic effects of the oil. The recovery of mosses was 53% and 70% in diesel and crude oil treated fen, respectively, whereas it was c. 30% in grassland; slightly higher than in diesel oil plots. Dry habitats are more vulnerable, recovering less than 1%. It is assumed that the smaller contact between toxic substances in the oil and underground plant parts in water-saturated soils is less than on the surface, resulting in a reduced uptake of toxics. Furthermore, increased horizontal leaching and dissolution of toxics may explain the better recovery in wet and moist habitats.

The long-term impact of diesel oil is most pronouced for the plant cover in dry habitats, whereas the recovery in habitats on wet and moist soils is moderate or good, respectively, mainly due to the ability of mosses to recover. All woody plants and most herbs were dead by the last recording date in diesel oil treated plots.

Plots treated with crude oil generally showed a better or nearly equal recovery compared to plots treated with diesel oil after eleven years, primarily due to the ability of mosses to recover.

The species diversity of vascular plants was generally reduced dramatically the year after the spills, particularly in the diesel oil treated plots. After eleven years the number of vascular species remained significantly reduced in all plant communities, most notably in plant communities on dry soils.

New species first colonize mesic and wet habitats. Species immigrated to or emerging in the plots a few years after the treatment were all dead the following year. More than half of all the new species were recorded for the first time eleven years after the spills. Herbs and graminoids are the most frequent immigrants and the greatest number of new colonizing species was recorded in the wet fen.

The fact that very few immigrants and recovered plants were recorded in dry habitats indicates that the speed of revegetation is slower in dry habitats than in wet and moist habitats.

The first fertile plants appeared six years after the spills. Graminoids, especially *Carex* spp. and *Juncus* spp., are the most frequently immigrated or recovered species to flower. Fertile plants occur the first year a species was recorded, or up to five years after the first recording of regeneration or immigration. There is no difference between the frequency of fertile plants in diesel and crude oil treated plots.

1 Introduction

Research focusing on the impact of oil spills on arctic ecosystems began in the early 1970's with the onset of oil exploration in Prudhoe Bay, Alaska. The emphasis was placed on documenting the responses of different plant communities to oil spills (Deneke et al. 1975, Hutchinson 1973, Hutchinson and Hellebust 1974) and the changes of abiotic and biotic characteristics of the below ground part of the ecosystems (Miller 1975 and 1976, Everett 1978). One of the most comprehensive oil spill projects focusing on biological as well as physical and chemical aspects in aquatic and terrestrial ecosystems was conducted at Barrow, Alaska (summarized by Costerton et al. (1978)).

No environmental studies of the effects of hydrocarbon spills on terrestrial ecosystems were conducted in Greenland before oil exploration was initiated in Jameson Land in the early 1980's. Greenland Environmental Research Institute (now: National Environmental Research Institute, Dpt. of Arctic Environment) organized biological studies concerning the impact of activities related to the oil exploration on the biological environment. The botanical part of the studies focused on vegetation mapping, studies of impacts of vehicle traffic and seismic work on the vegetation, and the effects of experimental spills on different plant communities. The vulnerability of the individual plant communities and the importance to wildlife as breeding, molting, and foraging habitats were studied. A set of environmental guidelines were prepared for the oil exploration activities, which took place in 1982-1986, monitored by Greenland Environmental Research Institute.

2 Study area

The study area at Mesters Vig (72°14´N., 23°55´W.), 75 km north of Jameson Land, was chosen as it was one of the most accessible areas when the oil exploration started in East Greenland, with an air strip and a manned station. Inspections of the oil plots could be carried out annually at relatively low cost. The flora and vegetation at Mesters Vig is comparable to that present at Jameson Land. The vegetation in Jameson Land was classified and mapped (Bay and Holt 1986) and this classification of the plant communities was used in the Mesters Vig study. Due to the geographical position of Jameson Land, just north of the transition zone (app. 70°N.) between the Low and High Arctic in East Greenland the species diversity is high andthe vegetation is relative luxuriant with a big cover of plants. Dwarf shrub heaths of several types are dominant in mesic and dry habitats whereas two types of fens and grassland are common on wet and moist soils.

Figure 1. View over the study site near Mesters Vig, where the experimental oil spills were carried out on five plant communities. The sites are marked with numbers: 1) dry *Dryas-Cassiope* heath, 2) moist grassland, 3) moist *Vaccinium uliginosum* heath, 4) wet fen, and 5) dry *Cassiope* heath.

3 Materials and methods

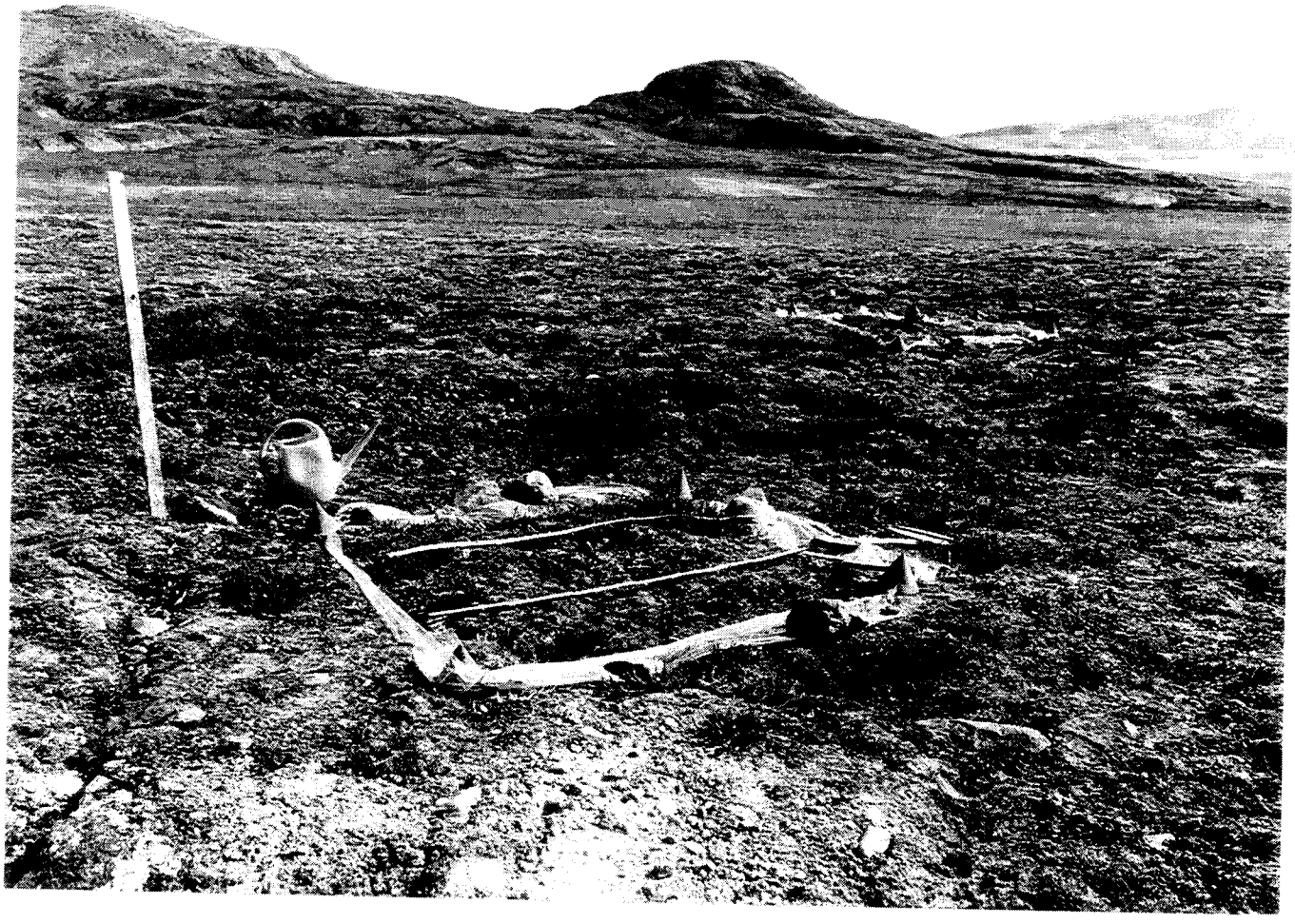
Ten liters of either unrefined North Sea crude oil or arctic diesel oil were experimentally spilled on two neighbouring one by one meter squares in each of the five plant communities (Figure 2). Only one third of a square meter was treated with crude oil in the dry *Cassiope* heath because of insufficient crude oil. The plant communities occurred along a topographic-moisture gradient, with dry *Dryas-Cassiope* heath and dry *Cassiope* heath communities occurring on a wind exposed ridge, moist, mossy *Vaccinium uliginosum* heath and grassland communities on a south-west facing slope, and a fen community on level, wet ground. Plastic liners 10 cm broad were placed around the plots and inserted into the soil in order to prevent leaking of the oil to the surroundings, and thereby reducing the oil concentration in the plots. The experimental oil spill set up was similar to studies in other regions of the Arctic (Walker et al. 1978).

Prior to the spills, vegetation analyses were carried out by recording frequency and visually estimating the cover of all vascular plants, mosses, and lichens in each plot. These were further divided into three sections in order to get a more detailed study, where the history of individual plants can be followed. As the plant groups (vascular plant, mosses, and lichens) were estimated separately, the total cover can exceed 100%. Photos were taken at all plots in order to carry out a comparison with intact vegetation, and to document the process of destruction and revegetation. Additionally, it was noted whether the species were fertile.

Recordings of the frequency and species cover in oil spill plots took place each year from 1983-1985, 1988-1990, and 1993 (Appendix 1). The results of the recordings in 1983 and from the period 1982-1985 were discussed by Bay and Holt (1984) and Holt (1987), respectively. The registrations from the period 1988-1990 were summarised by Bay (1990).

Crude oil and diesel oil were applied to the plots on August 8 1982, and recordings over the following years took place in the last part of the growing season i.e. ultimo August with the exception of 1988, where they took place on July 12. In 1989 the recordings were carried out by another researcher, and this probably explains the fact that percent cover in several of the plots was relatively higher this year. The recordings in 1990 from the wet habitat were difficult because of silt deposition resulting from heavy rainfall prior to the date of recording. This fact is taken into consideration when discussing the results.

Figure 2. The experimental design at the dry habitat on the wind exposed ridge. The plastic liners prevented leaking of the oil to the surroundings.



4 Results

A description of changes in species composition and cover from the status in 1985 and changes between the following years until 1993 are given for each plot in Appendix 1, which also includes summarized field notes for each plot.

A summary of data comparing some of the years is given in Figure 3 and Table 1. The plant species are arranged in the plant groups: Woody plants, forbs, graminoids, mosses, and lichens. Gramminoides include species from the plant families: Cyperaceae, Poaceae, and Juncaceae. The frequencies are presented in Figure 4.

Table 1. The degree of cover (%) of the plant groups in the plant communities and the number of vascular species in the undisturbed vegetation in 1982 and ten years after the spills in 1993. Number of species in 1993 not occurring in the undisturbed vegetation is also given. Cover less than 1% is indicated as +.

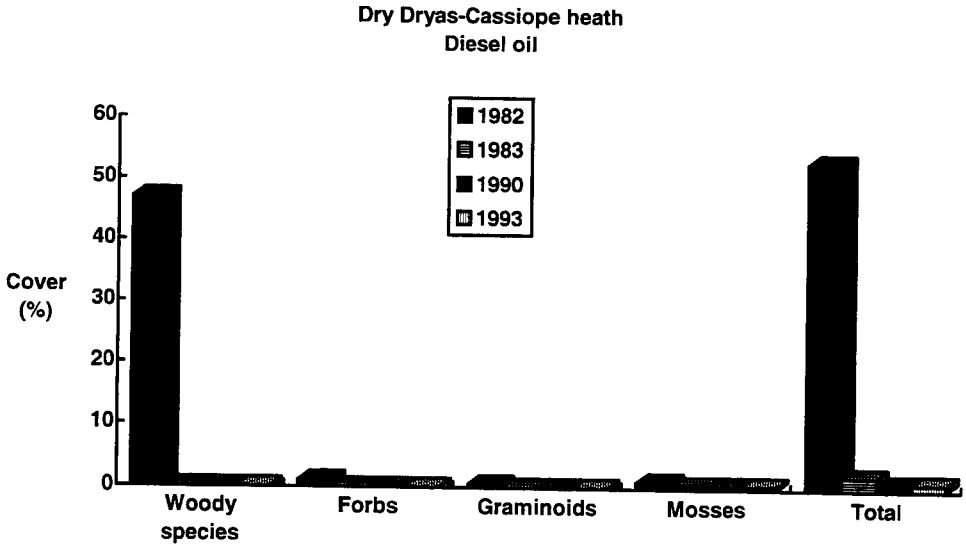
Diesel oil	Woody plants		Forbs		Graminoids		Mosses		Lichens		No. of vasc. spp.		No. of new vasc. spp.
Plant community	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	in 1993
Dry *Dryas-Cassiope* heath	47	0	+	0	+	+	1	+	3	+	7	1	0
Dry *Cassiope* heath	33	0	1	0	0	0	37	1	8	+	10	1	0
Moist *Vaccinium* heath	27	0	11	0	3	+	60	6	0	0	13	2	3
Moist grassland	1	0	1	+	41	2	76	22	0	0	15	8	1
Wet fen	10	0	2	0	11	+	100	53	0	0	5	1	3

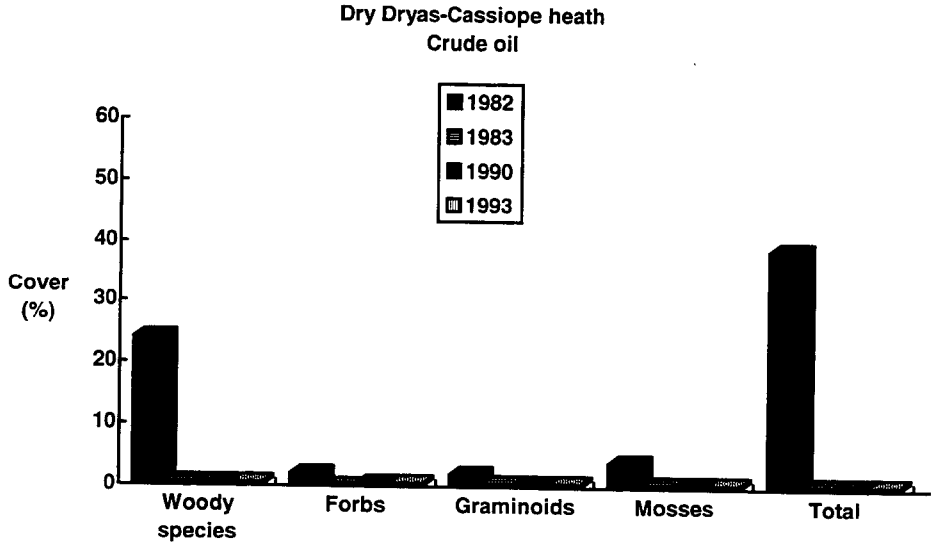
Crude oil	Woody plants		Forbs		Graminoids		Mosses		Lichens		No. of vasc. spp.		No. of new vasc. spp.
Plant community	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	1982	1993	in 1993
Dry *Dryas-Cassiope* heath	24	+	+	+	+	+	4	+	6	+	12	4	1
Dry *Cassiope* heath	31	4	+	0	+	0	30	+	1	+	4	1	0
Moist *Vaccinium* heath	19	0	18	0	8	+	67	3	0	0	14	4	2
Moist grassland	1	+	1	0	43	3	73	20	0	0	10	7	1
Wet fen	18	+	2	0	5	+	100	70	0	0	5	3	2

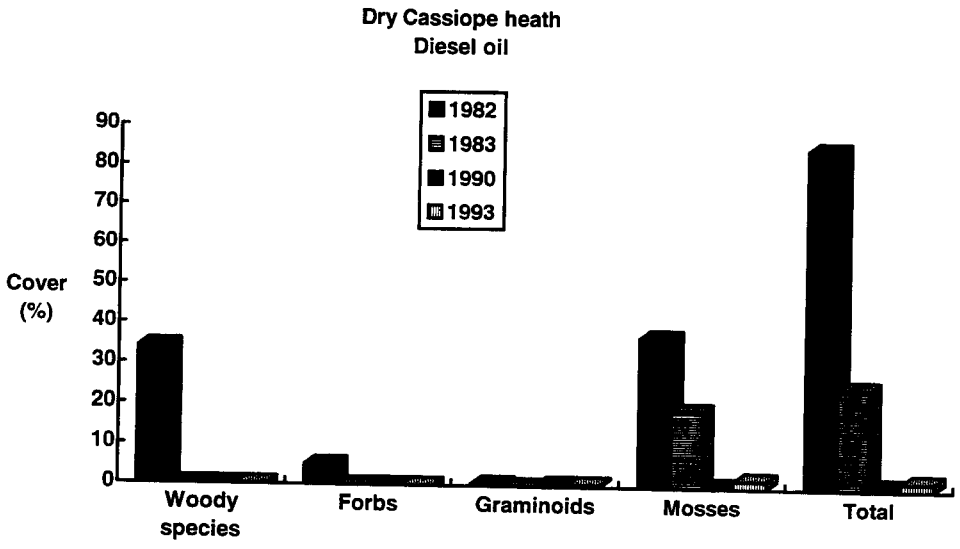
Table 2. Immigration or emergence by seed germination in plant communities treated with diesel and crude oil.

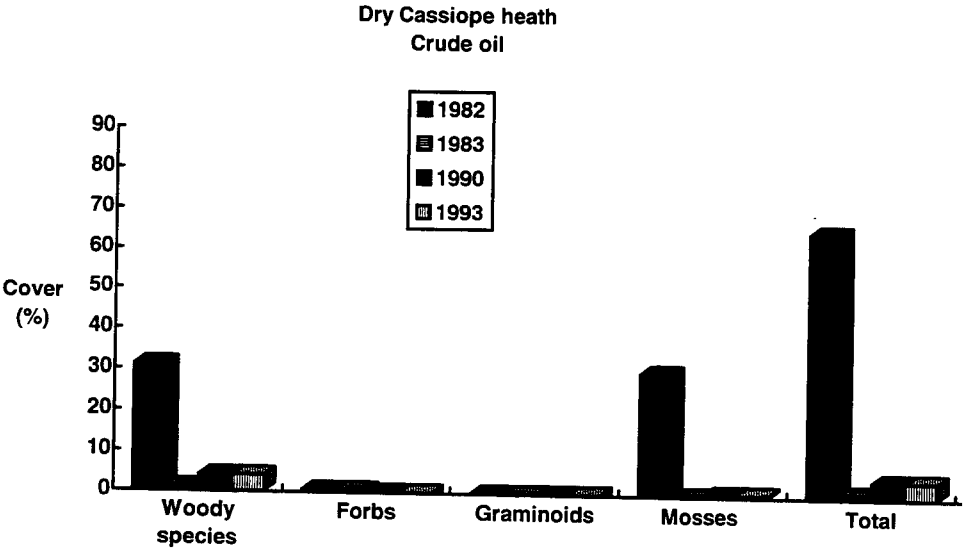
Vascular species	Plant community	Water regime in soil	Treatment	Year of immigration/ emerging	Year of extinction
Koenigia islandica	Fen	Wet	Crude oil	1993	-
Eriophorum scheuchzeri	Fen	Wet	Crude oil	1990	-
Carex lachenalii	Fen	Wet	Diesel oil	1993	-
Carex misandra	Fen	Wet	Diesel oil	1993	-
Koenigia islandica	Fen	Wet	Diesel oil	1993	-
Saxifraga foliolosa	Fen	Wet	Diesel oil	1990	-
Saxifraga cernua	Fen	Wet	Diesel oil	1990	-
Polygonum viviparum	*Vaccinium* heath	Moist	Crude oil	1985	1990
Carex misandra	*Vaccinium* heath	Moist	Crude oil	1993	-
Eriophorum triste	*Vaccinium* heath	Moist	Crude oil	1985	-
Juncus castaneus	*Vaccinium* heath	Moist	Diesel oil	1988	-
Vaccinium uliginosum	*Vaccinium* heath	Moist	Diesel oil	1993	-
Eriophorum triste	*Vaccinium* heath	Moist	Diesel oil	1990	-
Carex misandra	*Vaccinium* heath	Moist	Diesel oil	1993	-
Saxifraga oppositifolia	Grassland	Moist	Crude oil	1984	1984
Pedicularis flammea	Grassland	Moist	Crude oil	1990	-
Eriophorum triste	Grassland	Moist	Crude oil	1993	-
Salix arctica	Grassland	Moist	Crude oil	1993	-
Polygonum viviparum	Grassland	Moist	Crude oil	1985	1985
Carex misandra	Grassland	Moist	Crude oil	1993	-
Euphrasia frigida	Grassland	Moist	Diesel oil	1985	1985
Minuartia stricta	Grassland	Moist	Diesel oil	1993	-
Saxifraga foliolosa	Grassland	Moist	Diesel oil	1993	-
Kobresia simpliciuscula	Grassland	Moist	Diesel oil	1993	-
Draba arctica	*Dryas-Cass.* heath	Dry	Crude oil	1989	1991
Minuartia rubella	*Dryas-Cass.* heath	Dry	Crude oil	1993	-
Carex nardina	*Dryas-Cass.* heath	Dry	Diesel oil	1993	-

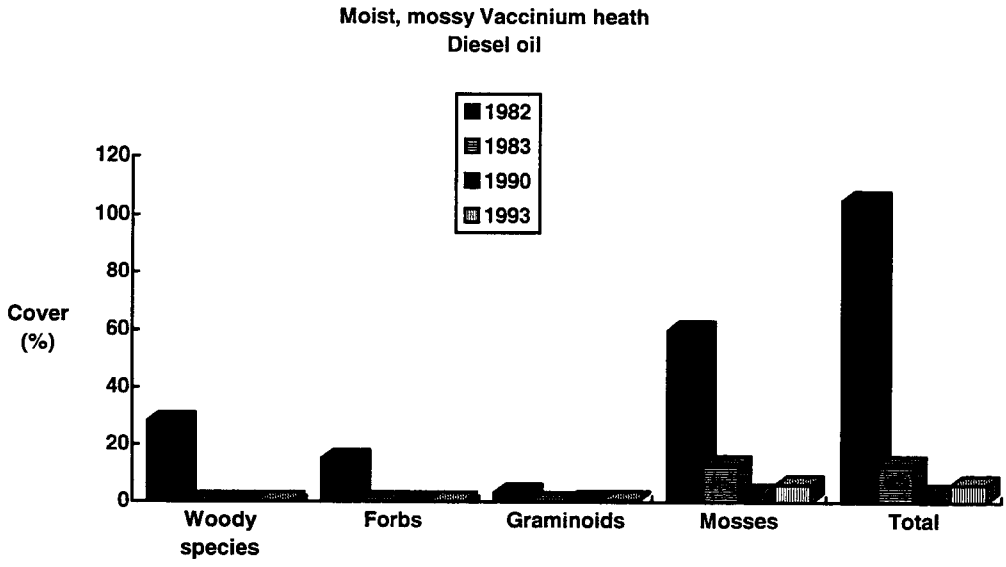
Figure 3. Cover of woody species, forbs, graminoids, and mosses prior to (1982), the year after (1983), seven years after (1990), and eleven years after (1993) diesel and crude oil spills in five plant communities. Note the different scales in the recordings from the different plant communities. Degree of cover less that 1% is given as 0.5%. The moss cover in the fen is recorded in 1989 instead of in 1990 due to silt deposition.

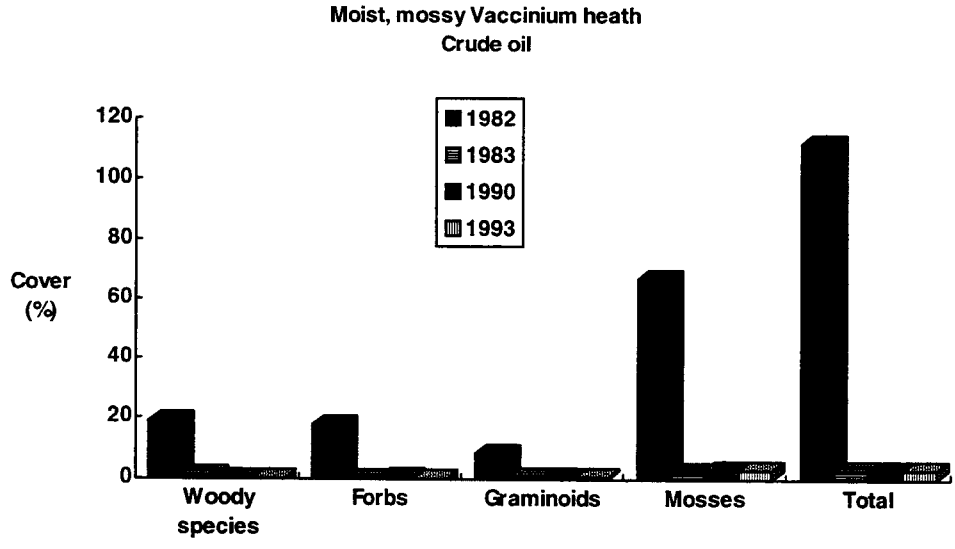


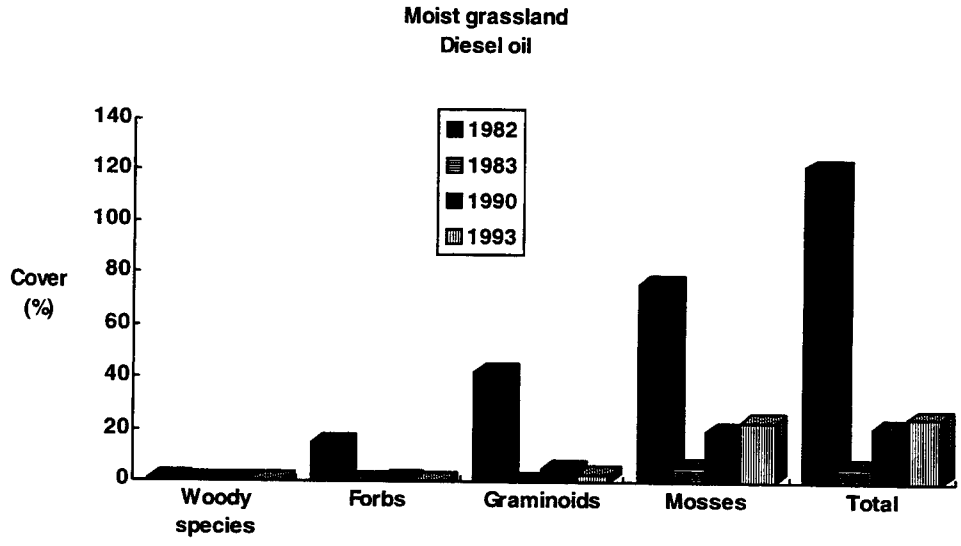


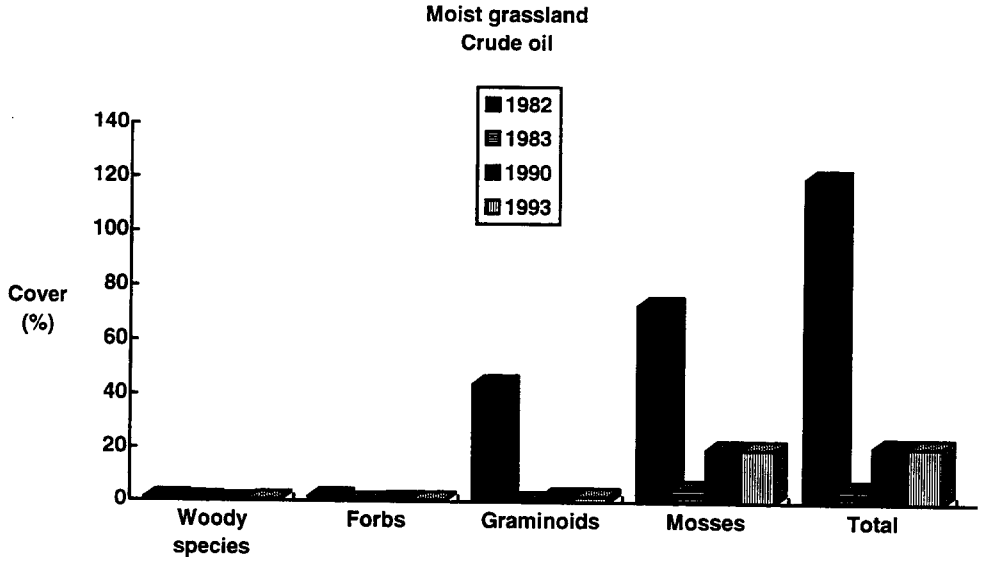

Dry Cassiope heath
Diesel oil
1982
1983
1990
1993
Cover (%)
90
80
70
60
50
40
30
20
10
0
Woody species
Forbs
Graminoids
Mosses
Total

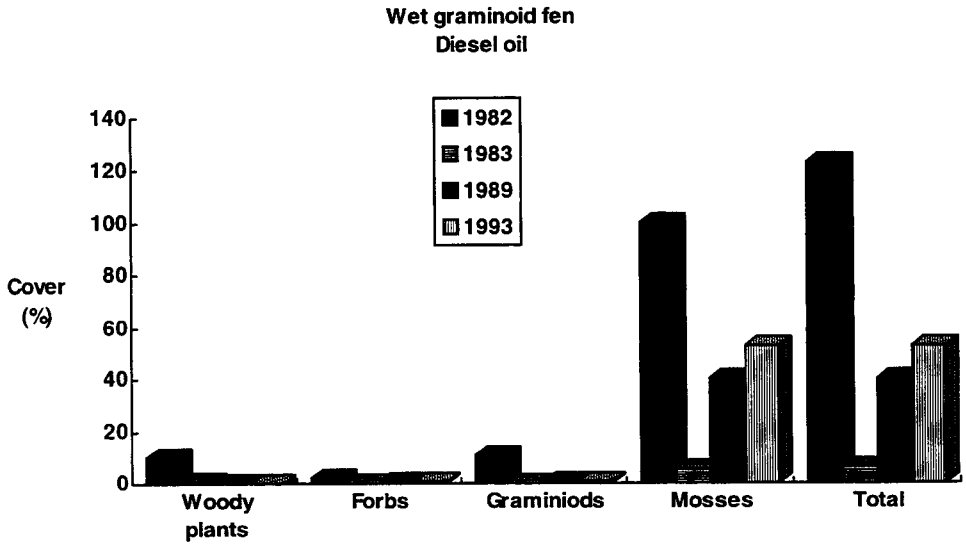

Dry Cassiope heath
Crude oil
1982
1983
1990
1993
Cover (%)
90
80
70
60
50
40
30
20
10
0
Woody species
Forbs
Graminoids
Mosses
Total


Moist, mossy Vaccinium heath
Diesel oil
1982
1983
1990
1993
120
100
80
60
40
20
0
Cover
(%)
Woody species
Forbs
Graminoids
Mosses
Total


Moist, mossy Vaccinium heath
Crude oil
1982
1983
1990
1993
120
100
80
60
40
20
0
Cover
(%)
Woody species
Forbs
Graminoids
Mosses
Total


Moist grassland
Diesel oil
1982
1983
1990
1993
Cover
(%)
140
120
100
80
60
40
20
0
Woody species
Forbs
Graminoids
Mosses
Total


Moist grassland
Crude oil
1982
1983
1990
1993
Cover
(%)
140
120
100
80
60
40
20
0
Woody species
Forbs
Graminoids
Mosses
Total


Wet graminoid fen
Diesel oil
1982
1983
1989
1993
Cover (%)
140
120
100
80
60
40
20
0
Woody plants
Forbs
Graminiods
Mosses
Total

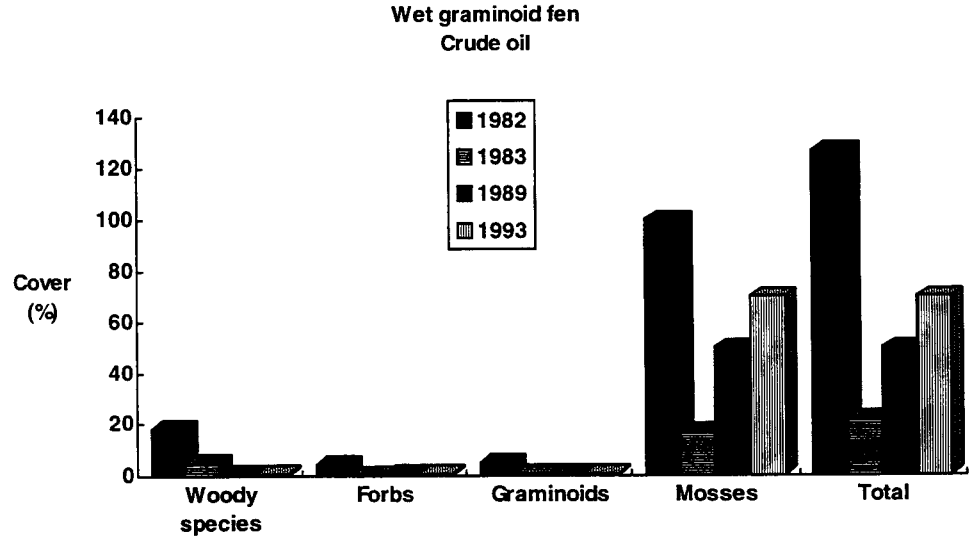
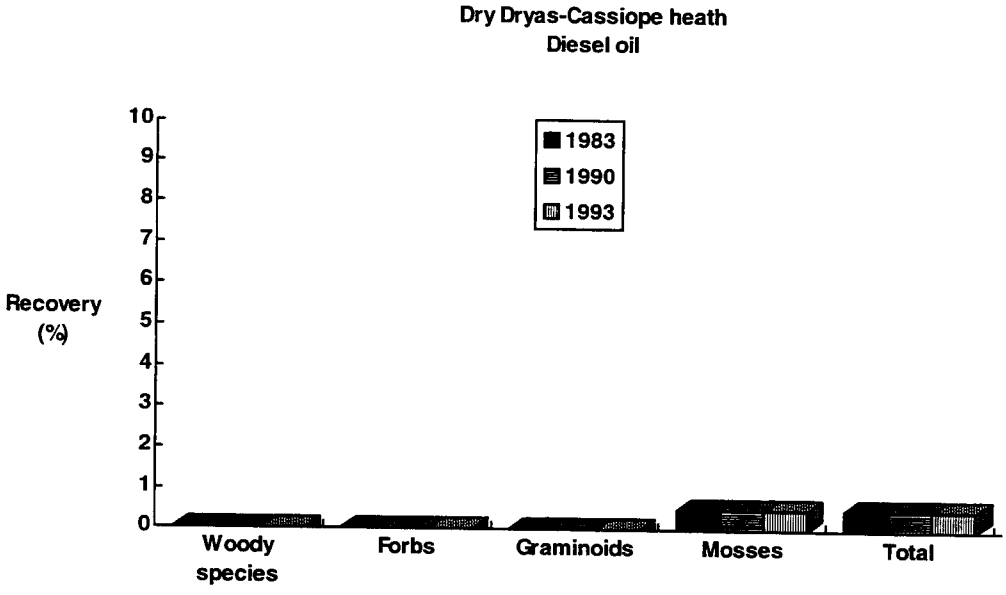
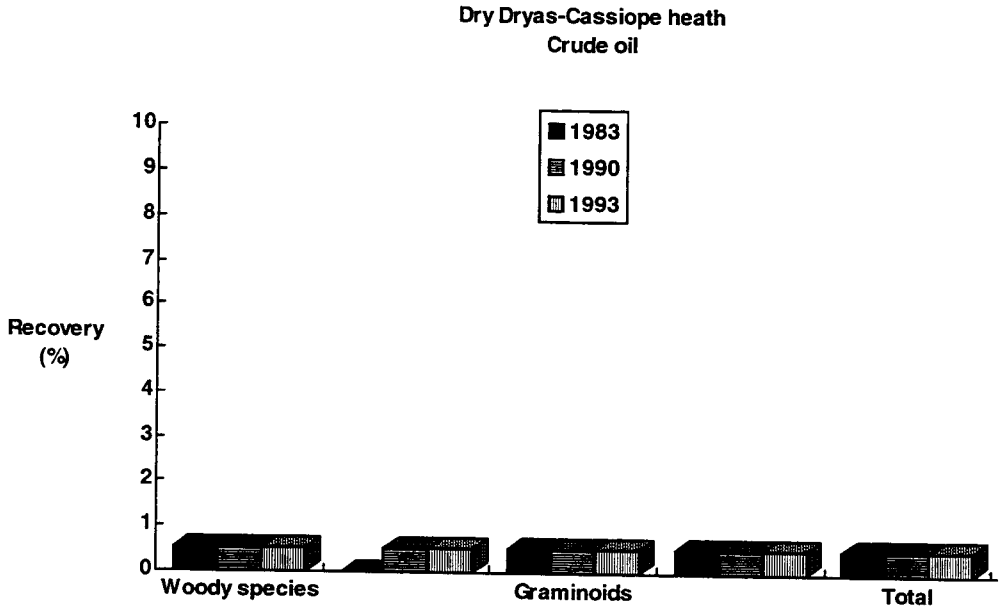
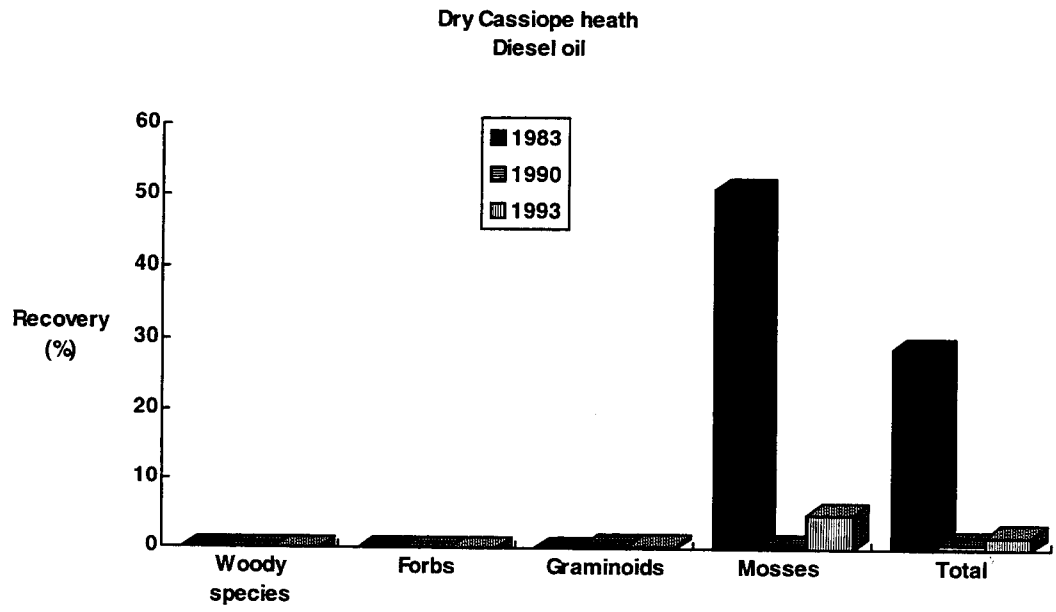
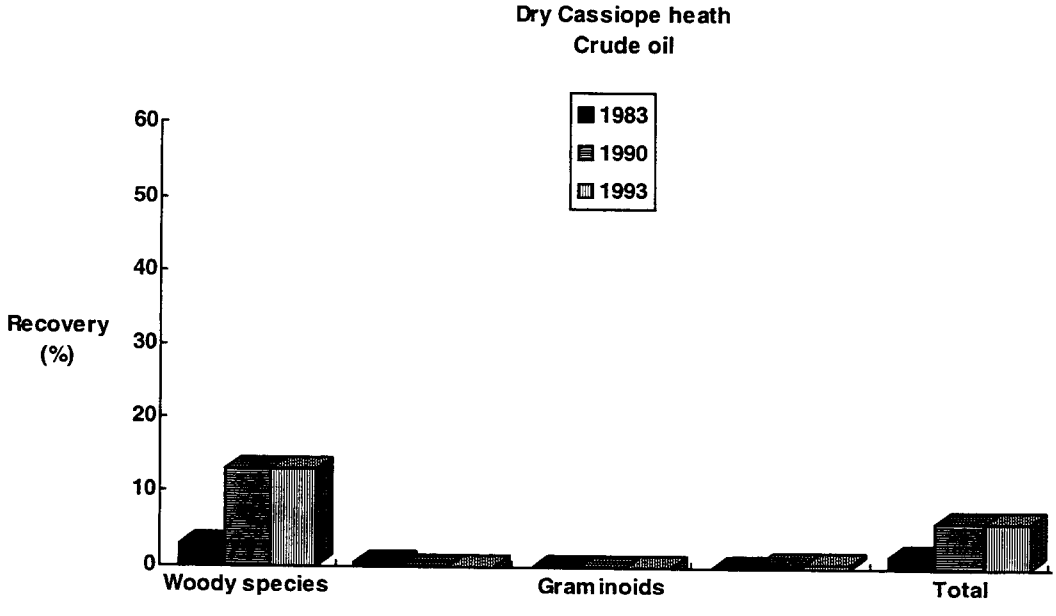

Wet graminoid fen
Crude oil
1982
1983
1989
1993
Cover (%)
140
120
100
80
60
40
20
0
Woody species
Forbs
Graminoids
Mosses
Total

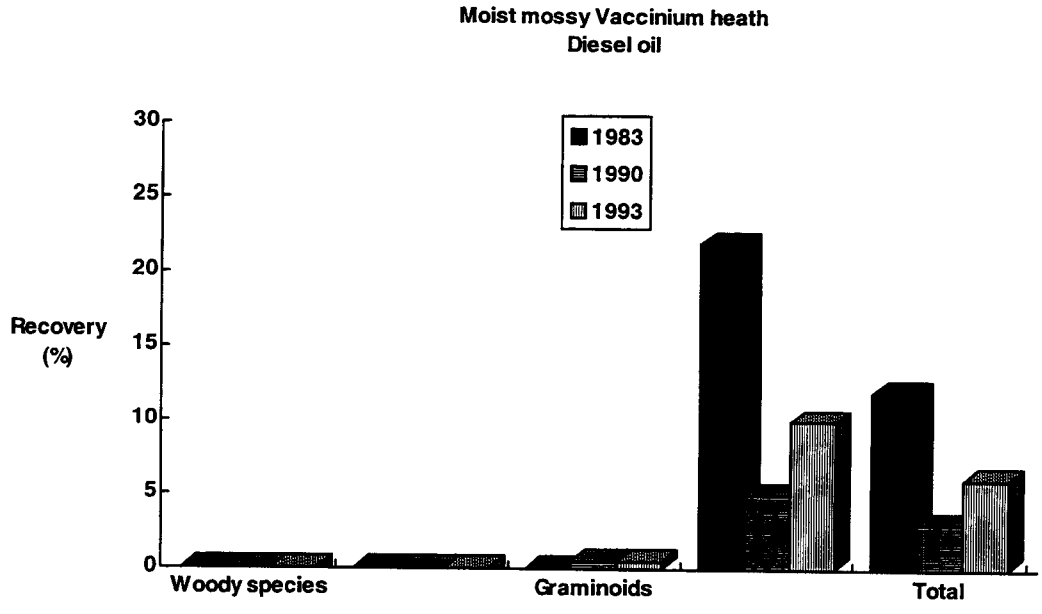
Figure 4. Recovery of woody species, forbs, graminoids, and mosses the year after (1983), seven years after (1990), and eleven years after (1993) the spills of diesel oil and crude oil on five plant communities. Note the different scales. Species covering less that 1% is given as 0.5%. The moss cover in the fen is recorded in 1989 instead of in 1990 due to silt deposition.

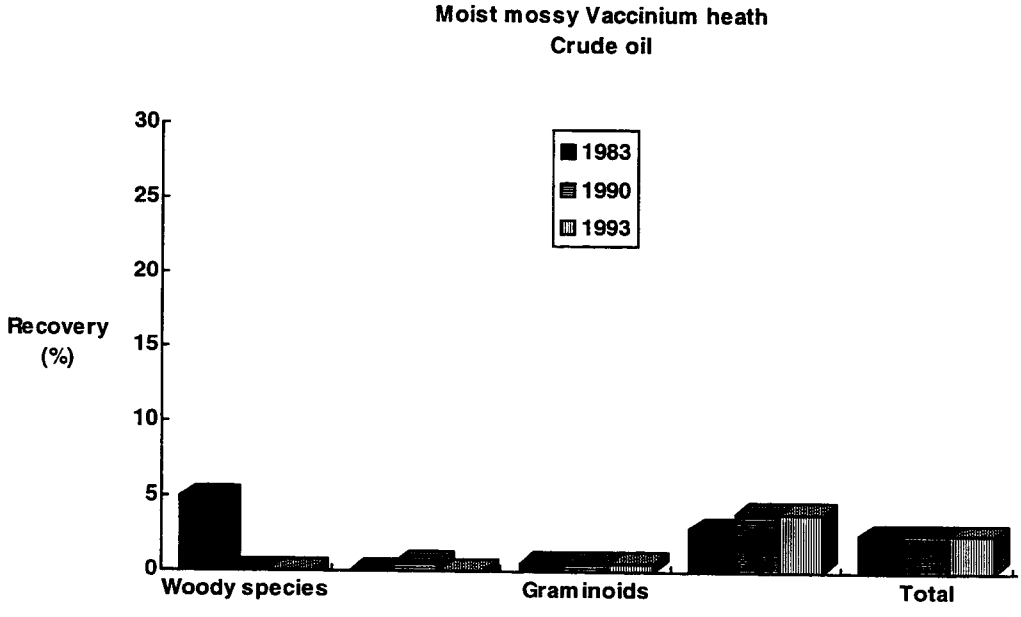


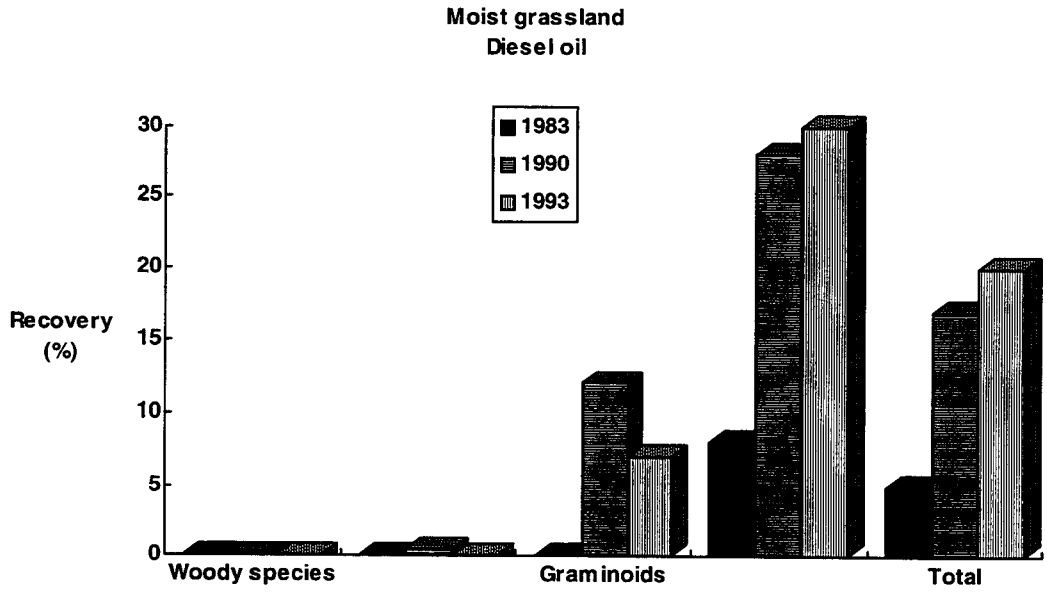


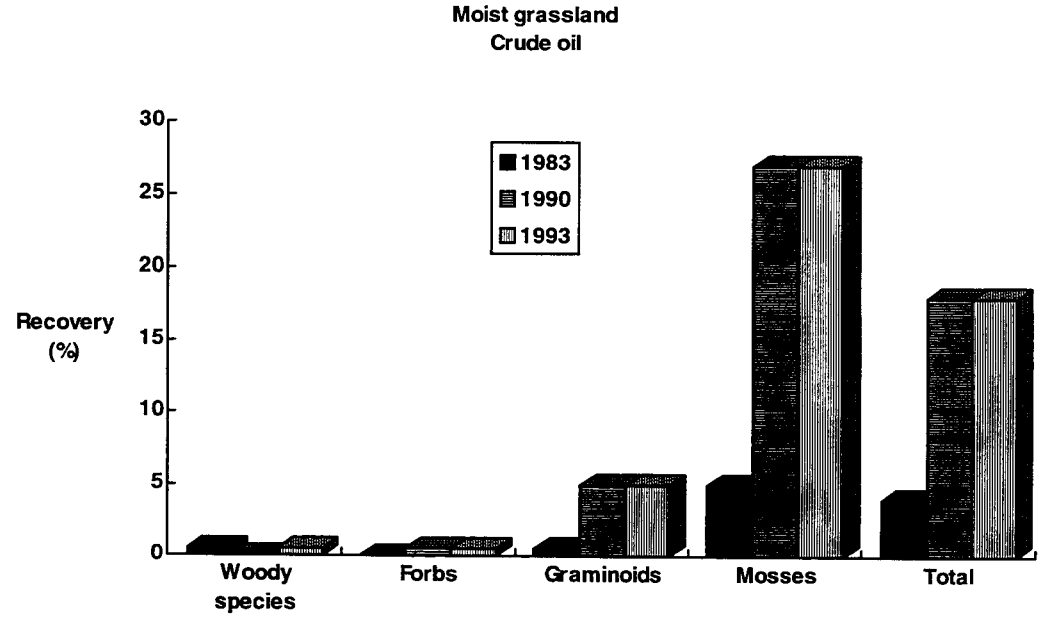

Dry Cassiope heath
Diesel oil
1983
1990
1993
Recovery (%)
60
50
40
30
20
10
0
Woody species
Forbs
Graminoids
Mosses
Total

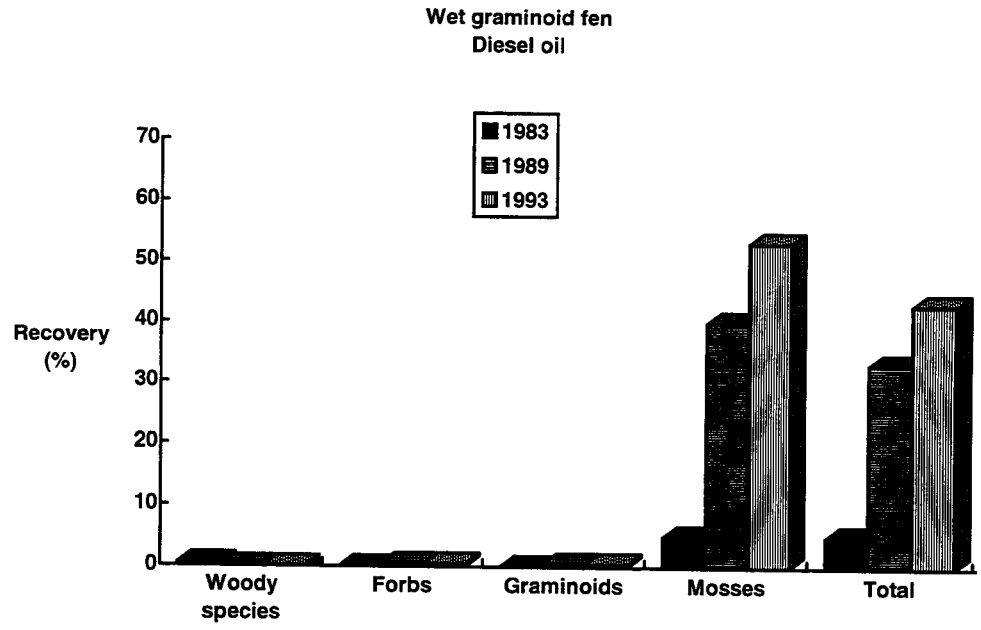

Dry Cassiope heath
Crude oil
1983
1990
1993
Recovery (%)
60
50
40
30
20
10
0
Woody species
Graminoids
Total


Moist mossy Vaccinium heath
Diesel oil
Recovery (%)
30
25
20
15
10
5
0
1983
1990
1993
Woody species
Graminoids
Total


Moist mossy Vaccinium heath
Crude oil
Recovery (%)
30
25
20
15
10
5
0
1983
1990
1993
Woody species
Graminoids
Total


Moist grassland
Diesel oil
1983
1990
1993
Recovery (%)
30
25
20
15
10
5
0
Woody species
Graminoids
Total


Moist grassland
Crude oil
1983
1990
1993
Recovery (%)
30
25
20
15
10
5
0
Woody species
Forbs
Graminoids
Mosses
Total


Wet graminoid fen
Diesel oil
1983
1989
1993
Recovery (%)
70
60
50
40
30
20
10
0
Woody species
Forbs
Graminoids
Mosses
Total

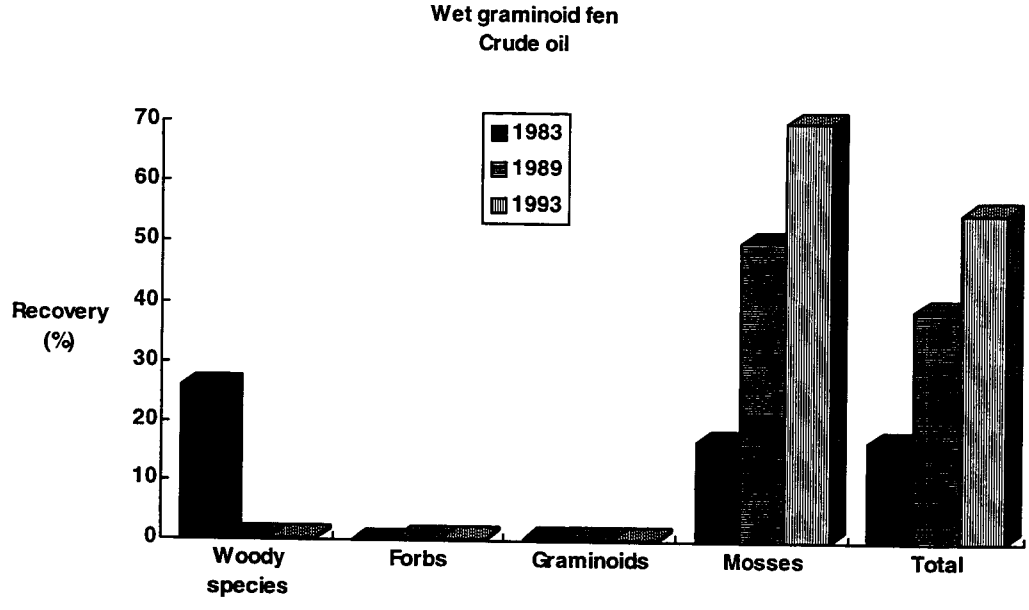
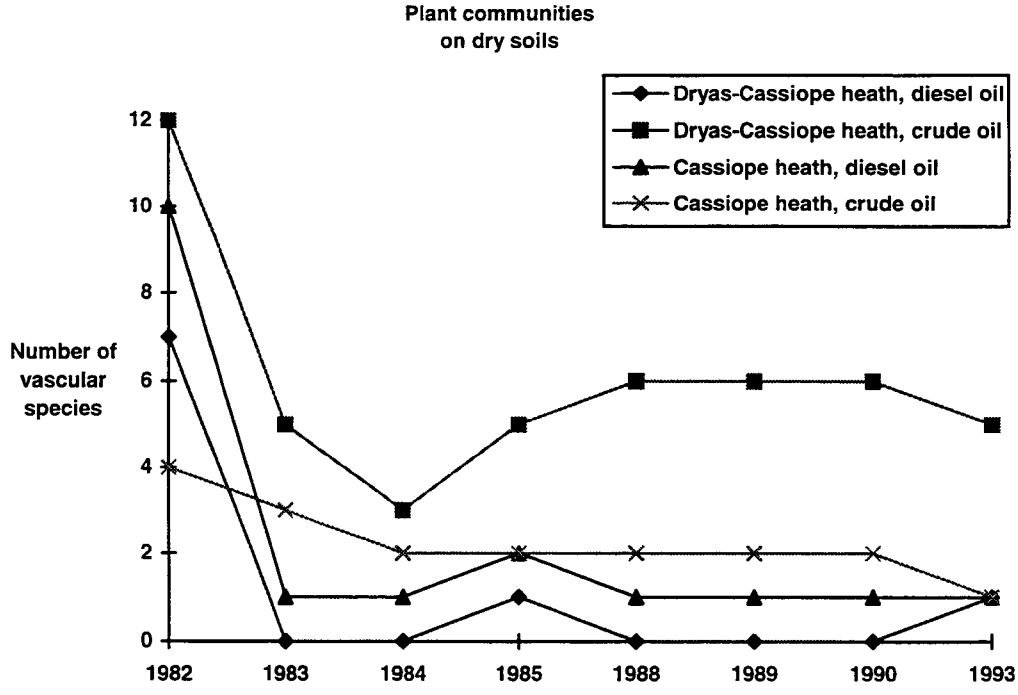
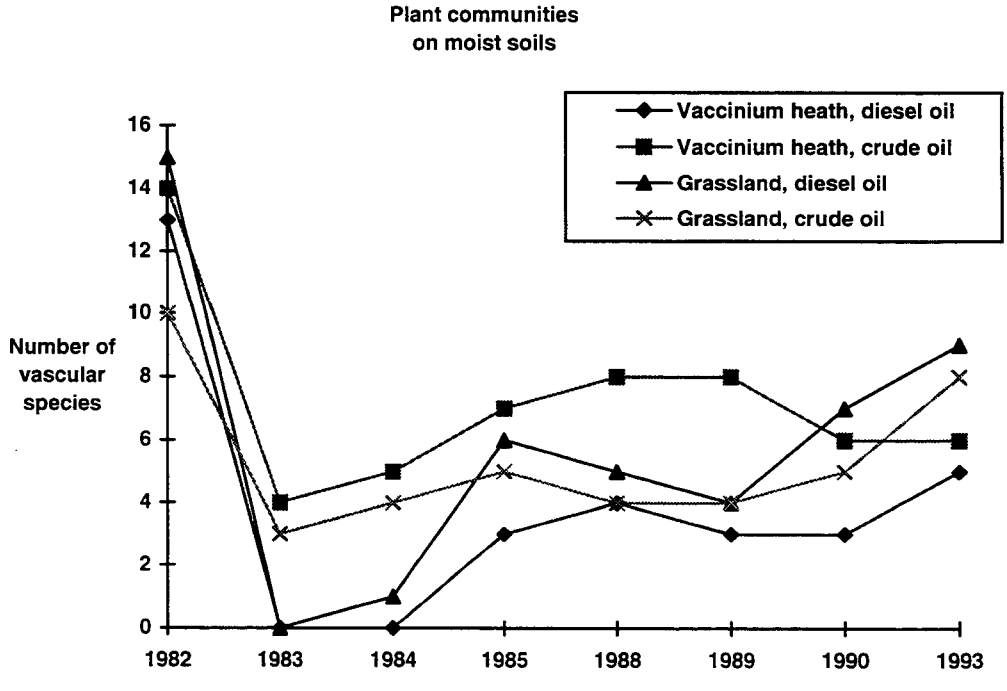

Wet graminoid fen
Crude oil
1983
1989
1993
Recovery (%)
70
60
50
40
30
20
10
0
Woody species
Forbs
Graminoids
Mosses
Total

Figure 5. Changes in the number of vascular plant species in plant communities on dry, moist, and wet soils. Note the different scales.





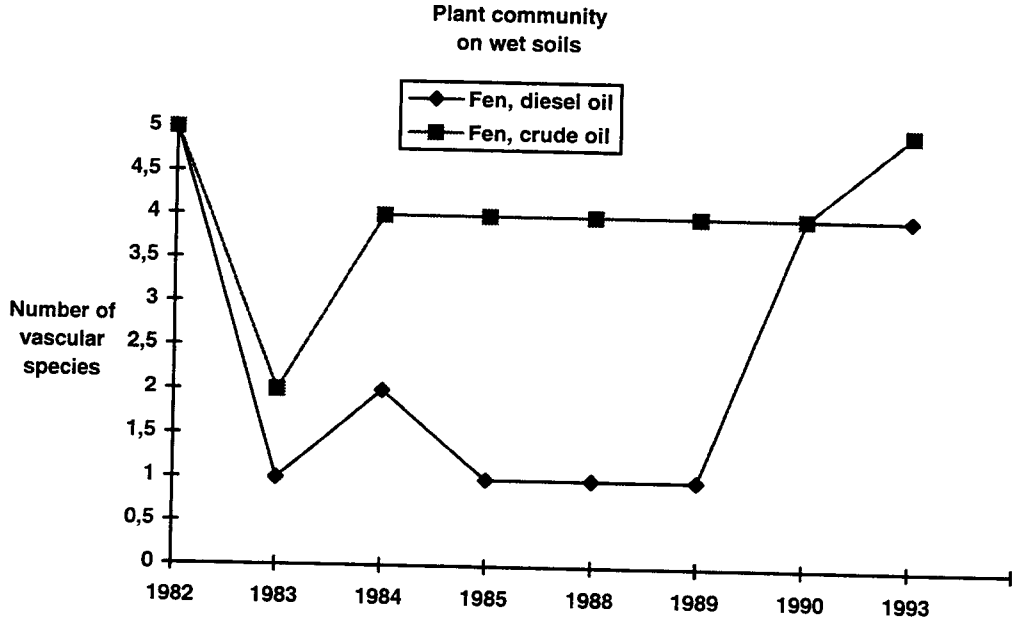
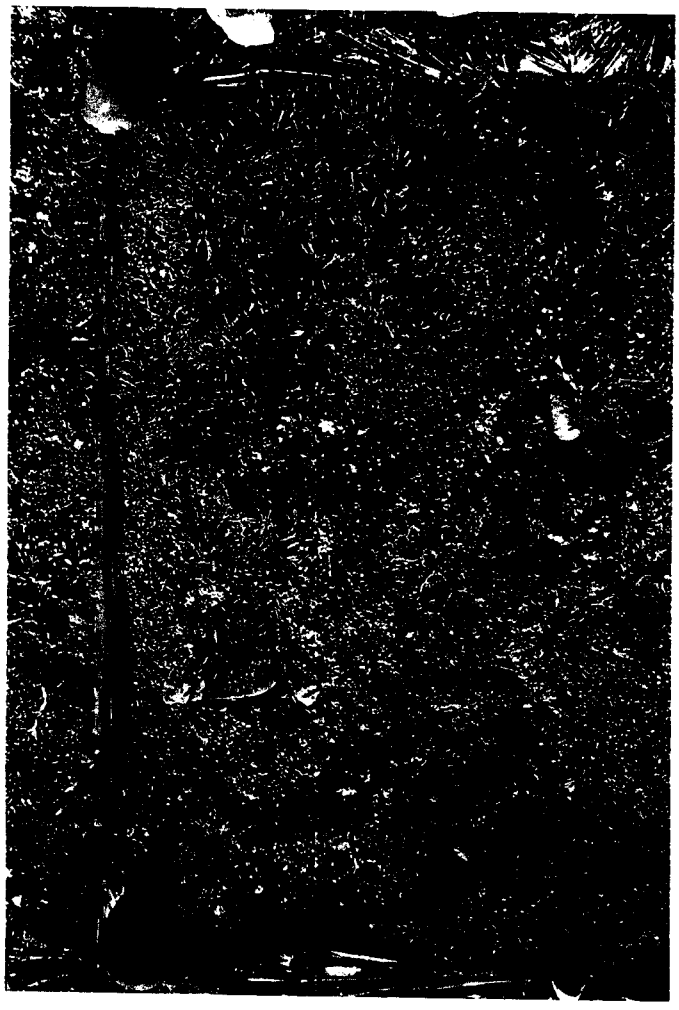
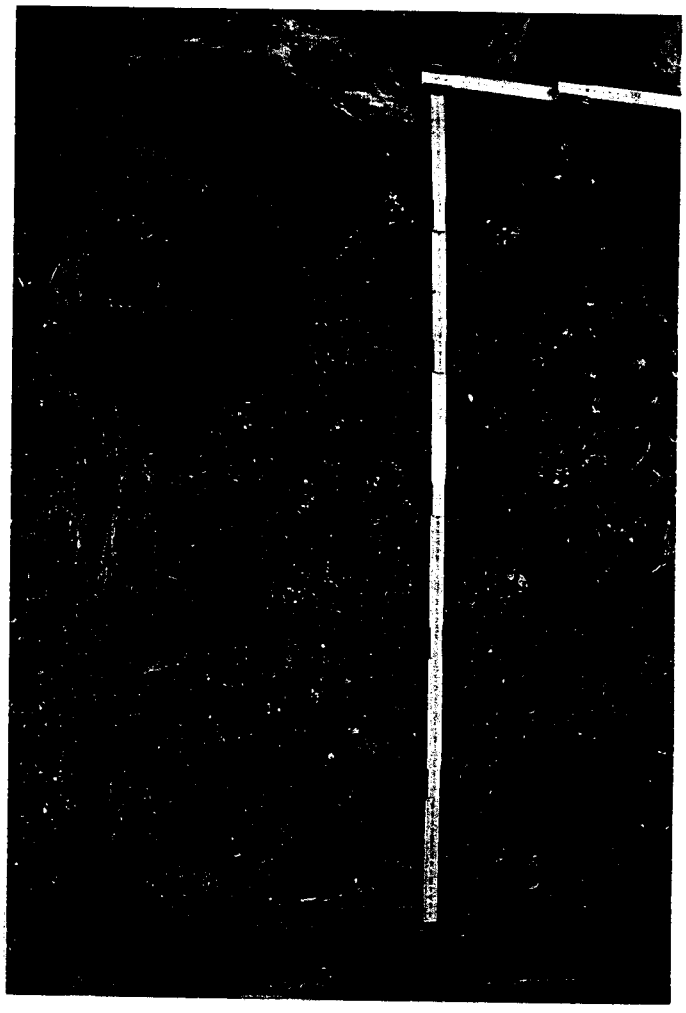
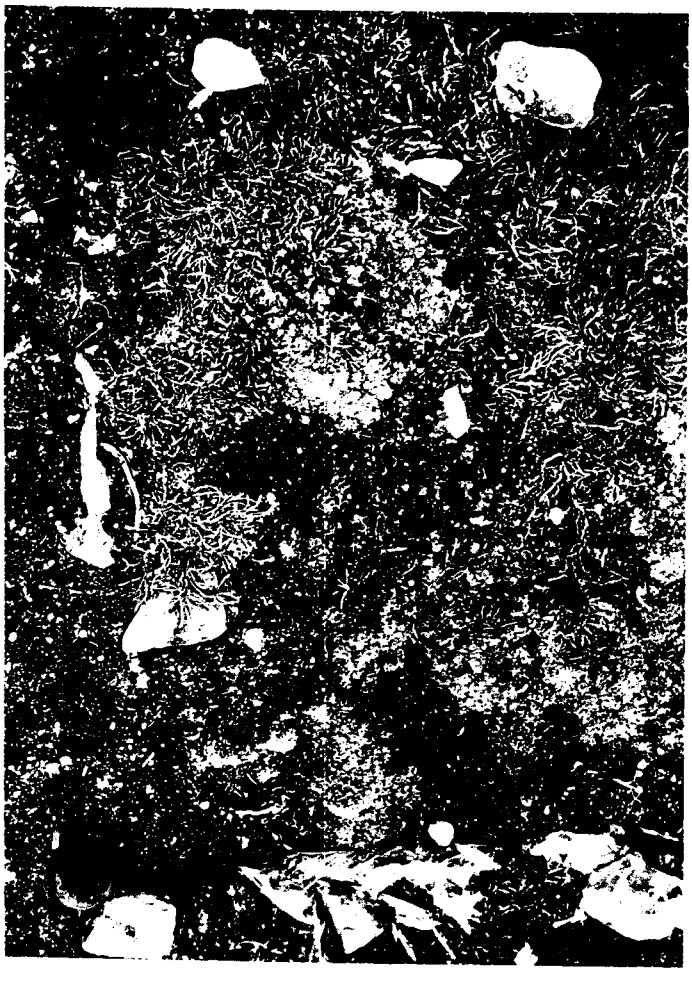


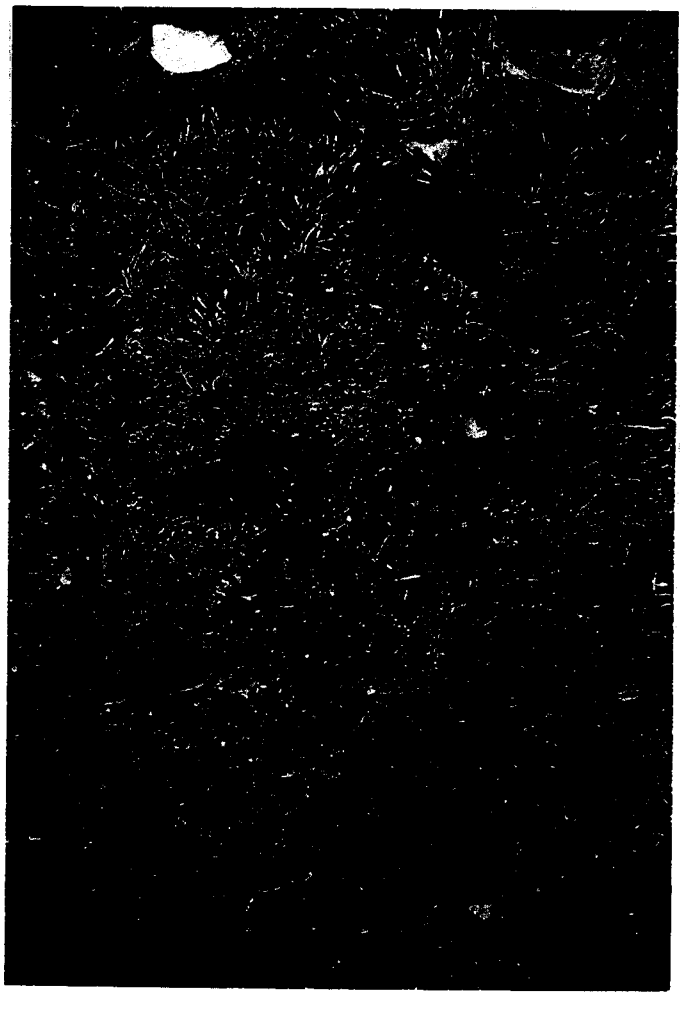
Figure 6. (Next page.) Diesel oil spill on dry *Dryas-Cassiope* heath. The photos are taken before the spill in 1982 (upper left), the year after (upper right), 7 years after the spill (lower left), and eleven years after (lower right).

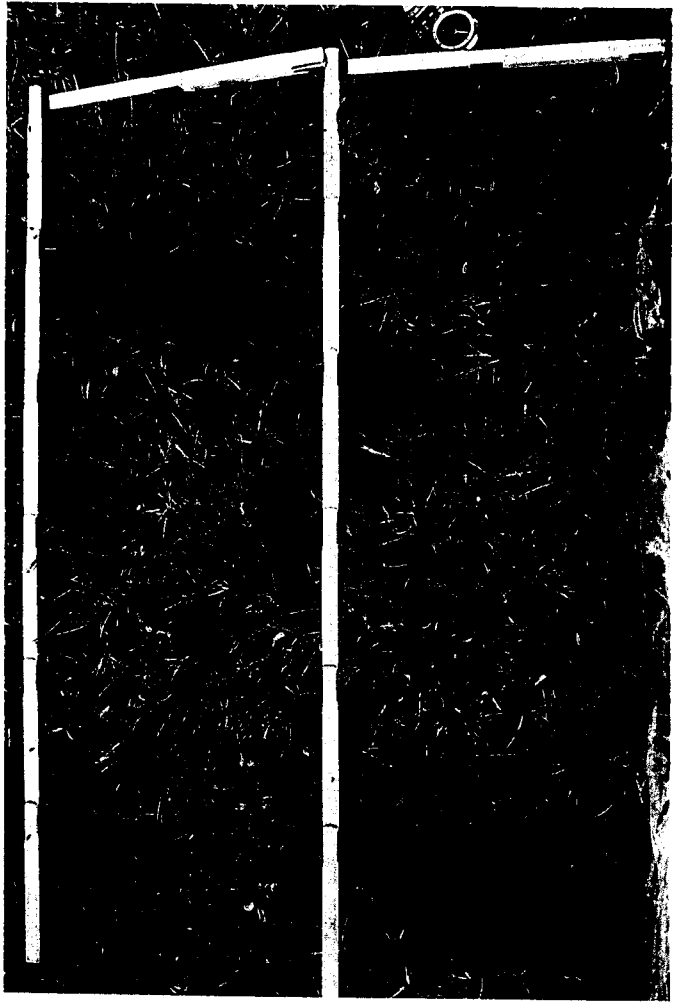
Figure 7. (Page 26.) Diesel oil spill on wet fen vegetation. The photos are taken before the spill in 1982 (upper left), the year after (upper right), 6 years after the spill (lower left), and eleven years after (lower right).

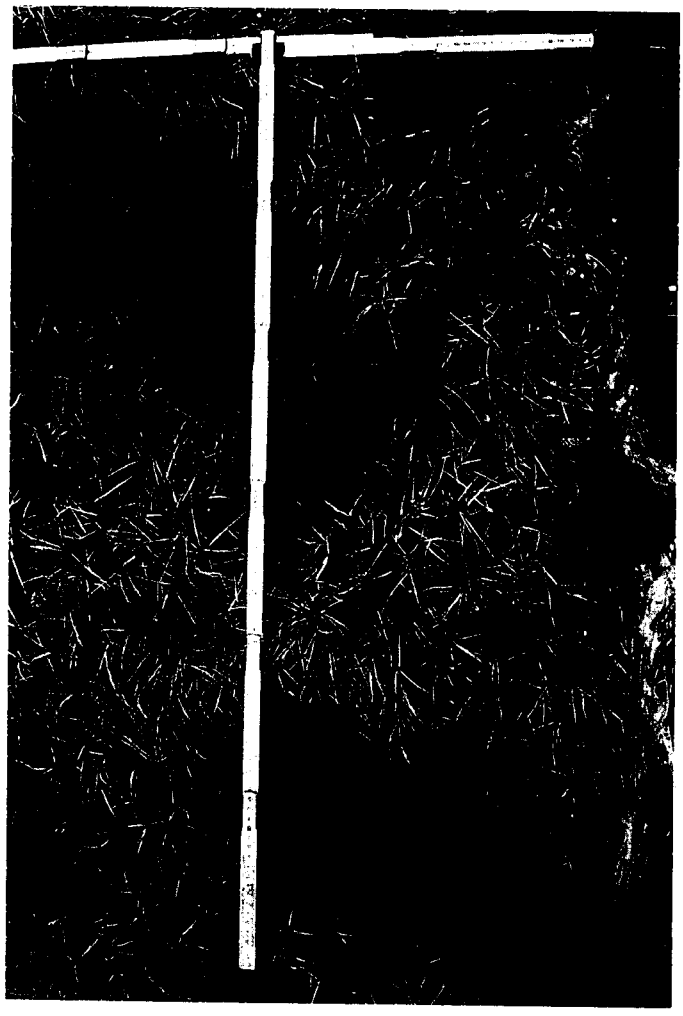


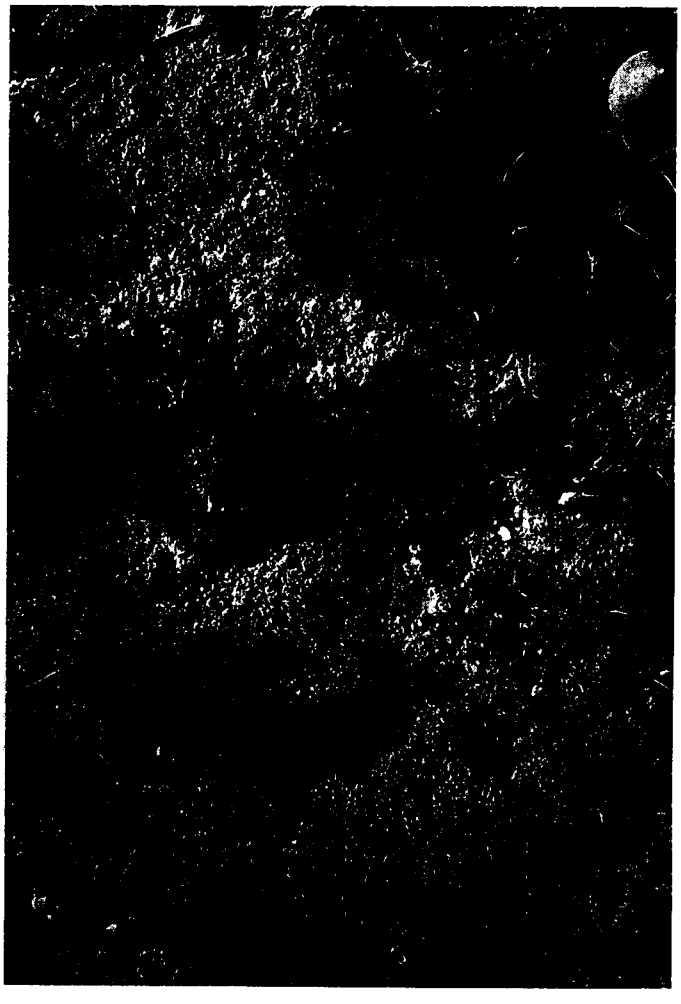












5 Discussion

5.1 Effects on vegetation cover

There was, generally, an immediate significant effect in the first growing season after the experimental spills. The cover of all plant groups was either reduced to a few percent of the original cover, or the vegetation died (Figure 3, Appendix 1). A delay in the reduction of moss cover was recorded in three plots treated with diesel oil. Plant communities on moist and wet soils are not as vulnerable as the dry habitats. Judging from the total recovery the year after the spills, the short-term effects of crude oil are more severe to plant communities on dry and moist habitats compared to diesel oil. This contrasts with conclusions from other studies (Walker et al. 1978, Freedman and Hutchinson 1976) and the long-term effects recorded in the present study. These showed that mosses are the most resilient vegetation, and that this plant group has a better recovery in moist and wet habitats. This contrasts with the conclusions of several other authors (Walker et al. 1978, 1987, Freedman and Hutchinson 1976), who stated that sedges and willows are most resilient plants, having a substantial recovery, while mosses are much more vulnerable the year after the crude oil treatment.

Eleven years after the spills, there was no or only minor recovery among woody species, forbs, and graminoids, whereas mosses have displayed a good ability to recover or a large potential for immigration (Figure 4). Woody species are absent from the plots or cover less than 1% (Table 1). This effect is most pronounced in plots treated with diesel oil, where all individuals of woody plants were killed and there were no new immigrants. However, an exception is the recovery in *Cassiope* heath treated with crude oil, where 13% of the woody plants recovered. Lichens showed a similar response with a cover of less than 1% in both types of oil treated plots. Herbs were the most vulnerable life form to both types of oil treatment displaying only minor survival in two plots. Graminoids were present in all plots except in the dry *Cassiope* heath treated with crude oil, generally with a cover of less than a few percent - mostly less than 1%. In the grassland plots the recovery of graminoids is 5% and 7% for diesel and crude oil treated plots, respectively.

As mosses are the only plants which are able to recover substantially, the total recovery of plant communities on dry soils, which have few mosses, is less than 1%. Similar severe effects were recorded in xeric sites in arctic Alaska (Lawson et al. 1978). In moist habitats, the recovery of mosses were 4-10% and 27-30% in *Vaccinium* heath and grassland, respectively (Figure 4), most pronounced in diesel oil treated plots. Mosses in wet fens displayed the greatest recovery. After the moss cover was reduced to 5% and 17% the year after the spills in the diesel and crude oil plots, respectively, it gradually increased the following years to a final status of 53% and 70% of the cover in the untreated vegetation in 1982. Walker et al. (1985) recorded a similar recovery of mosses in crude oil plots. The minimal

contact between oil and underground plant parts in water-saturated soils results in a reduced uptake of toxic substances from oil, as stated by Walker et al. (1978, 1987). In addition to this the increased horizontal leaching may explain the better recovery in wet and moist habitats.

The long-term impact of diesel oil is most pronounced for the plant cover in dry habitats, whereas recovery in habitats on moist and wet soils are moderate and good, respectively, mainly due to the ability of mosses to recover or immigrate. The crude oil treated plots generally showed a better, or nearly equal recovery compared to the diesel oil treated plots after eleven years. With the exception of most herbs other plant groups survived with a few individuals, resulting in a cover of less than 1%.

As concluded in other studies, the effects of oil spills are closely related to soil conditions (Walker et al. 1978, 1987), and the extent of the contact between oil and roots is a crucial factor determining the magnitude of the impacts. The vulnerability of the species is closely related to water content of the soil. Species with a large ecological range, occurring in dry habitats as well as in moist habitats have the best survival and recovery on soils with a high water content. Recovery is markedly species specific. According to Freedman and Hutchinson (1976), rhizomatous graminoids and dwarf shrubs showed a high ability to recover whereas mosses, lichens, and ericaceous shrubs showed little ability to recover or recolonize.

5.2 Effects on species diversity

The species diversity of vascular plants is generally reduced dramatically the year following the spills, and this is most pronounced for plots treated with diesel oil (Figure 5). In most plots the lowest number of species is reached the year after the spills with a gradual increase in numbers over the following years as expected by Holt (1987).

After eleven years the number of vascular species was still significantly reduced in all plant communities. This was most pronounced in plant communities on dry soils (Figure 5). In three of the four plots on dry soils, only one vascular species was recorded in 1993. A reduction to 10-25% of the original number of vascular species was generally recorded. No more than four species in the crude oil treated plot in *Dryas-Cassiope* heath were recorded, of which *Minuartia rubella* was new. In moist habitats, the number was reduced to 15% and 28% of the original number in diesel and crude oil treated *Vaccinium* heath, respectively, whereas in moist grassland the number of vascular plants was reduced to 53% and 70% of the original number in the two treatments. The difference in reduction of species reduction in fen plots is significant: 60% survived in the crude oil plot while only 20% survived in the diesel oil plot. On the other hand, the latter type had the highest number of immigrated species of all plots together with diesel oil treated *Vaccinium uliginosum* heath. The rapid increase in diversity from 1989 to 1993 in diesel oil

treated fen is partly caused by the immigration of new species, and partly by regeneration of species present in the original vegetation.

In the process of revegetation, two kinds of changes in number of species are recognised. Vegetative regeneration takes place by growth from survived plant parts e.g. stolons, rhizomes, roots, and lignified stems, whereas seedlings originate from seeds either from a seed bank within the plot or from diaspores dispersed to the plot from plants in the surrounding vegetation.

Colonization either by species new to the plots or by seed germination of species found earlier in the plots, occur almost exclusively in moist (52%) and wet habitats (33%) (Table 2). Of the 21 recordings of seed colonizing species, 7 occurred in wet fen, 6 in moist *Vaccinium uliginosum* heath, 5 in moist grassland, and only 3 species were recorded in dry habitats. Except for one seedling of *Vaccinium uliginosum,* no dwarf shrubs had colonized the plots 11 years after the spills. Two of the species are annuals (*Koenigia islandica* and *Euphrasia frigida*), whereas 13 are herbs (*Draba arctica, Minuartia rubella, Polygonum viviparum, Pedicularis flammea, Saxifraga cernua, S. foliolosa,* and *S. oppositifolia*) 6 of which are sedges (*Kobresia simpliciuscula, Eriophorum triste, E. Scheuchzeri, Carex misandra, C. nardina,* and *C. lachenalii*), and one is a rush (*Juncus castaneus*). *Carex misandra* is the most frequent colonizing species, occurring three times. *Koenigia islandica* is recorded twice, whereas all other species are recorded only once. Generally, forbs were found to be immigrants in plots as frequently as graminoids. Species which have either a large seed production or superior vegetative reproductive systems have a large potential for immigration, as has been concluded in other long-term studies (Lawson et al. 1978).

Saxifraga oppositifolia and *Euphrasia frigida* were recorded as the first immigrants to the plots two and three years after the spills, respectively, but disappeared the following year (Table 2). Most species, i.e., 76%, were recorded for the first time in either 1990 (24%) or 1993 (52%), eight and eleven years after the oil treatment, respectively. 11 years after the spill 13 colonizing species were recorded in plots, *Juncus castaneus* being the species which appeared first after the spills in 1988. 57% of the immigrated species were recorded in habitats treated with diesel oil. In most cases, the new species did not spread to all sections of the plot within the few years after the time of immigration, and consequently, the cover remained less than one percent.

The fact that there were very few immigrants and recovered plants recorded in dry habitats indicates that the speed of revegetation is slower in dry habitats than in wet and moist habitats.

5.3 Effects on fertility

Carex spp. and *Juncus* spp. were generally the most frequently immigrated or recovered species to flower (Appendix 1). The first recovered or immigrated plants, the graminoids (*Juncus biglumis, J. castaneus, J. triglumis,* and *Carex stans*) and the herb *Saxifraga cernua*

flowered six years after the spills. The number of fertile plants recorded more than doubled in the year after the first occurrence of fertile plants. Fertile plants of species occurring in the original vegetation, which regenerated vegetatively, started flowering already the first year or up to five years after their recorded regeneration. In 1993, no fertile plants were found in the dry habitats. 30% of the species in wet habitats were flowering, whereas the figure for moist habitats was 50%. There was no significant difference between the frequency of fertile species in diesel and crude oil treated plots.

Fertile plants from seedlings only occurred in three of the plots. *Eriophorum scheuchzeri* flowered three years after it was recorded for the first time. *Juncus castaneus* flowered already one year after immigrating to a plot, and *Kobresia simpliciuscula* flowered the year it was recorded for the first time, but they were absent by the last recording in 1990, and no further records were made during the period 1990-1993. The plant was probably one or two years old before flowering. It may have been older because it is difficult to recognise the species vegetatively.

6 Conclusions

The ecological effects of oil spills depend on several parameters: 1) the specific sensitivity of the plants to the toxic effects of oil, 2) the rate at which oil is decomposed by microbial decomposition and weathering, and 3) the survival and contact to mycorrhizal fungi (Antibus and Linkins 1978, Linkins and Antibus 1978). Eleven years after the experimental oil spills, the damage was still substantial and the recovery is minor. This is in contrast to the estimate of Freedman and Hutchinson (1976), who expected complete cover to be reestablished within a 10- to 15-year period. The wet habitats are most resilient, whereas the dry habitats are very vulnerable. Contrary to results from arctic Alaska (Freedman and Hutchinson 1976, Walker et al. 1978) mosses have a substantial recovery, whereas shrubs have a poor recovery potential. As seen in other places, sedges including *Carex* spp. and *Eriophorum* spp. have good recovery potential. As concluded by Walker et al. (1987) long-term effects of diesel oil spills are more severe to plants than crude oil spills.

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Appendix I

The cover of the species and plant groups in the intact vegetation in 1982 and the successive reduction of cover and colonising of species during the recording period 1983-1993. F = fertile, S = seedling, - obs = no recording in 1990 due to silt deposition.

Plot 1
Dry *Dryas-Cassiope* heath
Diesel oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Salix arctica	3							
Polygonum viviparum	+							
Carex nardina	+			+				+ S
Dryas octopetala	23							
Cassiope tetragona	21							
Silene acaulis	+							
Saxifraga oppositifolia	+							
Mosses								
Moss sp. indet.	1	+	+	+	+	+	+	+
Lichens								
Cetraria delisei	3	3	3	1	+	+	+	+
Cetraria nivalis	+	+	+	+	+	+	+	+
Cetraria islandica	+	+	+	1	+	2	1	1
Cladonia sp.							+	+
Lichen sp. indet.					+	+	+	+
Number of new vascular species								
Total number of vascular species	7	0	0	1	0	0	0	1

1988: The last vascular plant - *Carex nardina* - has disappeared since 1985. A slight reduction of the cover of lichens.

1989: No vascular plants are recorded and the cover and frequency of lichens and mosses is unchanged except for the cover of *Cetraria islandica;* now estimated to a few percent.

1990: The status is unchanged compared to 1989. For the first time since the spill it was possible to identify some of the undifferentiated lichens as *Cladonia* sp.

1993: One seedling of *Carex nardina* is recorded. The species has been absent from the plot since

1985. No other changes concerning the frequency and cover since 1990. Only one of the original seven vascular species occur while all the species of lichens are recorded.

Plot 2
Dry *Dryas-Cassiope* heath
Crude oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Salix arctica	2	+	+	1	+	+	+	+
Carex bigelowii	+	+	+	+	+	+	+	+
Polygonum viviparum	+				+	+ S	+	+
Carex nardina	+	+		+				
Saxifraga cernua	+				+	+ F	+ F	
Dryas octopetala	7			1	+			
Cassiope tetragona	15	+	+	1	+	+	+	+
Draba arctica						+S	+	
Carex misandra	+	+						
Silene acaulis	+							
Papaver radicatum	+							
Saxifraga oppositifolia	+							
Draba sp.	+							
Minuartia rubella								+S
Mosses								
Moss sp. indet.	4	+	+	+	+	+	+	+
Lichens								
Cetraria delisei	6		+	1	+	+	+	+
Cetraria nivalis	+							
Cetraria islandica	1		+	1	+	+	+	+
Cladonia sp.							+	
Number of new vascular species						1		1
Total number of vascular species	12	5	3	5	6	6	6	5

1988: There was only minor changes. *Polygonum viviparum* and *Saxifraga cernua* are recorded in two of the sections for the first time since the spills. The total cover is less than a few percent. Three of the originally four species of dwarf shrubs occur with a few alive plants. A reduction in cover of lichens has taken place.

1989: *Dryas octopetala* is absent and *Saxifraga cernua* is reduced in frequency, but is fertile for the first time in one of the sections. New seedlings of *Polygonum viviparum* have appeared and *Draba arctica* is recorded for the first time since 1982, where a *Draba* sp. was recorded.

1990: Fewer specimens of *Polygonum viviparum* are recorded. *Cladonia* sp. is recognised for the first time and *Saxifraga cernua* is fertile this summer too.

1993: With few exceptions unchanged since 1990. The last plants of *Saxifraga cernua* and *Draba arctica* have disappeared. *Cetraria islandica* is now recorded in all three sections of the plot and *Minuartia rubella* is new to the plot. Only four of the original 11 species of vascular plants occur and one new species.

Plot 3
Moist grassland
Diesel oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Salix arctica	1							
Carex bigelowii	37			1	+	6 F	3 F	2
Carex saxatilis	2		+			3 F	2 F	2 F
Carex scirpoidea	+							
Carex rupestris	+							
Carex misandra	2				+		+	+ F
Juncus castaneus	+			+	+ F	2 F	+ F	+ F
Juncus biglumis	+				+ F	+ F	+ F	+ F
Juncus triglumis	+						+ F	+ F
Polygonum viviparum	1			+	+		+	
Pedicularis flammea	+			+				
Saxifraga foliolosa	+							+S
Chamaenerion latifolium	+							
Koenigia islandica	+							
Minuartia stricta	+							+S
Euphrasia frigida				+				
Kobresia simpliciuscula								+ F
Mosses								
Moss sp. indet.	76	7	15	20	22	20	20	22
Number of new species				1				1
Total number of vascular species	15	0	1	5	5	4	7	9

1988: Slight improvement in respect to the cover of mosses and the establishment of new species. The moss cover is increased a few percent, now averaging 29% of the original cover. The frequency of *Carex bigelowii* and *Polygonum viviparum* is unchanged compared to 1985, while the cover of *Carex bigelowii* is slightly reduced. It was not possible to find individuals of *Pedicularis flammea* and *Euphrasia frigida* which were recorded in 1985. Fertile plants of *Juncus castaneus* and *J. biglumis* are recorded for the first time since 1982. Sterile plants of *Juncus castaneus* were first recorded in the plots three years after the spill.

The recording took place on July 12 and the plots were very wet with streaming water and a deposition of green algae in the most low-lying parts.

1989: In a section of the plot *Carex bigelowii* has increased its cover to 10%, thus giving a mean of 6%. The cover of *Juncus castaneus* is estimated to an increase to 2% and fertile plants occur now only in the middle section. All vascular species are flowering; *Carex bigelowii* and *C. saxatilis* for the first time. A slight reduction in the moss cover.

1990: *Polygonum viviparum* and *Carex misandra* have returned to one of the sections of the plot after having been absent in 1989. The cover of *Juncus castaneus* is estimated to less than 1% which is a decrease compared to 1988. A decrease of a few percent is also recorded for *Carex bigelowii* and

C. saxatilis. This could be explained by the fact that the recordings in 1989 were carried out by a new observer. *Juncus biglumis* is now also recorded in the last section of the plot. *Juncus triglumis* is recorded for the first time since 1982. The three *Juncus* spp., *Carex saxatilis*, and *C. bigelowii* are flowering. The degree of cover is unchanged compared to the previous years.

1993: The cover of *Carex bigelowii* is halved to 5% in one of the sections, but unchanged in the rest of the plot. All the plants are without inflorescences. Except for few *Juncus biglumis* in one of the sections there are fertile plants of *J. biglumis* and *Carex saxatilis* i all sections. *Carex misandra* is flowering for the first time. A fertile *Kobresia simpliciuscula* is a new species to the plots, while *Saxifraga foliolosa* and *Minuartia stricta* have re-established after 10 years of absence. The cover of mosses is increased to a few percents. The number of vascular species is now 9 of which one was not among the originally 15 species.

Plot 4
Moist grassland
Crude oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Salix arctica	1	+						+S
Carex bigelowii	40	+	1	1	+	4 F	1 F	1 F
Polygonum viviparum	1			+S				
Juncus biglumis	+		+	+	+	+ F	+ F	+ F
Carex saxatilis	1	+	+	2	1 F	1 F	1 F	1 F
Juncus triglumis	+			1	+	+ F	+	+ F
Pedicularis flammea	+						+ S	+ S
Carex misandra	2							+S
Equisetum variegatum	+							
Stellaria longipes	+							
Saxifraga oppositifolia			+					
Eriophorum triste								+
Mosses								
Moss sp. indet.	73	5	8	4	20	20	20	20
Number of new vascular species			1					1
Total number of vascular species	10	3	4	5	4	4	5	8

1988: The cover of mosses is increased significantly from 4% to 20%, but still comprising only 27% of the original cover. No new vascular plants have shown up. All individuals of *Juncus biglumis* are fertile. *Polygonum viviparum* is not found. A slight reduction in cover of *Carex bigelowii* and *Carex saxatilis.*

1989: The degree of cover of *Carex bigelowii,* which is fertile for the first time in all parts of the plot is increased to 4%. The degree of cover of *Carex saxatilis* is increased with a few percent in one of the sections, and some plants of *Carex saxatilis, Juncus biglumis,* and *Juncus triglumis* are fertile for the first time since the spills. The degree of cover of mosses is unchanged.

1990: The cover of *Carex bigelowii* is estimated to 1%. The decrease could be explained by the fact that a new observer carried out the recordings in 1989. Several plants of *Carex saxatilis* occur within two of the three sections of the plot being fertile in both. A seedling of *Pedicularis flammea* is found for the first time since 1982.

1993: Generally, no changes in the degree of cover, but some species have colonised the plot for the first time or have re-established themselves. *Eriophorum triste* is new, while *Salix arctica* and *Carex misandra* have re-established. *Juncus biglumis* is only fertile in one of the three sections, where it flowered the previous years. The cover of *Carex saxatilis* is reduced to a few percents in the section with the biggest cover, but the average is still 1%. The moss cover of 20% is unchanged since 1988. Seven of the originally 10 species occur in addition to one new species.

Plot 5
Moist, mossy *Vaccinium uliginosum* heath
Diesel oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Carex bigelowii	1				+	+	+	+
Polygonum viviparum	+			+	+			
Carex capillaris	+							
Dryas octopetala	8							
Cassiope tetragona	1							
Juncus castaneus					+S	+ F	+ F	+ F
Carex parallela	2			+	+	+		
Arctostaphylos alpina	4							
Juncus triglumis	+							
Eriophorum triste							+S	+
Carex scirpoidea	+							
Vaccininum uliginosum	14							+ S
Pedicularis flammea	2			+S				
Silene acaulis	11							
Saxifraga oppositifolia	1							
Carex misandra								+S
Mosses								
Moss sp. indet.	60	13	8	6	8	3	3	6
Number of new vascular species					1		1	1
Total number of vascular species	13	0	0	3	4	3	3	5

1988: The moss cover has increased now comprising 13% of the original cover. *Carex bigelowii* was recorded in the plot again and *Juncus castaneus* is new to the plot. Several unidentifiable Cyperaceae seedlings occur in the first section. *Pedicularis flammea* has disappeared, and both *Polygonum viviparum* and *Carex parallela* have decreased in frequency. The moss cover is slightly higher.

1989: *Polygonum viviparum* is absent and the moss cover is more than halved; now comprising only 3%. *Juncus castaneus* is flowering for the first time since the spill.

1990: *Carex parallela* has disappeared, while *Eriophorum triste* is new to the plot. *Juncus castaneus* is now only in one of the sections and fertile again. The moss cover is unchanged compared to the previous year.

1993: The moss cover has increased to 6%, now comprising 10% of the original cover. *Juncus castaneus* and *Eriophorum triste* are both recorded in two compared to only in one of the sections in 1990. *Juncus castaneus* is fertile in both sections. *Carex misandra* is established in two sections as a new species. One dicotyledon seedling is found - possibly *Vaccinium uliginosum*. Only two of the 13 species still occur eleven years after the spill, while three have colonised the plot.

Plot 6
Moist, mossy *Vaccinium uliginosum* heath
Crude oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Salix arctica	1	+						
Carex bigelowii	1	+	+	+			+	+ F
Polygonum viviparum	1			+S	+	+	+	
Carex parallela	5	+	+	+	+	2 F	+ F	+ F
Dryas octopetala	5		+	+	+	+		
Juncus castaneus	+				+	+ F	+	+
Juncus biglumis	+				+ F	+		
Carex capillaris	2							
Juncus triglumis	+		+		+ F	+ F	+ F	+ F
Eriophorum triste				+S	+	+	+	+
Vaccininum uliginosum	13	1	+	+	+	+		
Pedicularis flammea	2			+				
Silene acaulis	14							
Carex misandra								+S
Saxifraga oppositifolia	1							
Saxifraga foliolosa	+							
Mosses								
Moss sp. indet.	67	2	2	2	3	3	3	3
Number of new vascular species				1				1
Total number of vascular species	14	4	5	7	8	8	6	6

1988: The moss cover is increased to 3%, and constitutes less than 10% of the original. The three rush species *Juncus biglumis, J. castaneus,* and *J. triglumis* were recorded after having not been recorded in three years (*Juncus castaneus, J. biglumis*) and one year (*Juncus triglumis*). The two latter are flowering in two section for the first time. *Carex bigelowii* and *Pedicularis flammea* have disappeared from the plot.

1989: The frequency and cover of vascular plants and mosses are unchanged except for a minor increase of *Carex parallela. Juncus castaneus* and C. *parallela* are flowering for the first time since they appeared in 1988.

1990: *Carex bigelowii* occurs in all three sections after having not been recorded in five years. *Dryas octopetala, Vaccinium uliginosum,* and *Juncus biglumis* have disappeared. *Eriophorum triste* has spread, now occurring in all sections. *Juncus castaneus* was not flowering this summer.

1993: No changes in degree of cover. *Carex bigelowii* has disappeared from two of the three sections, and it is fertile for the first time after the spills. *Carex misandra* is recorded as new pecies while *Polygonum viviparum* is not recorded. Only five of the original 14 species occur and one new species has colonised the plot.

Plot 7
Wet graminiod fen
Diesel oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Polygonum viviparum	1							
Carex stans	11		+	+	+ F	+ F	+	+ F
Salix arctica	10	+	+					
Equisetum variegatum	1							
Saxifraga cernua							+	
Saxifraga foliolosa							+	
Eriophorum scheuchzeri	+						+	
Carex misandra								+
Koenigia islandica								+S
Carex lachenalii								+
Mosses								
Moss sp. indet.	100	6	35	55	61	40	-obs	51
Number of new vascular species							2	3
Total number of vascular species	5	1	2	1	1	1	4	4

1988: The situation is almost unchanged compared to 1985. The moss cover is unchanged in two of the sections, but increased with 20% in the last one. Thus, the average is increase with 6%, now totally 61%. *Carex stans* is represented by few plants and the degree of cover is less than 1%, and some of the plants are flowering for the first time.

1989: *Carex stans* now occurs in all sections being the only vascular species in the plot and even flowering. The cover of mosses is reduced from 60% to 40%.

1990: *Carex stans* was not flowering. *Saxifraga cernua* and *S. foliolosa* are recorded for the first time, whereas *Eriophorum scheuchzeri* is recorded after eight years of absence. It was not possible to estimate the moss cover because of the silt deposition after heavy rainfalls in mid August.

1993: Significant changes in respect to degree of cover of mosses and species diversity. The degree of cover of mosses has increased to 51%. *Koenigia islandica, Carex misandra,* and *C. lachenalii* have established for the first time, while *Saxifraga cernua* and *S. foliolosa* have disappeared. Only one of the five originally recorded species was still within the plot in addition to three recently colonising vascular species.

Plot 8
Wet graminiod fen
Crude oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Polygonum viviparum	2							
Carex stans	5	+	+	+	+ F	+ F	+	+ F
Salix arctica	18	4	4	2	+	+	+	+
Equisetum arvense	+		+	+	+	+		
Equisetum variegatum	1		+	+	+	+	+	+
Eriophorum scheuchzeri							+	+ F
Koenigia islandica								+S
Mosses								
Moss sp. indet.	100	17	38	19	40	50	-obs	70
Number of new vascular species							1	1
Total number of vascular species	5	2	4	4	4	4	4	5

1988: The cover of mosses has been doubled and constitutes 40% of the original, whereas the frequency and cover of vascular plants are unchanged except for the disappearance of *Equisetum variegatum* and *Carex stans* each in one section. *Carex stans* was flowering in one of the sections. The cover of *Salix arctica* is reduced to less than 1%.

1989: The situation is unchanged for the vascular plants whereas the moss cover is increased with 10%. *Carex stans* was flowering in all sections of the plot.

1990: *Equisetum arvense* is not found, and *E. variegatum* occurs in only one of the sections. *Carex stans* is sterile. *Eriophorum scheuchzeri* is established in all sections of the plot for the first time. The degree of cover of mosses is not estimated because of the silt deposition.

1993: The moss cover is increased to 70%. *Eriophorum scheuchzeri* was flowering now three years after its establishment, and *Carex stans* is flowering again. *Koenigia islandica* is established in two of the sections for the first time. No changes in the cover of vascular plants.

Plot 9
Dry *Cassiope* heath
Diesel oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Polygonum viviparum	+							
Dryas octopetala	+							
Salix arctica	5							
Cassiope tetragona	28	+	+	+				
Saxifraga cernua	+							
Saxifraga oppositifolia	+							
Huperzia selago	+							
Oxyria digyna	+							
Silene acaulis	1							
Carex misandra	+			+	+	+	+	+
Mosses								
Polytrichum sp.					+	+	+	+
Moss sp. indet.	37	19	17	1	+	+	+	1
Lichens								
Cetraria nivalis	+	+	+	+	+	+	+	+
Cetraria islandica	8	5	5	1	+	+	+	+
Cetraria delisei				+	+	+	+	+
Stereocaulon sp.	+		+					
Number of new vascular species								
Total number of vascular species	10	1	1	2	1	1	1	1

1988: The last alive *Cassiope* plant was dead, and *Carex misandra*, established three years earlier, is the only vascular species. The cover of mosses is less than 1%.

1989: The situation is unchanged compared to 1988.

1990: The situation is unchanged compared to 1989.

1993: The cover of mosses has increased to 1% since 1985. *Carex misandra* is new to one of the sections, now occurring in two of the sections and being the only of the ten vascular species originally recorded in the plot.

Plot 10
Dry *Cassiope* heath
Crude oil

Species/Year	1982	1983	1984	1985	1988	1989	1990	1993
Vascular plants								
Luzula confusa	+	+						
Salix arctica	6	1	2	2	2	4	4	4
Cassiope tetragona	25	+	1	1	1	1	1	
Festuca brachyphylla	+							
Mosses								
Moss sp. indet.	30							+
Lichens								
Cetraria nivalis	1							
Cetraria islandica	3							+
Number of new vascular species								
Total number of vascular species	4	3	2	2	2	2	2	1

1988: The situation is unchanged compared to 1985.

1989: The cover of *Salix arctica* has increased to 4%. The situation is otherwise unchanged.

1990: The situation is unchanged compared to 1989.

1993: The last individual of *Cassiope tetragona* has died. *Cetraria islandica* was recorded for the first time since the spill. Only one of the four species recorded in 1982 is still in the plot.