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Effects of Crude and Diesel Oil Spills on Plant Communities at Prudhoe Bay, Alaska, and the Derivation of Oil Spill Sensitivity Maps

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ABSTRACT. Crude oil was spilled on six of the major Prudhoe Bay plant communities at an intensity of 12 l m^{-2}. The communities occurred along a topographic-moisture gradient. The reaction of the major species of the various communities was recorded one year following the spills.

Sedges and willows showed substantial recovery from crude oil spills. Mosses, lichens, and most dicotyledons showed little or no recovery. On a very wet plot with standing water, the vegetation showed total recovery one year following the spill. Dry plots, on the other hand, showed very poor recovery. *Dryas integrifolia* M. Vahl, the most important vascular species on dry sites, was killed. Identical experiments using diesel oil rather than crude oil showed all species except an aquatic moss to be killed. A sensitivity index for the communities was calculated on the basis of the percentage cover of the resistant species divided by the original total plant cover of the community. With this information an oil spill sensitivity map for an area of Prudhoe Bay was constructed using a vegetation map as a base.

Using the crude oil data from Prudhoe Bay together with some from the literature, a predictive sensitivity map was also constructed for an accidental crude oil spill at nearby Franklin Bluffs. In this example all the community types are considered to have moderate to excellent recovery potential.

Implications of the experiments and the mapping exercises for oil spill contingency planning are discussed.

RÉSUMÉ. On a écoulé du brut au taux de 12 litres/m^2 sur 6 des principales colonies végétales de Prudhoe Bay. Les colonies se situaient suivant un gradient à l'humidité, liée à la topographie. Un an après l'écoulement, on enregistrait la réaction des principales espèces de ces colonies diverses.

Les roseaux et saules montraient un recouvrement substantiel provenant de l'écoulement de pétrole. Les mousses, lichens et la plupart des dicotyledons montraient peu ou pas de recouvrement. Sur un terrain très humide, avec de l'eau stagnante la végétation montrait un recouvrement total, un an après l'écoulement. D'autre part, sur les terrains secs, on ne voyait qu'un faible recouvrement. "*Dryas intergrifolia*," l'espèce vasculaire la plus importante sur les sites secs, crevait. Des différences identiques, en utilisant du gazoil plutôt que du brut, montraient que toutes les espèces, sauf une mousse aquatique, crevaient. On calculait un index de sensibilité des colonies, sur la base du pourcentage du recouvrement des espèces résistantes par rapport au recouvrement total original de la colonie végétale. A partir de cette information, une carte de sensibilité à l'écoulement du pétrole, était dessinée pour une région de Prudhoe Bay, en utilisant comme base une carte de végétation. En utilisant les données de traitement du pétrole venant de Prudhoe Bay avec d'autres tirées de la litérature, on dessinait aussi une carte de prévision de sensibilité en cas d'un écoulement accidentel

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du brut au voisinage de Franklin Bluffs. Dans cet exemple, on a considéré que tous les types de colonies avaient un potentiel de recouvrement modéré à excellent.
On discute des implications de ces expériences et des essais de cartes en vue d'un programme éventuel d'écoulement de pétrole.
Traduit par Alain de Vendigies, Aquitaine Co. of Canada Ltd.

INTRODUCTION

Prudhoe Bay with its many oil wells and the web of flowlines, has a higher likelihood of major terrestrial spills than any other place in Alaska. Oil spill contingency planning is an integral part of Prudhoe Bay operations. This can be complimented by preparation of maps which predict the sensitivity of various ecosystems to oil spills. This approach can be used for locating future drill sites and pipelines so that sensitive areas might be avoided, and in the event of a spill, selection of clean-up techniques might be suggested. Such maps must be based on a thorough understanding of the ecology of the region including the plant communities, landforms, soils and animal populations.

METHODS

A vegetation map was constructed at a scale of 1:6,000 for a small area near the Putuligayuk River (70° 16' 30'' N. 148° 32' W) at Prudhoe Bay. The vegetation map was constructed using the master map method (Everett *et al.*, 1978). A master map is one which has vegetation, soil, landform and slope information all encoded on a single map. The map area used for this investigation was well known as it was studied during the U.S. International Biological Programme Tundra Biome program (Brown, 1975; Webber and Walker, 1975) and also has been the site for off-road vehicle testing (Walker *et al.*, 1977).

The data necessary for the derivation of the sensitivity map from the vegetation map was acquired by spilling Prudhoe Bay crude oil and diesel oil on plots within each of the six major plant communities. Within each of the six communities, oil was spilled on one 1 x 1 m^2 plot and diesel fuel was spilled on a similar nearby plot. Diesel fuel was included in the experiment since it has been accidently spilled in many areas at Prudhoe Bay. Areas adjacent to the plots were used as control areas. The six communities spanned the topographic-moisture gradient from a dry ridge through a moist upland to a very wet marsh. The dry end of the gradient was dominated by *Dryas integrifolia, Oxytropis gorodkovii Jurtsev, Saxifraga oppositifolia L.*, and crustose lichens. The gradient extended through a moist gently sloping upland community dominated by *Eriophorum angustifolium* Honck., *Dryas integrifolia,* a moss *Tomenthypnum nitens* (Hedw.) Loeske, and scattered fruticose lichens including *Thamnolia subuliformis* Ehrh., *Cetraria islandica* (L.) Ach., and *Dactylina arctica* (Hook.) Nyl. The lower end of the gradient passed through an area of weakly expressed low-center polygons dominated by *Carex aquatilis* Wahlenb. and the moss *Drepanocladus lycopodioides* var. *brevifolius* (Lindb.) Moenk. and continued to a very wet low-center polygon covered by 10 to 15

TABLE 1. Summary of quadrat data from the six treated plant communities (see Table 3 for names). The table shows environmental data for each community and the plant species found in the plot. For the species, the site columns are divided into 3 parts. The left hand column (labeled C) is the percentage cover before the treatment and this may be regarded as the control value; the middle column (labeled O) shows the recovery in the crude oil plot one year after treatment; the right hand column (labeled D) shows recovery in the diesel oil plot. Percentage cover for most taxa is given for the live fraction only, except in those cases where the standing dead component is fairly large; in these cases a fraction representing the live/(standing dead) is listed. Recovery for each taxon is given as follows: (++++) no apparent effect, complete recovery after one year; (+++) nearly complete recovery, minor phenological differences noted between treated and untreated areas; (++) very noticeable phenological differences between treated and untreated areas, but plants showing good recovery; (+) plants showing very slight recovery; (0) no recovery; (?) recovery questionable, i.e., difficult to tell live plants from dead plants. Taxa follow Löve and Löve (1975) for vascular plants, Crum *et al.* (1973) for mosses and Hale and Culberson (1970) for lichens.

Environmental Factors	Plant Community					
	B2	B1	U3	U4	M2	M4
Moisture regime (1 (dry) to 10 (emergent))/Depth of H_2O	2	2	4	8/0-3 cm	5	10/10-15 cm
Snow regime (1 (wind swept) to 10 (deep snowbank))	2	2	4	5	5	5
Slope	2°N	0°	1°S	0°	0°	0°
Evidence of frost activity (1 (no evidence) to 4 (greater than 75% of surface disturbed by frost))	2	3	1	1	1	1
Depth to permafrost (6/28/76) TH — measured from tops of hummocks, BH — measured between hummocks	23 cm TH	28 cm TH	15 cm BH	20 cm BH	10 cm	18 cm
Terrain description	side of small ridge	top of small ridge	unpatterned slope	low polygon center	polygon rim	low polygon center
Size of microrelief features (i.e., hummocks)	15 cm	<5 cm	10 cm	8 cm	13 cm	—
Estimate of bare soil	<1%	15%	0	0	0	0
Animal activity	old caribou feces	—	—	—	caribou feces	—
Percentage standing dead	20	20	30	25	30	4
Percentage prostrate dead and litter	3	2	10	40	15	20

Species	Plant Community																	
	B2			B1			U3			U4			M2			M4		
	C	O	D	C	O	D	C	O	D	C	O	D	C	O	D	C	O	D
Shrubs:																		
Cassiope tetragona (L.) D. Don ssp. *tetragoua*	2						.1	0	0									
Salix arctica Pall.	.1	+	0				.1	++	0	2	++	0	.1	++	0			
S. reticulata L.							.1	++	0	.1	+	0						
S. rotundifolia Trautv.							.1	+	0									
Mat and cushion dicotyledons:																		
Dryas integrifolia M. Vahl.	10/20	0	0	15/15	0	0	10/20	0	0				10/15	0	0			
Lidia arctica (Stev.) Löve & Löve (= Minuartia arctica (Stev.) A. & Gr.)	1	0	0															
Oxytropis gorodkovii Jurtsev (= *Oxytropis nigrescens* (Pall.) Fisch. ssp. *pygmaea*)				2	0	0												
Saxifraga oppositifolia L.	1	+	0	.5	0	0	.5	0	0				.5	0	0			
Erect dicotyledons:																		
Bistorta vivipara (L.) S.F. Gray (= *Polygonum viviparum* L.)										.1	0	0						
Dendranthema integrifolia (Richards.) Tzvelev. (= *Chrysanthemum integrifolium* Richards.)	.1	+	0	.5	+	0	.1	+	0									
Draba alpina L.	.5	+	0															
Papaver macounii Greene							.5	0	0									
Pedicularis lanata Cham. & Schlect. ssp. *lanata*	.1	0	0	.1	0	0												
Saussurea angustifolia Willd.	.1	0	0															
Tephroseris kjellmanii (A.E. Porsild) Löve & Löve (= *Senecio atropurpureus* auct., *non* (Ledb.) B. Fedtsch.)	.1	0	0				.1	0	0									

Species	Plant Community																	
	B2			B1			U3			U4			M2			M4		
	C	O	D	C	O	D	C	O	D	C	O	D	C	O	D	C	O	D
Horsetails:																		
Hippochaete variegata (Schleich.) Bruhin (+ *Equisetum variegatum* Schleich.)										1	0	0						
Monocotyledons:																		
Carex aquatilis Wg.										.1	+	0	.1	+++	0	5/20	+++	0
C. rotundata Wg.	2/2	++	0				2/7	+++	0									
C. rupestris All.	5/5	++	0	2/	++	0												
Eriophorum angustifolium Honck.	1/1	+++	0				5/5	+++	0	10/10	+++	0	10/15	+++	0			
Juncus biglumis L.	.1	0	0															
Mosses:																		
Bryum sp.										1	0	0						
Calliergon richardsonii (Mitt.) Kindb. *ex.* Warnst.																		
Campylium stellatum (Hedw.) C. Jens.										.1	0	0	.1	0	0			
Cirrophyllum cirrosum (Schwaegr. *ex* Schultes) Grout													2	0	0			
Distichium capillaceum (Hedw.) B.S.G.	2	0	0															
Ditrichum flexicaule (Schwaegr.) Hampe				.5	0	0	5	0	0									
Drepanocladus lycopodioides (Brid.) Warnst. var. *brevifolius* (Lindb.) Moenk.							2	0	0	25	0	+	2	0	0			
Drepanocladus uncinatus (Hedw.) Warnst.				.1	0	0	1	0	0									
Eucalypta alpina Sm.				1	0	0							5	0	0			

Hypnum sp.							2	0	0							
Orthothecium chryseum (Schwaeger. *ex.* Schultes) B.S.G.	.1	0	0				.5	0	0							
Scorpidium scorpioides (Hedw.) Limpr.																90 + + + + + + + +
Thuidium abietinum (Hedw.) B.S.G.				.5	0	0										
Timmia austriaca Hedw.	.1	0	0				.1	0	0							
Tomenthypnum nitens Loeske	10	0	0	.1	0	0	10	0	0	.1	0	0	10	0	0	
Tortella arctica (Arnell) Crundw. & Nyl.							.1	0	0							
Tortula ruralis (Hedw.) Gaertn., Meyer & Scherb.	.1	0	0	2	0	0										
Lichens:																
Black soil crust	5	0	0	4	0	0										
Alectoria nigricans (Ach.) Nyl.	.5	0	0	.5	0	0	.5	0	0							
Cetraria cucullata (Bell.) Ach.	2	0	0	1	0	0	.5	0	0				.5	0	0	
C. islandica (L.) Ach.	1	0	0	1	0	0	.5	0	0							
C. nivalis (L.) Ach.																
Cladonia gracilis (L.) Willd.	.1	++	0	.1	++	0	.1	++	0				.1	++	0	
Clandonia pyxidata (L.) Hoffm.	.1	0	0	.5	0	0	.1	0	0							
Dactylina arctica (Hook.) Nyl.							.5	+	0				2	++	0	
Lecanora epibryon (Ach.) Ach.	1	0	0	4	0	0	.5	0	0							
Solorina saccata (L.) Ach.				.1	0	0										
Stereocaulon alpinum Laur.							.5	0	0							
Thamnolia subuliformis (Ehrh.) W. Culb.	5	0	0	5	0	0	2	0	0				2	0	0	

FIG. 1. Method of hydrocarbon application. The plot is sealed from its surroundings by polyethylene sheeting inserted into the tundra.

cm of water and dominated by *Carex aquatilis* Wg. and the moss *Scorpidium scorpioides* (Hedw.) Limpr. Complete quadrat data from the six 1 x 1 m^2 oil spill plots are presented in Table 1. The sites were quadrated on June 28, 1976 and as a result, a few late developing dicotyledon species may have been missed. Also the cover values reflect very high components of standing dead vegetation which would be expected early in the season.

The oil treatment plots were sealed from their lateral surroundings by 4 mill polyethylene sheeting inserted 5 to 10 cm below the surface and extending 10 cm or more above. This was done to confine the hydrocarbon spills to the plots and proved sufficient in all except the wettest site where the water raised to a level above the sheeting in the early summer of 1977. Twelve litres of either Prudhoe Bay crude oil or diesel fuel was applied on July 23, 1976, to each 1 x 1 m plot [equivalent to fluid depth of approximately 1.2 cm (McKendrick and Mitchell, this volume] using a can with a spout and sprinkling head (Fig. 1). This method had been shown previously to give a reasonably uniform oil coverage (Everett, this volume). The condition of the tundra during application was generally very dry in comparison to the previous three summers. Virtually no rain had occurred since June 25. This probably enhanced the depth of penetration by the hydrocarbons. Temperature during the spill was 6 °C, and there was a strong easterly wind, which might have aided in the volatilization of the lighter, more toxic, components of the oil. Photographs were taken of the 12 treatment plots before, immediately after, and one year following the spills. The cover of living plants in the spill plots was estimated after one year on July 2, 1977.

A Sensitivity Index (SI) was calculated for each community type represented by the spills. This index is the ratio of live plant cover one year following the spill (C_R) to the original live plant cover before the spill (C_T).

RESULTS

Diesel Spills. There was virtually no recovery on any of the diesel spill plots after one year (Table 1). All plants appeared to be completely dead with the exception of *Scorpidium scorpioides. Scorpidium* usually grows submerged in water and in this situation it is safe from the influence of either diesel fuel or crude oil since the hydrocarbons float on the water surface. The lack of an effect here suggests that contact is essential for a herbicide effect and that the soluble components are not enough to kill the moss. In some areas, however the *Scorpidium* becomes exposed to the atmosphere by late summer due to evaporation of the water and lowering of the water table due to increased active layer depth. In these situations the *Scorpidium* would undoubtedly be killed by the hydrocarbons (Hutchinson *et al.*, 1974). *Carex aquatilis* growing with *Scorpidium* appeared dead despite the fact that the diesel oil had no opportunity to contact the root systems. Apparently, mere contact of the diesel fuel with the leaves was enough to kill the plants.

Crude Oil Spills. One year following the spills, most species were dead on the crude oil plots (Table 1). On the dry plots *Dryas integrifolia, Cassiope tetragona* L., *Oxytropis gorodkovii,* and lichens are species common to dry sites which were killed by the oil. In more mesic and wet sites important mosses such as *Tomenthypnum nitens* Loeske, *Ditrichum flexicaule* (Schwaegr.) Hampe and *Drepanocladus lycopodioides* var. *brevifolius* were killed. Nearly all herbaceous dicotyledons, with the exceptions of *Dendranthema integrifolia* (Richards) Tzvelou and *Draba alpina,* L., were killed.

There were a few species which showed some degree of apparent recovery one year following the spills. Table 2 lists these species with an evaluation of their success in surviving the oil spills. It is apparent from the table that only the deciduous shrubs and sedges showed any substantial degree of recovery. Even on the driest sites where the oil penetrated to the roots, sedges and willows recovered. *Carex rupestris* All., however, was the only sedge to show substantial recovery on the dry sites.

Sensitivity indices were also calculated by extrapolation for the five remaining plant communities encoded on the master map (Fig. 2A and Table

TABLE 2. Summary of species recovery on the oil spill plots one year following treatment. All other species listed in Table 1 were apparently killed by the treatment.

Growth-form	Species	Degree of Recovery
Deciduous shrubs	*Salix arctica*	moderate - plants small but abundant
	S. reticulata	moderate — plants very small
	S. rotundifolia	slight — only one small plant detected.
Cushion dicotyledon	*Saxifraga oppositifolia*	slight — one small plant detected
Rosette dicotyledons	*Dendranthema integrifolia*	slight — but several plants detected
	Draba alpina	slight — one plant detected
Monocotyledons (sedges)	*Carex aquatilis*	good to excellent — most plants showing new vigorous growth, especially on the wetter plots, but no flowering
	C. rotundata	moderate — plants showing new growth, but phenologically much slower
	C. rupestris	moderate — plants showing new growth, but phenologically much slower
	Eriophorum angustifolium	good — plants showing new vigorous growth, but slower phenologically, no flowering
Mosses	*Scorpidium scorpioides*	excellent — however moss was never in direct contact with the oil since it was submerged beneath water surface
Lichens	*Dactylina arctica*	? — possibly recovering, upper parts of thalli are free of oil
	Cladonia gracilis	? — possibly recovering, upper parts of thalli are free of oil

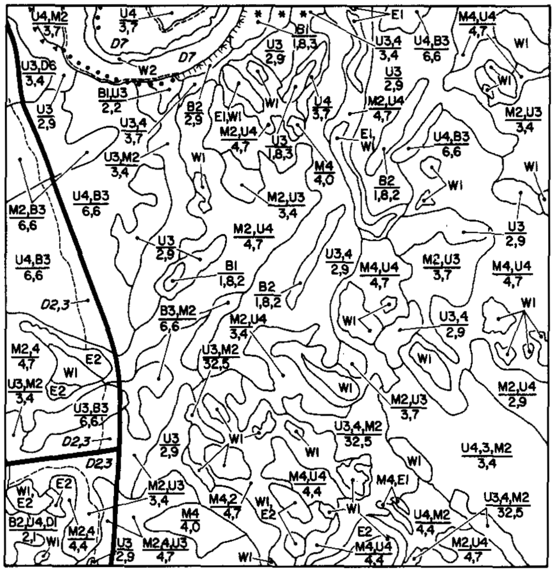

FIG. 2A. Master map of the study area. Each map unit contains a code expressed as a fraction. The numerator of the code represents the vegetation stand types listed in order of dominance. The first code in the denominator is the soil type; the second number in the denominator is the landform type. Key to the vegetation codes is in Table 3. Some codes have no denominators. These represent either disturbed areas (*D* codes) or water bodies (*W* and *E* codes) (see Everett *et al.*, this volume, for further code details). The location of the oil spill experiments is indicated by asterisks.

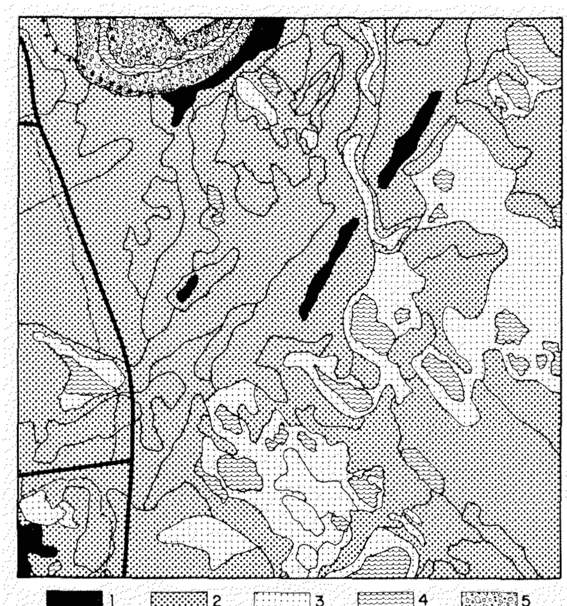

FIG. 2B. Crude oil spill sensitivity map of the Prudhoe Bay study area. The map is derived from the vegetation information on the master map in Figure 1 and represents the relative susceptibility of the various map units to a spill intensity of 12 l m^{-2}. 1 — high sensitivity (SI < 0.2); 2 — moderate sensitivity (0.2 < SI < 0.6); 3 — low sensitivity (0.6 < SI < 1.0); 4 — water; 5 — gravel.

3). This was possible because most of the major Prudhoe species had been encountered in the experimental plots. These plots represented the overall variability of the Prudhoe moisture gradient, and the response of the few species which did not occur in the spill plots could be deduced from the literature (McCown and Deneke, 1973; McCown *et al.*, 1973; Hunt *et al.*, 1973; Wein and Bliss, 1973; Hutchinson *et al.*, 1974; Deneke *et al.*, 1975; Hutchinson

TABLE 3. Sensitivity indices for 13 of the major Prudhoe Bay stand types. Values were obtained from quadrat data for the community types; N = number of sampled 1 x 1 m plots, C_T = mean percentage total cover, C_R = mean percentage cover of plants expected to recover, SI = sensitivity index (C_R/C_T).

Master Map Code	Community	N	C_T	C_R	SI	Recovery Potential
E2	VERY WET *Arctophila fulva* DEEP GRASS-MARSH	10	24	24	1.00	Excellent
E1	VERY WET *Carex aquatilis* SHALLOW SEDGE-MARSH	30	23	22	.96	Excellent
M4*	VERY WET *Carex aquatilis – Scorpidium scorpiodes* SEDGE MEADOW	20	43	41	.95	Excellent if there is enough water to cover moss carpet
M5	MOIST *Carex aquatilis – Salix* spp. SEDGE SHRUB MEADOW (CREEK BANKS)	20	57	40	.70	Very good
U7	MOIST *Salix rotundifolia – Carex aquatilis* PROSTRATE SHRUB MEADOW (SNOWBANKS)	10	111	41	.37	Moderate
M1	WET *Carex aquatilis – Drepanocladus lycopodioides – Carex rariflora* SEDGE MEADOW	20	47	16	.34	Moderate
M2*	WET *Carex aquatilis – Drepanocladus lycopodioides* SEDGE MEADOW	60	72	17	.24	Moderate
U4*	MOIST *Eriophorum angustifolium – Dryas integrifolia – Drepanocladus lycopodioides* SEDGE MEADOW	40	84	20	.24	Moderate
U3*	MOIST *Dryas integrifolia – Eriophorum angustifolium – Tomenthypnum nitens – Cetraria islandica* SEDGE MEADOW	60	97	20	.21	Moderate
U6	DRY *Dryas integrifolia – Cassiope tetragona* DWARF SHRUB HEATH (SNOWBEDS)	10	67	10	.15	Poor
B3	DRY *Dryas integrifolia – Saxifraga oppositifolia – Juncus biglumis* MAT DICOTYLEDONE HEATH (FROST BOILS)	3	38	4	.11	Poor
B2*	DRY *Dryas integrifolia – Saxifraga oppositifolia* MAT DICOTYLEDON HEATH	30	64	6	.09	Poor
B1*	VERY DRY *Dryas integrifolia – Oxytropis gorodkovii* MAT DICOTYLEDON HEATH	30	43	4	.09	Poor

*communities tested with spilled oil.

and Freedman, 1975; Freedman and Hutchinson, 1976; and McFadden *et al.*, 1977).

Using the sensitivity index (SI) for each community type a map showing the distribution of vegetation sensitive to crude oil spill was made (Fig. 2B). Three levels of sensitivity were mapped. These levels are high sensitivity (SI < 0.2), moderate sensitivity (SI between 0.2 and 0.6), and low sensitivity (SI > 0.6).

One source of concern was a new road which was constructed through the middle of the study in the spring of 1977. The road has caused a layer of dust to be deposited on the plots near the road, which may further stress the plants beyond the influence of the oil spill. This could cast doubt on the value of observations taken in future years. Incidents of this nature have occurred several times in the past at Prudhoe Bay (McKendrick and Mitchell, this volume, a) and point to the necessity of coordination between the scientific community and oil field planners, particularly with regard to long-term experiments.

DISCUSSION

At Prudhoe Bay very few species other than sedges (*Carex* spp. and *Eriophorum* spp.) and willows (*Salix* spp.) showed recovery from the oil spills in one year. Fortunately those which did recover often comprise a large proportion of the vegetation. Figure 3 shows bar graphs of the percentage cover of the major growth forms in four of the stand types. The bars are coded to show the cover of the growth forms which could be expected to recover or be killed from an oil spill. This experiment and one by McKendrick and Mitchell (this volume, a) show that sedges and shrubs are the most resilient species in the Prudhoe Bay region. It appears that certain growth forms are less susceptible to oil spill damage. Hutchinson and Freedman (1975) also noted that plant growth forms affected their ability to produce new plant tissue from tissues not contacted by the oil. In the case of the prostrate deciduous shrubs (e.g., *Salix arctica* Palla, *S. reticulata* L. and *S. rotundifolia* Trautv.), the new growth comes from rhizomes which create new shoots after the death of exposed apical buds. Mycorrhizal fungi also appear to be an important factor affecting the survivability of several tundra species (Antibus and Linkins, this volume; Linkins and Antibus, this volume). The sedges (e.g., *Carex aquatilis* and *Eriophorum angustifolium*) apparently have very resistant intervalary meristems. This coupled with a large underground reserve of food located in the rhizomes allows the sedges to recover rapidly following the death of all aboveground photosynthetic tissues. The grasses *Dupontia fisheri* R. Br. and *Arctagrostis latifolia* (R. Br.) Griseb., major components of some coastal communities, are apparently much less resistant to the effects of oil than are the sedges (McCown *et al.*, 1973a; 1973b).

Before any firm conclusions regarding the survivability of species can be made, the study plots will have to be observed for several additional seasons. This is true with regard to species which appear to recover after one year but which later die (e.g., *Dupontia fisheri* at Barrow, McCown *et al.*, 1973), and *Vaccinium vitis-idaea* L. at Norman Wells (Hutchinson *et al.*, 1974)), and

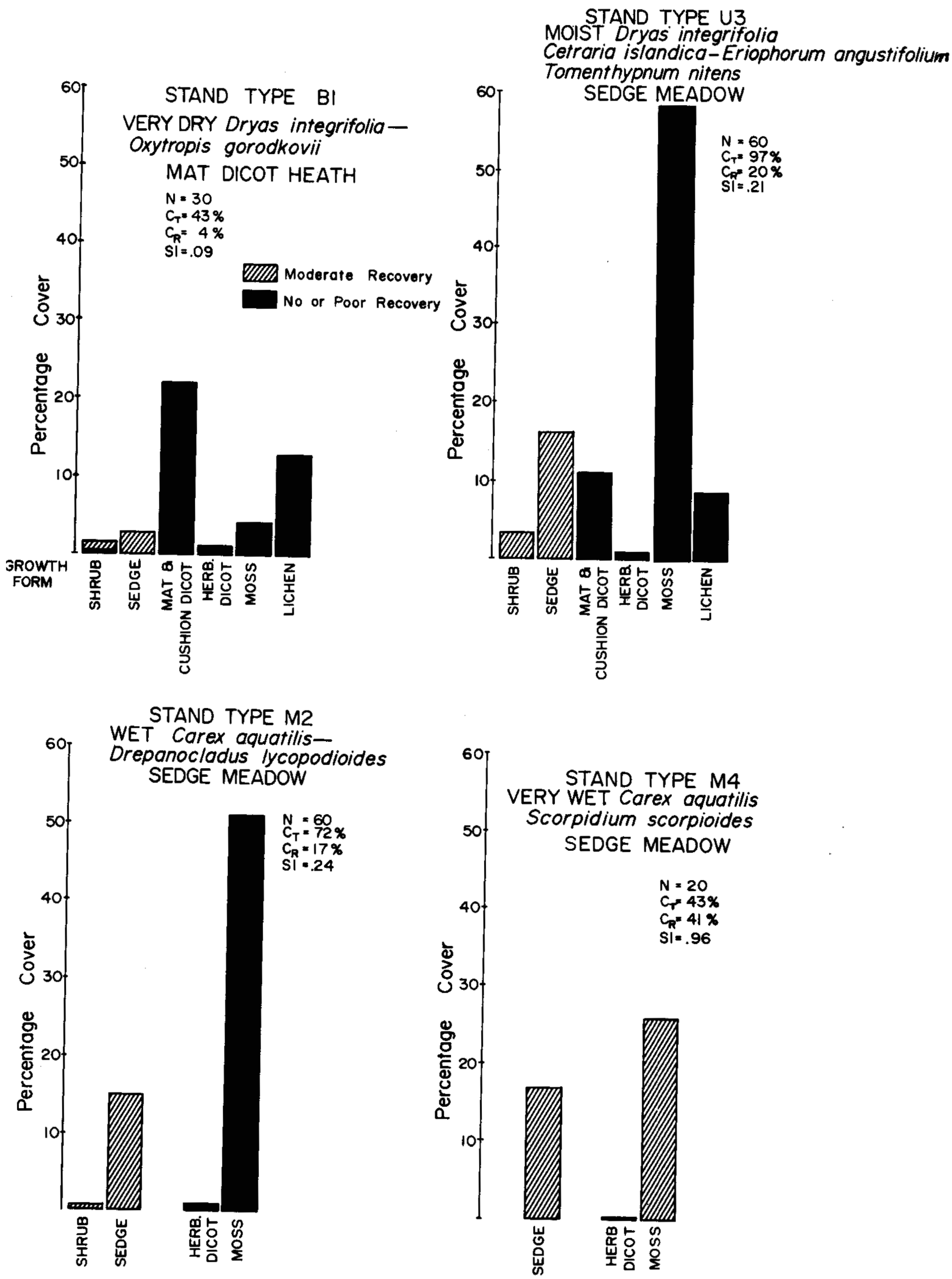

FIG. 3. Cover of six growth forms for four Prudhoe Bay plant communities. The vertical bars are coded black to indicate the percentage cover of the various species which would likely be killed by a crude oil spill of 12 l m^{-2}. intensity. The diagonal hatching indicates the percentage cover of those species which would probably show good recovery. N is the number of sample plots used to characterize the stand types; C_T is the total percentage cover all by species. C_R is the original percentage cover of those species which would show at least moderate recovery one year following the spill. SI is the sensitivity index.

conversely with those species which appear to be dead but which later recover (e.g., mosses at Tuktoyaktuk, Hutchinson and Freedman, 1975). Wein and Bliss (1973) have also noted the different responses for a given species in different communities which they feel are reflections of abiotic properties of the communities. At Prudhoe, *Carex aquatilis* was an example of a species exhibiting varying responses in different microenvironments. In the very wet site the crude oil-treated plants actually appeared healthier, i.e., greener, than plants in the surrounding areas; whereas, oil-treated *Carex aquatilis* in more mesic conditions was noticeably shorter and less vigorous. It appears, however, both from this work and from studies by investigators in other parts of the arctic, that the sedges and willows are the two components of the Prudhoe vegetation which can be expected to show recovery from an oil spill of a magnitude which moderately saturates the soil. This is true for the dry to wet end of the spectrum, but not the very wet sites. In the latter situations where there is standing water to prevent oil from penetrating to the moss canopy or the root zone of the vascular plants, the entire community can be expected to recover.

Recovery potential, as discussed here, is based only on those species already in a community and does not consider plants which would colonize a site from outside the spill area. Such colonization could be important but it is very difficult to predict successional patterns based on the paucity of information and because colonization of oil-killed areas on the Arctic Slope is very slow to occur (Komárková and Webber, 1978). Thus the sensitivity index used here is probably a fair indicator of community's ability to return towards its pre-spill condition.

It should be emphasized that the map derived from this experiment indicates the sensitivity of vegetation to crude oil spills of up to 12 l m^{-2} and under the field conditions existing during the experiment. As McCown *et al.* (1973) have noted, soil moisture is a particularly important parameter to consider, since relatively dry soils allow for deeper penetration of the oil. The test at Prudhoe was conducted during a very dry period, hence the effects are likely to be maximum except in the very wet areas. It should also be stressed that the map pertains only to the vegetation and does not take into account other factors of the biotic environment, such as mammals, birds, and fish, which should be considered in comprehensive oil spill sensitivity maps.

The 1977 Franklin Bluffs Oil Spill – An Applied Example

An 1800 bbl crude oil spill occurred on 20 July 1977, near Franklin Bluffs on terrain similar to that at Prudhoe Bay. The spill created a gradient of oil contamination fanning out from a damaged valve in the Trans-Alaska pipeline. The oil apparently squirted vertically for 35 m at the time of the spill, and a strong north wind created a fan-shaped pattern over the impact area. Figure 5 shows the vegetation map of the oil spill site and a derived sensitivity map which also shows the area of the oil spill. The spill is divided into three impact zones. An area stretching approximately 100 m downwind from the spill source was the most heavily impacted by both the spill itself and the subseqent clean-up operations. The soil was totally saturated and a thick layer of oil lay on most of the surface. Recovery in this area will probably require a major revegetation effort if an attempt is made to do so. Approximately 1400 bbl of oil were removed during the clean-up operations (Dietrick, pers. comm. 1977); all of this was from the area of heavy impact (approximately 0.8 hectares). This left about 400 bbl which was distributed by the wind over about 8.3 hectares. Downwind from the area of severe impact is a middle zone (approximately 1.8 hectares) where the vegetation received a heavy spray. This area is somewhat comparable to the situation at the Prudhoe Bay

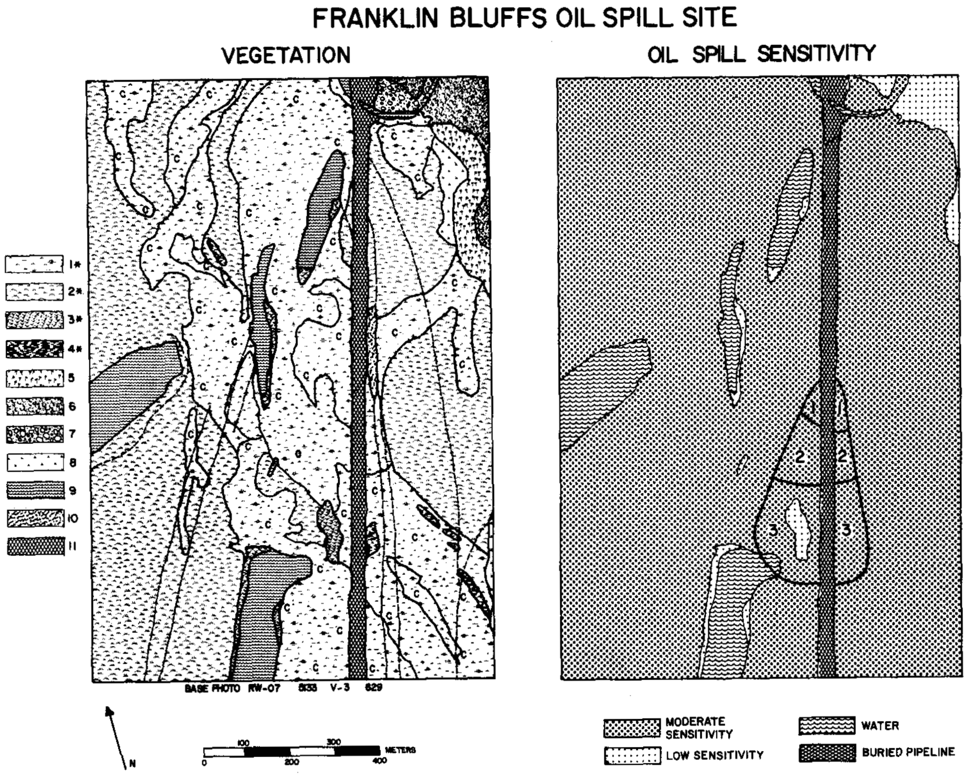

FIG. 4. Franklin Bluffs oil spill site, vegetation and crude oil spill sensitivity maps.

Vegetation map: 1 — WET *Eriophorum angustifolium – Drepanocladus lycopodioides* var. *brevifolius* SEDGE MEADOW (Sensitivity Index = .33); 2 — MOIST *Eriophorum angustifolium – Dryas integrifolia – Salix lanata* ssp. *richardsonii – Tomenthypnum nitens* SEDGE DWARF SHRUB MEADOW (SI = .34); 3 — VERY WET *Arctophila fulva – Scorpidium scorpioides* DEEP GRASS-MARSH (SI = 1.00); 4 — VERY WET *Carex aquatilis – Eriphorum angustifolium* SHALLOW SEDGE-MARSH (SI = 1.00); 5 — MOIST *Salix lanata* ssp. *richardsonii – Carex aquatilis* DWARF SHRUB MEADOW (SI = .29); 6 — DRY *Salix glauca – Arctous alpina* ssp. *alpinus* DWARF SHRUB RIVER TERRACES (SI = .72); 7 — DRY *Salix alaxensis – Astragalus alpinus* ssp. *alpinus* SPARSELY VEGETATED GRAVEL BARS (SI = .27); 8 — DRY *Dryas integrifolia – Arctous alpina* ssp. *rubra* PROSTRATE SHRUB HEATH (SI = .43); 9 — Water; 10 — Disturbed; 11 — Buried pipeline; *Stand types impacted by the 1977 oil spill.

Oil spill sensitivity map: The map shows the area of the oil spill in 1977. The spill is divided into 3 zones, Zone 1 — heavily impacted, soil totally saturated; Zone 2 — heavy spray; Zone 3 — light spray.

experimental spill sites. The intensity of the spill was probably less than 12 l m^{-2}, but the ground cover of mosses and lichens was nonetheless heavily coated with oil. Beyond this middle zone is a third zone (approximately 5.7 hectares) which received only a light spray which was evident mainly on the windward side of plant stems and leaves.

Vegetation mapping of the spill site was begun eight days after the spill (Fig. 4). Sensitivity indices were calculated for all the communities based mainly on the Prudhoe experiment. There were, however, several major species which do not occur at Prudhoe. For example, *Arctous alpina* spp. *rubra* (Rehd. & Wils.) Fern, *Vaccinium uliginosum* L, *Rhododendron lapponicum* (L.) Wahlenb. and *Hedysarum alpinum* ssp. *americanum* Michx. occur on most mesic sites. For some species we could rely on the work of investigators in other parts of the arctic to define ability to recover. For others we based our judgment on plant growth forms. For example, we assumed that all mosses and lichens except for *Polytrichum juniperinum* Hedw. (Wein and Bliss, 1973; Freedman and Hutchinson, 1976) would be killed by a major spill. We assumed the same for most mat, cushion, and herbaceous dicotyledons. Most shrubs, including *Salix glauca* L., *S. lanata* L., *S. alaxensis* Cov., *Rhododendron lapponicum, Arctous alpina* ssp. *rubra,* and *Vaccinium uliginosum,* were assumed to have good ability to recover. All sedges, including *Carex, Eriophorum,* and *Kobresia,* were assumed to have good recovery potential. Grasses, on the other hand, were assumed to have poorer recovery potential. Horsetails (*Hypochaetae variegata* (Schleich.) Bruhin and *Equisetum arvense* L. *variegatum*) form an important component in several of the Franklin communities. At Prudhoe horsetails did not recover from oil, but in studies in otherparts of the arctic (Hutchinson *et al.*, 1974) horsetails in emergent situations have shown good recovery. At Franklin the horsetails occurred mainly in non-emergent situations and were assumed to have poor recovery potential.

It should be emphasized that this oil spill sensitivity map actually applies only to spills of magnitude of 12 l m^{-2}. Probable vegetation recovery is very much affected by the intensity of the spill. Such maps however, are useful for indicating those areas which are relatively more susceptible to oil spill damage.

The Franklin Bluffs observations indicated that dry areas away from the coast may be more resilient than those at the coast since *Arctuous alpina* spp. *rubra* becomes a major component of the vegetation which increases recovery potential of these sites. An implication from moisture-recovery patterns is that if an oil spill is allowed to flow it will tend to flow toward areas with higher recovery potential, that is, toward wetter areas. It may be worth allowing the oil to flow into small lakes rather than taking precautions to protect them from a summer spill. There will be minimum damage to the lacustrine vegetation. Such lakes are also generally without fish. Other components of lake ecosystems also appear to be only temporarily affected (Vestal *et al.*; Jordan and Hobbie; Horowitz *et al.*; Miller *et al.*; O'Brien; Mozley and Butler; all in this volume). The major threat is to waterfowl which could probably be kept off the oil slick by inexpensive compressed air noise-makers. With proper containment, the oil can be more easily skimmed from a lake surface than it can from a terrestrial surface.

CONCLUSIONS

This report has demonstrated that regional crude oil spill sensitivity maps can be derived from a detailed vegetation base map. The major requirements for such a map are community information and information on the oil spill response of at least the major species. Plant growth forms are undoubtedly an important consideration in predicting the response of species, however, more information needs to be gathered before growth form generalities can be reliably used.

The recovery potential of moist and wet sedge meadows which cover a large portion of the Arctic Coastal Plain is considered moderate. The sedges and most shrubs are likely to recover from a large spill whereas the mosses and lichens are likely to be killed. At Prudhoe dry sites dominated by *Dryas integrifolia* and other mat and cushion dicotyledons are very sensitive to spill contamination. On the other hand, emergent communities are very resilient.

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REFERENCES

BROWN, J. (ed.), 1975. *Ecological Investigations of the Tundra Biome in the Prudhoe Bay Region, Alaska.* Biological Papers of the University of Alaska, Special Report Number 2.

CRUM, H. A., W. C. STEERE, and L. E. ANDERSON, 1973.A new list of mosses of North America north of Mexico. *The Bryologist.* 76(1): 85-130.

DENEKE, F. J., B. H. McCOWN, P. I. COYNE, W. RICKARD, and J. BROWN. 1975. Biological aspects of terrestrial oil spills, USA CRREL oil research in Alaska, 1970-1974. USA CRREL Research Report 346. 66pp.

DIETRICK, L. 1977. Personal communication, letter to J. Brown dated October 25, 1977.

EVERETT, K. R. 1978. Effects of oil on the physical and chemcial characteristics of wet tundra soils. *Arctic* (this volume).

——, D. A. WALKER, P. J. WEBBER, J. BROWN, and R. J. PARKINSON. (in preparation). Distribution, characterization, and maps of the landforms, soils and vegetation of the Prudhoe Bay, Alaska, region. USA CRREL Report.

——, P. J. WEBBER, D. A. WALKER, R. J. PARKINSON, and J. BROWN (in press). A geoecological mapping scheme for Alaskan coastal tundra. Third International Permafrost Conference to be held in Edmonton, Alberta, Canada, July 1978. National Research Council of Canada: 234-365.

FREEDMAN, W. and T. C. HUTCHINSON. 1976. Physical and biological effects of experimental crude oil spills on Low Arctic tundra in the vicinty of Tuktoyaktuk, N.W.T., Canada. *Canadian Journal of Botany.* 54: 2219-2230.

HALE, M. E. and W. L. CULBERSON. 1970. A fourth checklist of the lichens of the continental United States and Canada. *The Bryologist,* 73(3): 499-543.

HOROWITZ, A., A. SEXSTONE, and R. ATLAS. 1978. Hydrocarbons and microbial activities in sediment of an arctic lake 1 year after contamination with leaded gasoline. *Arctic* (this volume).

HUNT, P. G., W. E. RICKARD, F. J. DENEKE and R. P. MURRMAN. 1973. Terrestrial oil spills in Alaska: environmental facts and recovery. *In* Prevention and control of oil spills, *Amer. Petroleum Inst.,* Washington, D.C., pp. 733-740.

HUTCHINSON, T. C. and W. FREEDMAN. 1975. The impact of crude oil spills on arctic and sub-arctic vegetation. *In* Proceedings of the Circumpolar Conference on Northern Ecology, 15-18 Sept. 1975, Ottawa, Canada, pp. 177-182.

——, J. A. HELLEBUST and M. TELFORD. 1974. Oil spill effects on vegetation and soil microfauna at Norman Wells and Tuktoyaktuk, N.W.T. Environ.-Soc. Comm. North. Pipelines. Task Force North. Oil Develop. *Information Canada,* Ottawa, Ontario.

JORDAN, M. and J. HOBBIE. 1978. Response of microbial populations to petroleum hydrocarbons in an arctic lake. *Arctic* (this volume).

KOMÁRKOVÁ, V. and P. J. WEBBER. 1978. Geobotanical investigations. *In* Tundra disturbances and recovery following 1949 drilling, Fish Creek, Alaska. *USA CRREL Special Report* (in Press).

LINKINS, A. E. and R. K. ANTIBUS. 1978. Ectomycorrhizal fungi of *Salix rotundifolia. Arctic* (this volume).

McCOWN, B. H., J. BROWN and R. J. BARSDATE. 1973a. Natural oil seeps at Cape Simpson, Alaska: localized influences on terrestrial habitat. *In* Proceedings, Symposium on the Impact of Oil Resource Development on Northern Life No. 1, University of Alaska, pp. 86-90.

——, F. J. DENEKE, W. RICKARD and L. L. TIESZEN. 1973b. The response of Alaskan terrestrial plant communities to the presence of petroleum. *In* Proceedings, Symposium on the Impact of Oil Resource Development on Northern Life No. 1, University of Alaska, pp. 34-43.

McCOWN, D. D. and F. J. DENEKE. 1973. Plant germination and seedling growth as affected by the presence of crude petroleum. *In* Proceedings, Symposium on the Impact of Oil Resource Development on Northern Life No. 1, University of Alaska, pp. 44-51.

McFADDEN, T., T. JENKINS, C. COLLINS, L. JOHNSON, B. McCOWN and E. SPARROW. 1977. Fate and effects of crude oil spilled on permafrost terrain, second annual progress report June 1976 to July 1977. *USA CRREL Special Report 77-44. 48pp.*

McKENDRICK, J. D. and W. W. MITCHELL. 1978a. Effects of burning crude oil spilled on six habitat types in Alaska. *Arctic* (this volume).

—— and ——. 1978b. Fertilization hastens recovery of oil-damaged arctic tundra, Prudhoe Bay, Alaska. *Arctic* (this volume).

MILLER, M., V. ALEXANDER and R. BARSDATE. 1978. Effects of oil on phytoplankton in lakes and ponds. *Arctic* (this volume).

MOZLEY, S. and M. BUTLER. 1978. Effects of crude oil on aquatic insects of tundra ponds. *Arctic* (this volume).

O'BRIEN, J. 1978. Effects of crude oil on zooplankton in arctic ponds. *Arctic* (this volume).

VESTAL, J. R., P. BERGESTIN, T. GEISBUHLE and N. GARG. 1978. Effects of crude oil on the microflora of arctic lakes and ponds. *Arctic* (this volume).

WALKER, D. A., P. J. WEBBER, K. R. EVERETT and J. BROWN. 1977. The effects of low-pressure wheeled vehicles on plant communities and soils at Prudhoe Bay, Alaska. *USA CRREL Special Report 77-17.* 49 pp.

WEBBER, P. J. and D. A. WALKER. 1975. Vegetation and landscape analysis at Prudhoe Bay, Alaska: a vegetation map of the Tundra Biome study area. *In* Ecological Investigations of the Tundra Biome in the Prudhoe Bay Region, Alaska (J. Brown, Ed.). *Biological Papers of the University of Alaska,* Special Report Number 2, pp. 81-91.

WEIN, R. W. and L. C. BLISS. 1973. Experimental crude oil spills on Arctic plant communities. *Journal of Applied Ecology.* 10:671-682.