

Effects of Experimental Releases of Oil and Dispersed Oil on Arctic Nearshore Macrobenthos. III. Macroalgae

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ABSTRACT. An experimental subsurface release of chemically dispersed oil at Cape Hatt, northern Baffin Island, resulted in short-term relatively high oil concentrations in the waters of two adjacent bays. Untreated oil released onto the surface of the third bay could not be detected in the water below a depth of 1 m. Both releases, however, resulted in measurable contamination of sediments in shallow water.

Macroalgae at 3 m depth were sampled by a diver-operated airlift sampler in three treatment bays and in a fourth (reference) bay during the open water seasons of 1980-83 (two pre-spill and four post-spill sampling periods). Biomass, number of species and reproductive condition of the dominant understory algae at 3 m depth did not seem to be adversely affected either by oil in subtidal sediments or by chemically dispersed oil in the water column. No oil effects were detected in data on the biomasses of total algae or of two of the three species analyzed (*Stictyosiphon tortilis* and *Pilayella littoralis*). In the third species, *Dictyosiphon foeniculaceus*, growth increased in the year following the oil release, either stimulated by low levels of oil in sediments or through natural annual variability. The lack of major effects on macroalgae may have been partly attributable to the lack of effects on herbivores and the vegetative mode of reproduction in the dominant macroalgal species.

Key words: arctic macroalgae, oil effects, dispersed oil effects, experimental oil releases, Baffin Island, macrobenthos, *Stictyosiphon tortilis*, *Pilayella littoralis*, *Dictyosiphon foeniculaceus*

RÉSUMÉ. Un déversement expérimental de pétrole chimiquement dispersé sous la surface au cap Hatt (au nord l'île Baffin), a amené à court terme des concentrations de pétrole relativement élevées dans les eaux de deux baies adjacentes. Le pétrole non traité déversé à la surface de la troisième baie n'a pu être détecté dans l'eau à une profondeur supérieure à 1 m. Les deux déversements cependant ont causé une pollution mesurable des sédiments en eau peu profonde. Durant les saisons d'eau libre de 1980 à 1983, lors de deux périodes d'échantillonnage antérieures et quatre postérieures au déversement de pétrole, on a testé des macro-algues poussant à 3 m de profondeur, grâce à un appareil d'échantillonnage à air comprimé, à remontée automatique, opéré par un plongeur. Ni le pétrole dans les sédiments sous la marée, ni le pétrole chimiquement dispersé dans la colonne d'eau n'ont semblé avoir un effet négatif sur la biomasse, sur le nombre d'espèces et sur les conditions de reproduction des algues dominantes de la couche de fond à 3 m. On n'a pas détecté d'effets dus au pétrole dans les données sur les biomasses de toutes les algues ou de deux des trois espèces analysées (*Stictyosiphon tortilis* et *Pilayella littoralis*). Dans le cas de la troisième espèce, *Dictyosiphon foeniculaceus*, la croissance a augmenté durant l'année suivant le déversement de pétrole, soit qu'elle ait été stimulée par de faibles niveaux de pétrole dans les sédiments, soit qu'elle ait résulté de la variabilité annuelle naturelle. On peut attribuer l'absence d'effets majeurs sur les macro-algues à l'absence d'effets sur les herbivores et au mode végétatif de reproduction chez les espèces de macro-algues dominantes.

Mots clés: macro-algues arctiques, effets dus au pétrole, effets dus au pétrole dispersé, déversements expérimentaux de pétrole, île Baffin, macrobenthos, *Stictyosiphon tortilis*, *Pilayella littoralis*, *Dictyosiphon foeniculaceus*

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INTRODUCTION

In a recent appraisal of the fate and effects of oil and dispersants in Canadian marine environments (Sprague *et al.*, 1981, 1982), several major data gaps were identified. These included the fate and effects of dispersants in general, the fate and effects of oil in the Arctic and knowledge of natural processes in the marine environment, particularly in the Arctic. In spite of early recommendations that field studies of oil effects be carried out (e.g., Moore and Dwyer, 1974; National Academy of Sciences, 1975), experimental field studies are still needed (Teal and Howarth, 1984).

The papers in this volume report results of the Baffin Island Oil Spill (BIOS) Project. The BIOS Project assessed the use of chemical dispersants on an oil slick in arctic nearshore waters by comparing the fate and effects of dispersed oil with those resulting from the option of allowing the untreated oil slick to contact the beach and be removed by natural processes. The effectiveness of various shoreline cleanup techniques was also evaluated in separate study areas. Sergy and Blackall (1987) summarize the rationale, design and overall results of the BIOS Project.

This paper describes effects of experimental oil releases on macroalgae, one component of the subtidal macrobenthos.

Effects on epibenthos and relatively immobile infauna are reported elsewhere in this volume (Cross *et al.*, 1987; Cross and Thomson, 1987), and a general description of subtidal communities in the study area is given in Snow *et al.* (1987).

The benthic marine algae of the North American Arctic have been studied intermittently since the early 19th century, but early reports consisted of little more than species lists (see review by Wilce, 1959). Recently, floristic and ecological studies have been performed in Labrador and Ungava Bay (Wilce, 1959), West Greenland (Wilce, 1964), Prince Patrick Island (Lee, 1966), Pangnirtung Fiord (Kent, 1972) and in several areas in the northern and southwestern Canadian Arctic (Lee, 1980). These studies have shown that macrophytic algae are a common feature of arctic and subarctic nearshore waters, both on exposed rocky coasts and on soft bottoms. In the latter case, the algae either are loose lying or are attached to mud, small rocks, shells and polychaete tubes (Lee, 1966; Lee, 1973, 1980). These floristic studies have provided much valuable information on species composition, zonation and reproduction of littoral and sublittoral macrophytes in high latitudes. Quantitative studies of the distribution of kelp and conspicuous understory algae have been carried out at several locations in the Lancaster Sound area (Thomson and Cross, 1980), in Foxe Basin (Chapman and Lindley, 1981) and in the Alaskan Beaufort Sea (Dunton *et al.*, 1982; Busdosh *et al.*, 1985). To date,

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combined floristic/biomass studies of benthic macroalgae have not been reported for the Canadian Arctic.

Macrophytic algae are important in arctic nearshore waters because they contribute substantially to the total primary productivity of nearshore areas (Dunton *et al.*, 1982) and because they provide habitats for a large number of invertebrates and fish, leading to greater faunal diversity and abundance (Mohr *et al.*, 1957; Busdosh *et al.*, 1985). Macroalgal production and standing crops are generally much lower in the Arctic than in temperate waters, largely because the growing season is much shorter. Moreover, only a small portion of macrophyte production is consumed directly by herbivores in the Arctic (Dunton *et al.*, 1982). Most macroalgal biomass probably enters detrital food webs as fragments and dissolved organic matter, as in temperate waters (Mann, 1973).

The overall effects of oil on macroalgal communities have not been studied in the Arctic, but Hsiao *et al.* (1978) determined that *in situ* primary production in two macroalgal species in the Beaufort Sea was significantly inhibited by all types and concentrations (3-147 ppm) of oil tested. In other latitudes, studies of oil spills with and without chemical dispersants have demonstrated changes in the abundance of macrophytic algae (see National Academy of Sciences, 1975:Table 4-1), but most have concerned intertidal species directly coated by oil. Conflicting results have been reported, ranging from widespread mortality following the *Torrey Canyon* spill (Bellamy *et al.*, 1967) and disappearance or reduction in vertical distribution of *Fucus* spp. following the *Arrow* spill (Thomas, 1977) to no measurable effect on *Fucus vesiculosus* following the *Tsesis* spill (Linden *et al.*, 1979; Teal and Howarth, 1984). The *Amoco Cadiz* spill caused a variety of effects on intertidal algae, including mortality of some species and replacement by others (Floc'h and Diouris, 1980; Gundlach *et al.*, 1981); no evidence of necrosis, abnormal mortality or infertility in fucoid species (Maurin, 1984); and increases in vertical distribution, possibly because of herbivore mortality (Floc'h and Diouris, 1980).

In contrast, few data are available concerning effects of oil spills on subtidal algae. Conan (1982) reported that there was no evidence of a severe direct impact of the *Amoco Cadiz* spill on any subtidal algal species. Maurin (1984) suggested that a density increase in *Laminaria digitata* shortly after the *Amoco Cadiz* spill was related to herbivore mortality and that increased growth in the following year was attributable to eutrophication caused by enrichment by organic matter.

METHODS

Study design and methods are described in Snow *et al.* (1987). Only a brief summary is given here. A discussion of possible sources of error is also given in Snow *et al.* (1987).

Four shallow embayments at Cape Hatt, northern Baffin Island, were selected as experimental bays (Fig. 1). During August 1981, approximately 15 m³ of Lagomedio crude oil was applied to the surface of one bay (Bay 11), and 15 m³ of dispersed oil (10 Lagomedio:1 Corexit 9527) was released underwater in another bay (Bay 9). The oil in both cases had been artificially weathered to remove 8% by volume. Surface oil in Bay 11 did not penetrate below 1 m depth in the 30 h following the release. The dispersed oil release, on the other hand, resulted in a severe exposure to benthos at 3 and 7 m depths in Bay 9, a lower and more realistic exposure in the third study bay (Bay 10) and very light exposure in the fourth

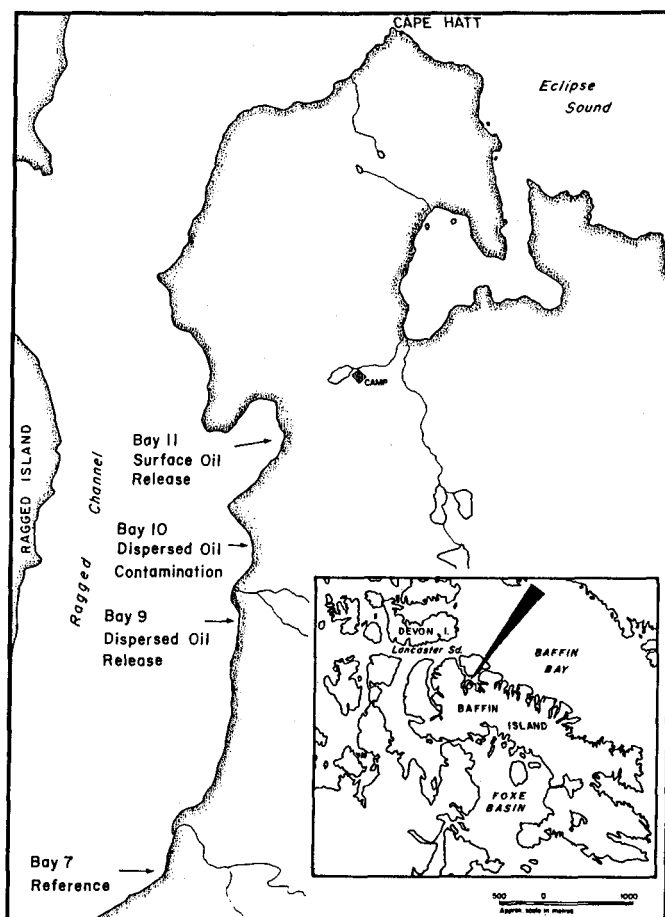


FIG. 1. BIOS site at Cape Hatt, northern Baffin Island (72°27'N, 79°51'W), showing the locations of study bays and oil treatments applied in August 1981.

(reference) bay (Bay 7). Details of the oil releases and of oil concentrations during the releases are given in Dickins *et al.* (1987) and in Humphrey *et al.* (1987) respectively.

Sampling of macroalgae was carried out in these bays during each of the two ice-free months (August and September) between September 1980 and August 1983; two of these six sampling periods (September 1980 and August 1981) preceded the experimental oil releases.

Three contiguous 50 m transects parallel to the shoreline were sampled at each of two depths (3 m, 7 m) in each of the four bays during five or six sampling periods. On each transect during each sampling period, eight randomly located replicate samples, each covering 0.0625 m², were collected using a diver-operated airlift fitted with a 1 mm mesh collecting bag (i.e., 5 or 6 periods × 4 bays × 2 depths × 3 transects × 8 replicates). In each bay, additional hand collections were made by divers. During 1983, observations on the reproductive status of algae were made by RTW in each of the study bays.

Algae and detritus were sorted from the airlift samples using flotation and decantation with water and hand sorting under binocular microscopes to separate animals from algae and detritus. Only samples from the 3 m depth were analyzed in detail. Large and conspicuous algal species were sorted from each sample and weighed. A subsample of approximately 2 g wet weight was separated from the balance of the sample and sorted completely into six categories: *Stictyosiphon tortilis*,

Dictyosiphon foeniculaceus, *Sphacelaria* spp., a mixture of *Pilayella littoralis* and tubular diatoms, other species and detritus (non-algal material). RTW examined each of these categories from each subsample in order to (1) check for adequate separation, (2) make a list of the species present in the "other" category and (3) make observations on the reproductive status of the plants. An appropriate subsample factor was then applied to extrapolate these results to the unsorted portion of the sample. Formalin wet weights were determined by rinsing in water, removing water by vacuum filtration and weighing immediately to the nearest mg.

To determine whether oil had an effect, temporal changes in biomass of macroalgae in the four bays were compared using three-factor (periods, bays and transects) fixed-effects analysis of variance (ANOVA), with transects nested within periods and bays. In statistical terms, a significant interaction between bay and period effects indicated a possible oil effect (Green, 1979; see also Snow *et al.*, 1987). Because of the nested design, the among-transects term rather than the residual error term was used to test the significance of main effects (periods, bays) and of the interaction between the main effects. When interaction terms involving transects were non-significant ($P > 0.05$), they were pooled with the transect term before testing for main effects. When interactions involving transects were significant ($P \leq 0.05$), they were not pooled with the transect term, which was used alone as the denominator in the tests.

All biomass data were log-transformed ($\log [x + 1]$) prior to analysis in order to reduce the skewness inherent in such data. Data on number of species in each sample were not transformed, as the data were normally distributed (BMDP 2D; Dixon, 1981). ANOVA was applied to five variables: the biomasses of the three dominant species (*Stictyosiphon tortilis*, *Dictyosiphon foeniculaceus*, and *Pilayella littoralis*), total algal biomass and the number of species observed in each sample. ANOVA was performed by the GLM procedure of the SAS computer program package (Helwig and Council, 1979; Freund and Littell, 1981).

The design of the experiment was unbalanced because there were no data from one bay (Bay 7) in the first pre-spill sampling period or from another bay (Bay 10) in the last post-spill sampling period. The unbalanced design necessitated the use of three different analytical procedures including three different combinations of bays and sampling periods (see Snow *et al.*, 1987), as results of a single analysis with two missing cells would have been ambiguous. In most parts of this paper, the results of only one analysis type are presented — the analysis including data from all four bays and excluding data from 1980 and 1983. However, when an oil effect was indicated only in one or both of the other types of analysis, this fact is mentioned.

RESULTS

These results are based on the "optimal impact study design" of Green (1979:70), in which the evidence for impact effects is a significant area-by-times interaction. Such an interaction would occur when temporal change in benthos was inconsistent among the study bays, each of which received a different oil treatment. Under the present study design, for such change to be considered significant in both statistical and practical terms, it would have to be large relative to variability within the bays. Within-bay variation included both variability among the transects (the "transect" term) and temporal variability that was not consistent among the transects (the "period-by-transect" term).

Significant periods-by-bays interaction terms could arise because of (1) actual effects of oil, (2) some other temporal change in only some bays or (3) type I errors in statistical inference (such errors are expected when a large number of tests are done). The third possibility is discussed for this study in Snow *et al.* (1987), and the second is treated in general by Hurlbert (1984). Because the experimental oil releases were carried out in the field, it was not possible to randomly allocate oil treatments to replicate samples, nor was it practical to replicate oil treatments (i.e., to release oil in the same manner in two or more bays). Hence, we are guilty of "pseudoreplication" as defined by Hurlbert (1984), and it is not possible to reach unequivocal conclusions on the effects of oil. To reduce the possibility of committing type I errors or of confounding oil effects with natural changes that were inconsistent among bays, the nature of each significant interaction was examined in relation to the type of oil treatment (surface vs. dispersed) and the concentrations of oil, both in the water during and immediately after the oil releases and in the subtidal sediments during 1981-83. Only if change in the benthos corresponded with change in oil concentrations was it concluded that a probable oil effect had occurred.

Community Description

A total of 60 species of benthic algae was collected in the study bays at Cape Hatt (Table 1). In any one bay and sampling period, numbers of species collected in airlift samples were considerably lower, ranging from 22 to 40 (Table 2).

Near 3 m depth: In each of the study bays, four horizontal bands of sublittoral vegetation were evident, each dominated by one or two macroalgal species. Just shoreward from the 3 m transects, *Fucus distichus evanescens* was abundant, growing on rocks and boulders scattered on the predominantly sand substrate. At 3-4 m, *F. distichus evanescens* was gradually replaced by a zone with a relatively even and nearly complete cover of algae that consisted primarily of loose-lying brown algae. The 3 m transect lines were within this zone, and this community is the only one for which quantitative data and analyses are given in the present study.

The dominant algal species at 3 m depth in the study bays were *Stictyosiphon tortilis*, *Pilayella littoralis* and *Dictyosiphon foeniculaceus*. These species, together with the tubular colonial diatom *Berkeleya rutilans*, constituted 76.1% of total macroalgal biomass when all bays and sampling periods were combined. Virtually all of this biomass was loose lying, and the component species formed the lower algal stratum — the understory vegetation. The understory vegetation also included *Sphacelaria* spp. (primarily *S. arctica* and *S. plumosa*), *Chaetomorpha linum* and *C. melagonium*, which together constituted 5.6% of macroalgal biomass, and a number of other species not weighed separately (2.1% of biomass).

The dominant canopy species at 3 m depth were *Neodilsea integra* (4.8% of total biomass), *Fucus distichus evanescens* (4.0%), *Laminaria* spp. (3.8%) and *Chorda* spp. (0.6%). Other less abundant canopy species were *Devaleraea ramentaceum*, *Rhodomela confervoides*, *Punctaria glacialis* and *Desmarestia* spp., which together made up less than 3% of macroalgal biomass.

Deeper than 3 m: With increasing depth and distance from shore, there was a kelp zone. It was dominated by *Laminaria saccharina* and also included *L. solidungula*, *L. longicruris* and

TABLE I. Species of benthic algae collected in four bays at Cape Hatt, northern Baffin Island, during August and September 1980-83

Species and authority	
Chlorophyceae	
<i>Ulothrix flacca</i> (Dilwyn) Thuret in LeJolis	<i>Agarum cribrosum</i> (Mertens) Bory
<i>Blidingia minima</i> (Nageli ex Kützing) Kylin	<i>Laminaria saccharina</i> (L.) Lamouroux
<i>Chlorochytrium schmitzii</i> Rosenvinge	<i>Laminaria solidungula</i> J. Agardh
<i>Chlorochytrium dermatocolax</i> Reinke	<i>Laminaria longicruris</i> Pyl.
<i>Spongomorpha sonderi</i> Kützing	<i>Haplospora globosa</i> Kjellman
<i>Spongomorpha</i> sp.	<i>Sphacelaria plumosa</i> Lyngbye
<i>Chaetomorpha linum</i> (O.F. Müller) Kützing	<i>Sphacelaria arctica</i> Harvey
<i>Chaetomorpha melagonium</i> (Weber et Mohr) Kützing	<i>Sphacelaria caespitula</i> Lyngbye
	<i>Fucus distichus</i> L. subsp. <i>evanescens</i> (C. Ag.) Powell
Phaeophyceae	
<i>Pilayella macrocarpa</i> Foslie	Rhodophyceae
<i>Pilayella littoralis</i> (L.) Kjellman	<i>Audouinella purpurea</i> (Lightfoot) Woelkerling
<i>Giffordia ovata</i> (Kjellman) Kylin	<i>Audouinella</i> sp.
<i>Pseudolithoderma</i> sp.	<i>Ahnfeltia plicata</i> (Hudson) Fries
<i>Myriactula lubrica</i> (Rupr.) Jaasund	<i>Neodilsea integra</i> (Kjellman) A. Zinova
<i>Symphycarpus strangulans</i> Rosenvinge	<i>Devaleraea rametaceum</i> (L.) Guiry
<i>Eudesme virescens</i> (Carmichael) J. Agardh	<i>Palmaria palmata</i> (L.) O. Kuntze
<i>Phaeostroma pustulosum</i> Kuckuck	<i>Polysiphonia arctica</i> J. Agardh
<i>Phaeostroma parasiticum</i> Børgesen	<i>Rhodomela confervoides</i> (Hudson) Silva
<i>Phaeostroma</i> sp.	<i>Phyllophora truncata</i> (Pallas) A. Zinova
<i>Elachistea lubrica</i> Ruprecht	<i>Ptilota serrata</i> Kützing
<i>Stictyosiphon tortilis</i> (Ruprecht) Reinke	<i>Odonthalia dentata</i> (L.) Lyngbye
<i>Platysiphon verticillatus</i> Wilce	<i>Harveyella mirabilis</i> (Reinsch) Reinke
<i>Omphalophyllum ulvaceum</i> Rosenvinge	<i>Halosaccicolax kjellmanii</i> S. Lund
<i>Chordaria flagelliformis</i> (O.F. Müller) C. Agardh	<i>Pantoneura baerii</i> (Postels et Ruprecht) Kylin
<i>Delamarea attenuata</i> (Kjellman) Rosenvinge	<i>Antithamnion boreale</i> (Gobi) Kjellman
<i>Dictyosiphon foeniculaceus</i> (Hudson) Greville	Chrysophyceae
<i>Coelocladia arctica</i> Rosenvinge	<i>Phaeosaccion collinsii</i> Farlow
<i>Desmarestia aculeata</i> (L.) Lamouroux	<i>Berkeleya rutilans</i> (Trent.) Ep.
<i>Desmarestia viridis</i> (O.F. Müller) Lamouroux	<i>Navicula ramosissima</i> (Agardh) Cleve
<i>Punctaria glacialis</i> Rosenvinge	<i>Nitzschia</i> sp.
<i>Chorda filum</i> (Linnaeus) Lamouroux	<i>Coscinodiscus</i> sp.
<i>Chorda tomentosa</i> Lyngbye	

TABLE 2. Species numbers of macrophytic algae at 3 m depth in four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983^a

Period	Bay 7 Reference	Bay 9 Dispersed oil release	Bay 10 Dispersed oil contamination	Bay 11 Surface oil release
Sep 80 (Pre-spill 1)	—	16.1 ± 2.5 (32)	14.4 ± 2.1 (29)	13.5 ± 2.2 (28)
Aug 81 (Pre-spill 2)	15.9 ± 2.1 (30)	13.8 ± 2.9 (31)	15.5 ± 4.2 (35)	13.0 ± 2.7 (30)
Sep 81 (Post-spill 1)	17.0 ± 2.2 (38)	14.9 ± 3.2 (29)	16.1 ± 3.6 (34)	14.0 ± 2.0 (22)
Aug 82 (Post-spill 2)	17.3 ± 2.2 (32)	15.0 ± 2.8 (31)	17.9 ± 2.0 (37)	14.8 ± 2.4 (32)
Sep 82 (Post-spill 3)	16.9 ± 1.9 (37)	17.6 ± 1.7 (38)	18.6 ± 2.7 (40)	13.7 ± 2.1 (30)
Aug 83 (Post-spill 4)	16.7 ± 2.0 (35)	16.3 ± 1.5 (32)	—	15.7 ± 2.3 (33)

^aSpecies numbers expressed as mean ± SD number of species per sample; total number of species collected given in parentheses. In each bay and period there were 19-24 airlift samples, each covering 0.0625m².

Alaria esculenta. These large kelps were generally attached to small rocks or bivalve shells. In Bays 10 and 11, densities of kelp within this zone were high to depths of 3-5 m, and *Laminaria* spp. were present to a depth of 7 m. The width of the *Laminaria* zone was greatest in Bay 11, where the slope of the bottom was considerably less than in any other bay. In Bays 7 and 9, *Laminaria* spp. were much less abundant at 3-5 m, and kelps of any kind were relatively rare at depths >5 m.

A second kelp zone dominated by *Agarum cribrosum* occurred at depths >5 m, where *A. cribrosum* and *Laminaria* spp. were attached to sparsely distributed boulders and large rocks. *Agarum cribrosum* occurred to depths of at least 30 m in the study area (N. Snow, pers. comm. 1981). Many of the understory species present at 3 m also occurred at 7 m depth, but substrate cover was considerably less; Cross and Thomson (1981) estimated

that percent cover of these algae was 68-90% at 3 m and 2-12% at 7 m depth. The large brown algae *Desmarestia aculeata* and *D. viridis* were also conspicuous along the deeper transects.

Biomass

Mean biomass of total macroalgae at 3 m depth was 74.7-1032.6 g·m⁻², depending on bay and period (Table 3). Understory species tended to be more evenly distributed among bays than were the larger canopy species. Of the latter, *Neodilsea integra* was present in all bays but rarest in Bay 9, *Laminaria* spp. were rare in Bays 7 and 9 and *Punctaria glacialis* and *Chorda* spp. were absent or rare in Bay 11 (Table 3). Because of the relatively even distributions of understory algae and the dominance of the three understory species *Stictyosiphon tortilis*,

Pilayella littoralis and *Dictyosiphon foeniculaceus*, detailed analysis was restricted to the biomasses of total algae and of these three species.

Most biomass variables differed significantly among tran-

sects within bays (Table 4). This indicates that there was considerable patchiness on a small (50 m) scale. Bay and period effects were sometimes confounded by significant period-by-bay interactions. Where interpretation of main effects was

TABLE 3. Mean biomass of all macroalgae and of the ten most abundant groups or species of macroalgae at 3 m depth in four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983^a

Species or group	Period ^b	Bay 7	Bay 9	Bay 10	Bay 11
<i>Stictyosiphon tortilis</i>	Pre-spill 1	—	60.83 ± 65.38	218.97 ± 177.62	145.67 ± 129.85
	Pre-spill 2	57.46 ± 40.08	42.04 ± 80.01	29.08 ± 34.40	328.89 ± 617.33
	Post-spill 1	43.69 ± 36.05	47.17 ± 82.31	38.52 ± 43.34	597.57 ± 1143.92
	Post-spill 2	142.16 ± 129.54	46.30 ± 79.21	214.03 ± 260.63	353.88 ± 391.35
	Post-spill 3	119.95 ± 121.55	40.58 ± 57.39	225.22 ± 351.58	779.54 ± 1284.41
	Post-spill 4	409.92 ± 353.20	190.67 ± 274.07	—	574.05 ± 379.02
<i>Pilayella littoralis</i> + <i>Berkeleya rutilans</i>	Pre-spill 1	—	118.38 ± 56.19	231.10 ± 262.59	115.05 ± 149.53
	Pre-spill 2	60.83 ± 34.89	32.82 ± 28.14	41.24 ± 40.32	89.84 ± 131.67
	Post-spill 1	65.94 ± 57.87	48.80 ± 39.22	44.50 ± 50.57	194.52 ± 305.28
	Post-spill 2	44.24 ± 40.56	18.27 ± 23.64	81.88 ± 88.45	135.29 ± 184.34
	Post-spill 3	43.60 ± 52.01	30.73 ± 22.04	95.81 ± 90.37	93.97 ± 129.01
	Post-spill 4	46.03 ± 40.17	9.09 ± 13.81	—	141.57 ± 190.85
<i>Dictyosiphon foeniculaceus</i>	Pre-spill 1	—	66.63 ± 117.28	183.42 ± 183.06	2.86 ± 6.83
	Pre-spill 2	2.57 ± 2.51	15.13 ± 24.89	7.43 ± 8.18	0.87 ± 1.82
	Post-spill 1	4.46 ± 4.25	20.49 ± 32.45	15.17 ± 21.21	0.43 ± 0.67
	Post-spill 2	143.18 ± 159.71	7.20 ± 6.59	289.75 ± 345.68	5.25 ± 10.33
	Post-spill 3	161.39 ± 170.93	33.76 ± 31.86	184.70 ± 173.71	1.42 ± 2.43
	Post-spill 4	48.72 ± 34.67	13.43 ± 17.38	—	1.14 ± 3.02
<i>Neodilsea integra</i>	Pre-spill 1	—	0.01 ± 0.05	30.73 ± 97.71	0.18 ± 0.49
	Pre-spill 2	17.40 ± 44.40	<0.01	58.81 ± 160.10	1.46 ± 5.34
	Post-spill 1	13.85 ± 39.46	0	106.29 ± 254.24	1.32 ± 3.40
	Post-spill 2	36.24 ± 102.58	<0.01	32.10 ± 50.69	2.77 ± 6.10
	Post-spill 3	21.65 ± 43.93	<0.01	73.92 ± 162.83	0
	Post-spill 4	63.64 ± 106.02	0.18 ± 0.36	—	8.28 ± 39.24
<i>Fucus distichus</i>	Pre-spill 1	—	1.29 ± 2.82	8.34 ± 18.11	44.12 ± 91.82
	Pre-spill 2	8.31 ± 33.52	0.21 ± 0.95	8.37 ± 37.92	14.65 ± 25.52
	Post-spill 1	0.55 ± 1.47	0.81 ± 1.80	15.46 ± 50.46	38.29 ± 85.82
	Post-spill 2	8.81 ± 18.34	0.30 ± 0.54	25.48 ± 86.65	12.75 ± 31.92
	Post-spill 3	8.05 ± 32.84	4.61 ± 18.30	119.26 ± 241.02	10.54 ± 35.19
	Post-spill 4	7.40 ± 14.09	23.13 ± 68.94	—	39.98 ± 104.06
<i>Laminaria</i> spp. ^c	Pre-spill 1	—	2.44 ± 11.09	5.54 ± 19.29	1.22 ± 3.30
	Pre-spill 2	1.04 ± 4.39	0.08 ± 0.32	19.15 ± 36.00	7.21 ± 23.99
	Post-spill 1	<0.01	0.01 ± 0.07	65.43 ± 128.87	12.81 ± 21.68
	Post-spill 2	0.41 ± 0.91	0.01 ± 0.03	47.04 ± 64.14	33.07 ± 77.62
	Post-spill 3	0.20 ± 0.86	0	119.22 ± 239.50	17.23 ± 44.06
	Post-spill 4	2.03 ± 9.48	0.01 ± 0.03	—	39.39 ± 113.62
<i>Sphacelaria</i> spp. ^c	Pre-spill 1	—	1.16 ± 1.36	50.66 ± 72.37	14.92 ± 24.32
	Pre-spill 2	1.08 ± 1.12	0.39 ± 0.54	13.96 ± 17.18	5.19 ± 7.44
	Post-spill 1	1.03 ± 1.24	0.65 ± 0.73	8.92 ± 14.83	16.50 ± 29.83
	Post-spill 2	3.04 ± 3.96	0.59 ± 1.18	38.22 ± 44.95	33.48 ± 53.53
	Post-spill 3	3.14 ± 4.28	0.68 ± 0.92	51.98 ± 74.26	59.38 ± 173.86
	Post-spill 4	7.40 ± 9.70	1.23 ± 1.45	—	60.66 ± 173.61
<i>Chorda</i> spp. ^c	Pre-spill 1	—	30.83 ± 29.97	5.13 ± 17.73	1.22 ± 3.17
	Pre-spill 2	0.11 ± 0.28	0.03 ± 0.05	0.03 ± 0.10	<0.01
	Post-spill 1	4.32 ± 8.62	3.12 ± 4.25	0.22 ± 0.67	0
	Post-spill 2	0.07 ± 0.26	0.15 ± 0.41	0.13 ± 0.28	<0.01
	Post-spill 3	0.44 ± 1.45	9.62 ± 14.18	1.07 ± 2.04	0.28 ± 0.94
	Post-spill 4	0.20 ± 0.53	0.02 ± 0.06	—	0
<i>Chaetomorpha</i> spp. ^c	Pre-spill 1	—	0.03 ± 0.07	2.91 ± 6.16	4.48 ± 9.77
	Pre-spill 2	0.09 ± 0.14	0.01 ± 0.04	1.42 ± 1.90	5.81 ± 8.71
	Post-spill 1	0.07 ± 0.18	0.01 ± 0.03	1.25 ± 1.85	20.71 ± 36.40
	Post-spill 2	0.27 ± 0.68	0.04 ± 0.08	5.54 ± 6.80	27.33 ± 41.84
	Post-spill 3	0.16 ± 0.24	1.19 ± 5.27	6.63 ± 9.75	43.93 ± 86.56
	Post-spill 4	0.27 ± 0.60	0.10 ± 0.18	—	65.15 ± 70.06
<i>Punctaria glacialis</i>	Pre-spill 1	—	0.45 ± 1.60	0	0
	Pre-spill 2	2.52 ± 5.16	0.11 ± 0.38	0.15 ± 0.47	0
	Post-spill 1	12.39 ± 16.58	0.86 ± 3.30	0.86 ± 2.47	0
	Post-spill 2	24.40 ± 50.55	0.97 ± 3.07	0.64 ± 1.34	0.12 ± 0.57
	Post-spill 3	12.40 ± 18.22	0.27 ± 0.87	11.74 ± 26.50	0.26 ± 1.13
	Post-spill 4	25.55 ± 38.69	0.95 ± 1.98	—	0.75 ± 1.89

(continued)

TABLE 3 continued

Species or group	Period ^b	Bay 7	Bay 9	Bay 10	Bay 11
Total algae ^d	Pre-spill 1	—	288.20 ± 161.56	765.77 ± 643.56	347.39 ± 333.91
	Pre-spill 2	154.26 ± 82.51	91.43 ± 112.54	187.46 ± 191.10	477.66 ± 762.82
	Post-spill 1	148.76 ± 102.67	124.12 ± 133.52	315.70 ± 311.30	940.84 ± 1483.13
	Post-spill 2	405.52 ± 403.83	74.66 ± 100.50	743.58 ± 702.06	627.05 ± 670.36
	Post-spill 3	372.20 ± 308.38	123.78 ± 92.37	907.84 ± 796.98	1032.63 ± 1595.16
	Post-spill 4	612.94 ± 423.03	239.18 ± 304.60	—	986.43 ± 670.57

^aBiomass expressed as mean ± SD g·m⁻² of 10% formalin preserved wet weight and based on 8 replicate 0.0625 m² airlift samples on each of three transects for each period and bay.

^bPre-spill 1 and 2 = September 1980 and August 1981. Post-spill 1-4 = September 1981, August and September 1982 and August 1983.

^cGenera listed include species listed in Table 1.

^dIncludes other species not weighed individually.

TABLE 4. Three-factor analyses of variance for the biomass and number of species of macrophytic algae at 3 m depth in four bays at Cape Hatt, northern Baffin Island, during September 1980, August and September 1981 and 1982 and August 1983

Variable	Taxon	Source of variation and df ^a				
		Period (3,8 or 32)	Bay (3,8 or 32)	Period by bay (9,8 or 32)	Transect (bay) (8,333)	Per by trans (bay) (24,333)
Number of species		5.54 **	13.22 ***	1.21 ns	4.91 ***	1.46 ns
Biomass	Total algae	7.19 ***	28.39 ***	1.79 ns ^b	3.85 ***	1.17 ns
	<i>Stictyosiphon tortilis</i>	1.54 ns	7.82 **	0.33 ns	8.93 ***	1.65 *
	<i>Dictyosiphon foeniculaceus</i>	— ^c	— ^c	30.79 ***	0.79 ns	2.01 **
	<i>Pilayella littoralis</i> + <i>Berkeleya rutilans</i>	— ^c	— ^c	2.74 *	3.14 **	0.75 ns

F-values are shown with significance levels (ns = P>0.05; *P≤0.05; **P≤0.01, ***P≤0.001).

^aWhere period-by-transect (bay) interaction was ns, it was pooled with transect (bay) effect to test bay, period and period-by-bay effects; where period by transect (bay) was significant (P<0.05), transect (bay) alone was used to test main effects.

^bIn analysis excluding data from Bay 7 (reference) and including data from September 1980, the period-by-bay interaction term was significant (F = 3.24; df = 9,32; P = 0.009).

^cInterpretation of main effects confounded by significant interaction of period-by-bay term.

possible, bay effects were significant in both cases (total algae, *Stictyosiphon tortilis*), whereas the period effect was significant in only one case (total algae; Table 4).

Possible oil effects on biomass were indicated by significant period-by-bay interaction effects for *Dictyosiphon foeniculaceus*, *Pilayella littoralis* and total algal biomass, but not for *Stictyosiphon tortilis* (Table 4). The interaction effect for total algal biomass was significant only when Pre-spill Period 1 was considered; hence the source of interaction was among-bay differences between pre-spill sampling periods — clearly not an oil effect. In the other two cases, inspection of the data (Fig. 2, Table 3) shows that the interactions were complex, and hence interpretation of the results is difficult.

Biomass of *Dictyosiphon foeniculaceus* at 3 m depth in Bay 11 was very low throughout the study period (Fig. 2), and within-bay variability was extremely high (Table 3). Biomass in Bay 9 was only slightly higher, and the greatest temporal variability was that between the two pre-spill sampling periods. The most likely source of the bay-by-period interaction was the marked increase in biomass between 1981 and 1982 in Bays 7 and 10, in contrast with little or no change in Bays 9 and 11 (Fig. 2). Most of the 1982 season's growth in Bays 7 and 10 apparently preceded the August sampling period. It is possible that this growth was stimulated by the low levels of oil present in the sediments of Bays 7 and 10 in (and presumably between) September 1981 and August 1982 (see Boehm *et al.*, 1987).

Another possibility, however, is that natural annual variability may account for the significant period-by-bay interaction in

Dictyosiphon foeniculaceus. In general, biomass of *D. foeniculaceus* was high in 1980 and 1982 and low in 1981 and 1983 (Fig. 2). Data from Bay 7 in 1980 and from Bay 10 in 1983 would allow a better evaluation of annual variability, but these data are not available.

Temporal changes in the biomass of *Pilayella littoralis* (+ *Berkeleya rutilans*) at 3 m depth were not consistent among bays, but the changes did not appear to be effects of oil. The most conspicuous inconsistencies were (1) more pronounced decreases in biomass in Bays 9 and 10 than in Bay 11 between the two pre-spill sampling periods and (2) a considerable biomass increase during 1981 only in Bay 11. The first case was clearly not an oil effect. The second case was probably not an oil effect, as the oil released on the surface in Bay 11 did not penetrate the water column below 1 m (Humphrey *et al.*, 1987) and oil was not incorporated into the sediment for several weeks (Boehm *et al.*, 1987). Furthermore, it does not seem likely that any effect of either the surface oil or dispersed oil release would be detectable in 1981, as the majority of the summer growing season preceded contamination by oil.

Thus, biomass data revealed no effects of oil on total algae or on two of the three species analyzed. In a third species, *Dictyosiphon foeniculaceus*, growth may have been stimulated by low levels of oil in sediments during the year following the oil releases, although natural annual variability was another possible explanation for the observed increases in biomass. Considerable amounts of oil were incorporated into 3 m sediments immediately after the dispersed oil release, and even

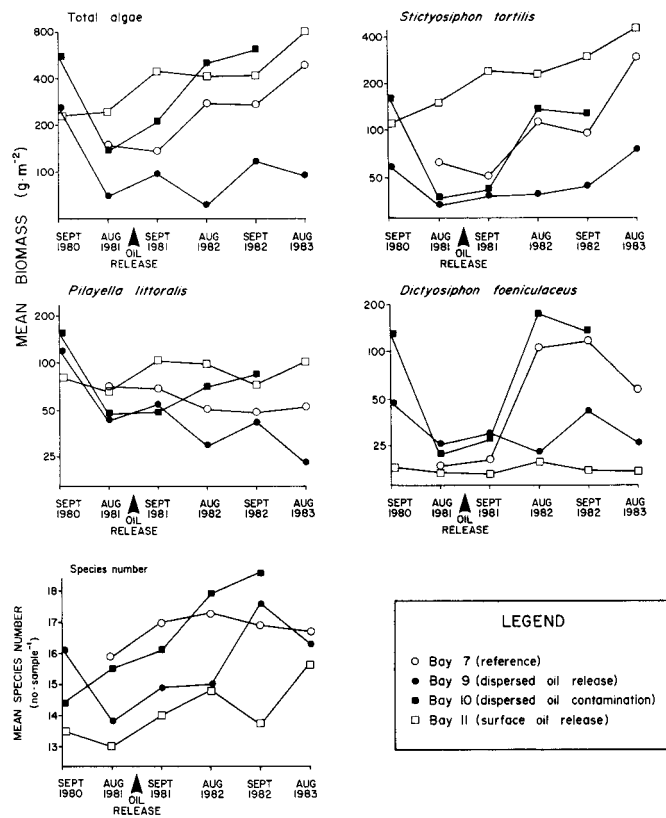


FIG. 2. Mean number of species of macroalgae and mean biomass of total algae and of dominant understory species at 3 m depth in four bays at Cape Hatt, northern Baffin Island, during pre- and post-spill sampling periods September 1980-August 1983.

greater quantities of oil originating from the 1981 oil releases were introduced into subtidal sediments during the open water seasons of 1982 and 1983. However, neither oil in sediments nor oil in the water during the dispersed oil release had any detectable adverse effect on biomasses of the dominant understory algae at 3 m depth in the study area.

Diversity

Mean number of species per sample and total number of species collected are given for each bay and period in Table 2. Variability in species numbers within bays and periods was relatively slight (Table 2). Mean number of species per sample (13.0-18.6, depending on bay and period) was considerably smaller than the total number of species collected in each bay and period (22-40).

There was no evidence of an effect of oil or dispersed oil on macroalgal diversity; the period-by-bay interaction was not significant (Table 4). Spatial variability was evident on small and large scales (among transects and among bays respectively), and temporal variability included both annual and seasonal (August-September) components (Table 2; Fig. 2). Caution should be exercised in the interpretation of these "significant" results because the use of ANOVA assumes that the interval

between possible values is small relative to the standard deviation; this was not true for data on species numbers.

Reproductive Condition

Observations by RTW revealed no apparent effects of oil or dispersed oil on the reproductive status of macroalgae in the study area. These observations were made on living specimens during 1983 and on preserved specimens during 1980-83. Peculiarities in the reproduction of some species (described below) were probably attributable to habitat characteristics rather than effects of oil; these peculiarities were apparent in specimens from all bays in all sampling periods.

During 1983, attached algal species appeared normal with respect to both the form and the periodicity of development of reproductive organs. Viable gametes and/or spores were produced by all attached species. Loose-lying algae, on the other hand, lacked the reproductive structures found in attached forms of the same species and developed entirely vegetatively during each year of the study. Viable fragments of mature axes of *Pilayella littoralis*, *Stictyosiphon tortilis* and *Dictyosiphon foeniculaceus* were present in August collections, and between August and September regeneration of new axes occurred from fragments of thalli developed during the previous summer. The form of the mature plants was atypical of the attached plants of the species. Axes were long, delicate, highly and irregularly branched and completely prostrate. In some species, especially *Pilayella littoralis*, cell length was considerably greater than that found in temperate waters. These aspects of the loose-lying understory algal community suggest that some of its species were perennial and free-living, rather than loose-lying forms of seasonally attached plants.

DISCUSSION

There were no detectable adverse effects of either the surface or the dispersed oil release on the biomass, diversity or reproductive condition of shallow water subtidal macroalgae at Cape Hatt. These results for dispersed oil were unexpected, because the exposure of shallow water macroalgae to dispersed oil in the water column of Bay 9 represented a "worst case" situation (Sergy and Blackall, 1987). The lack of adverse effects of oil in the sediments was less surprising, given the relatively low concentrations of oil present; however, there are no previous data with which to compare these results. Similarly, the concurrent studies of infauna and epibenthos at Cape Hatt showed that the oil and dispersed oil treatments had no major effects on those animals (Cross and Thomson, 1987; Cross *et al.*, 1987).

The only possible oil effect detected in the present study was growth stimulation in *Dictyosiphon foeniculaceus*, perhaps caused by low levels of oil in sediments. To our knowledge, oil concentrations in sediments have not previously been shown to enhance algal growth. However, there is some previous evidence that low concentrations of oil in the water stimulate macroalgal growth: Shiels *et al.* (1973) reported photosynthetic stimulation in several species at 7-700 ppb crude oil, and Thélin (1981) reported growth stimulation of *Fucus serratus* zygotes and germlings at low concentrations of crude oil and oil-Corexit 9527 mixtures (concentrations not measured). In both cases, the stimulatory effect was eliminated or reversed at higher oil concentrations (7 ppm; Shiels *et al.*, 1973). Steele (1977) reported growth stimulation in *Fucus edentatus* exposed to low concentrations (<200 ppb nominal) of three oil types, but no

such effect was evident on exposure to crude oil. These results pertaining to oil in the water support the possibility that oil in sediments in Cape Hatt stimulated growth of *D. foeniculaceus*. However, as already pointed out, natural annual variability in growth may have caused the observed increases in biomass.

Two factors that may have contributed to the lack of major effects on subtidal macroalgae at Cape Hatt are the lack of major effects on herbivores and the reproductive strategies of the dominant macroalgal species. Oil-related mortality of herbivores, which has apparently caused increases in macroalgal density or biomass elsewhere (North *et al.*, 1965; Nelson-Smith, 1968; Floc'h and Diouris, 1980; Maurin, 1984), was not apparent in the present study (Cross and Thomson, 1987; Cross *et al.*, 1987). Secondly, the vegetative mode of reproduction of the dominant macroalgae at Cape Hatt may have rendered them relatively insensitive to oil. Effects of oil on vegetative reproduction have not been studied, but the process of sexual reproduction in macroalgae is apparently extremely sensitive to oil. Previous studies on *Fucus* spp. have shown that very low concentrations of oil in the water may interfere with fertilization (Johnston, 1977; Derenbach and Gereck, 1980) or reduce the growth of zygotes and inhibit the adhesion of settling sporelings (Johnston, 1977). Steele (1977) reported that *Fucus edentatus* did not germinate or grow when exposed to oil immediately before or during the release of gametes, even at the lowest oil concentrations tested (0.2 ppb nominal).

Oil and dispersed oil released at Cape Hatt had no detectable adverse effects on macroalgae at 3 m depth. The 3 m macroalgal community consisted primarily of loose-lying species of brown algae that developed vegetatively. Macrophyte communities dominated by sexually reproducing species, on the other hand, may be affected by oil exposures similar to those at Cape Hatt, particularly if oil is present during the reproductive season. *Fucus* and *Laminaria* spp., which reproduce sexually, were not analyzed in the present study because they were rare and patchily distributed at the depth studied. Both genera, however, are common members of shallow water macrophyte communities at Cape Hatt and elsewhere in the Arctic (e.g., Wilce, 1964; Lee, 1973; Thomson and Cross, 1980; Dunton *et al.*, 1982). There was no evidence of reproductive failure in these genera in 1983, two years after the oil releases, but any such effects in 1981 or 1982 would not have been detected in the present study.

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