Marine Biology 73, 51–65 (1983)

Marine Biology
International Journal on Life in Oceans and Coastal Waters

The "Tsesis" Oil Spill: Acute and Long-Term Impact on the Benthos

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Abstract

The "Tsesis" oil spill in October 1977 resulted in the release of over 1 000 tons of medium grade fuel oil in an archipelago in the brackish Baltic Sea. Considerable oil quantities reached the benthos by sedimentation. Within 16 d benthic amphipods of the genus *Pontoporeia,* as well as the polychaete *Harmothoe sarsi* Kinberg, showed reduction to less than 5% of pre-spill biomasses at the most impacted station. The clam *Macoma balthica* (L.) was more resistant, and showed little or no mortality, but was heavily contaminated by oil (about 2 000 μg g^{-1} dry wt total hydrocarbons). The meiofauna was strongly affected, with ostracods, harpacticoids, Turbellaria and kinorhynchs showing clear reductions in abundance, while nematodes, as a group, were more resistant. In the winter following the spill gravid *Pontoporeia affinis* Lindström females showed a statistically significant increase in the frequency of abnormal or undifferentiated eggs. Food-chain transfer of oil to flounder [*Platichthys flesus* (L.)] was indicated. Not until the second summer after the spill were the first signs of recovery noted at the most heavily impacted station: Amphipods, *H. sarsi* and harpacticoids increased and the oil concentrations in *M. balthica* decreased (to about 1 000 μg g^{-1}). In the area where amphipods had been virtually eliminated, there was an unusually heavy recruitment of *M. balthica,* reaching 4 000 juveniles, of 1.5–2 mm length, per square metre, probably from settling in summer 1978. Three years after the spill *Pontoporeia* spp. biomass was still depressed in the most affected area, while *H. sarsi* showed normal biomass, and *M. balthica* abundance was inflated. Oil concentrations in *M. balthica* (about 250 μg g^{-1}) and flounder were only slightly elevated and the oil could no longer be confidently ascribed to "Tsesis" origin, even using GC/MS-analysis. Recovery was thus underway, but the long lifespan of *M. balthica* implies that the disturbed community composition may persist for many years at this station. Full recovery is likely to require more than 5 yr and may take a decade or more. An effort to evaluate the accumulated monetary loss to fishery from the accident indicates that direct costs of shoreline cleanup and vessel damage were considerably greater.

Introduction

Since the "Torrey Canyon" catastrophe in 1967, millions of dollars have been invested in research on the biological effects of oil pollution of the seas. Innumerable scientific papers, summarized in many books and reviews (e.g. GESAMP, 1977; McIntyre and Whittle, 1977; Cowell, 1977; Connell and Miller, 1980, 1981), have resulted. Most of these studies have, however, been concerned either with the surface layer of the sea, where plankton, fish and fish eggs as well as sea birds may be affected by a spill, or with the intertidal zone, where stranded oil may cause extensive destruction of the natural communities. Until recently little attention was paid to the effects of oil on subtidal benthic communities, even if several good field studies now exist (e.g. Addy *et al.,* 1978; Sanders *et al.,* 1980; Cabioch *et al.,* 1981). Most of these investigations were, however, concerned only with the benthic macrofauna. Except for a few of the "Amoco Cadiz" studies (Boucher, 1981; Renaud-Mornant *et al.,* 1981) the meiofauna was ignored, even though its significance in energy flow terms is often similar to that of the macrofauna (e.g. Ankar and Elmgren, 1976; Gerlach, 1978; Elmgren, 1978).

The grounding of the 19 300 dwt tanker "Tsesis", in the Södertälje ship channel on the Swedish Baltic coast (Lat. 55°49.7′N, Long. 17°43.8′E) on October 26, 1977, resulted in a spill of over 1 000 tons of oil, mostly a No. 5 fuel oil, but also some bunker oil. About two thirds of the oil was mechanically recovered, but an estimated 34 km²

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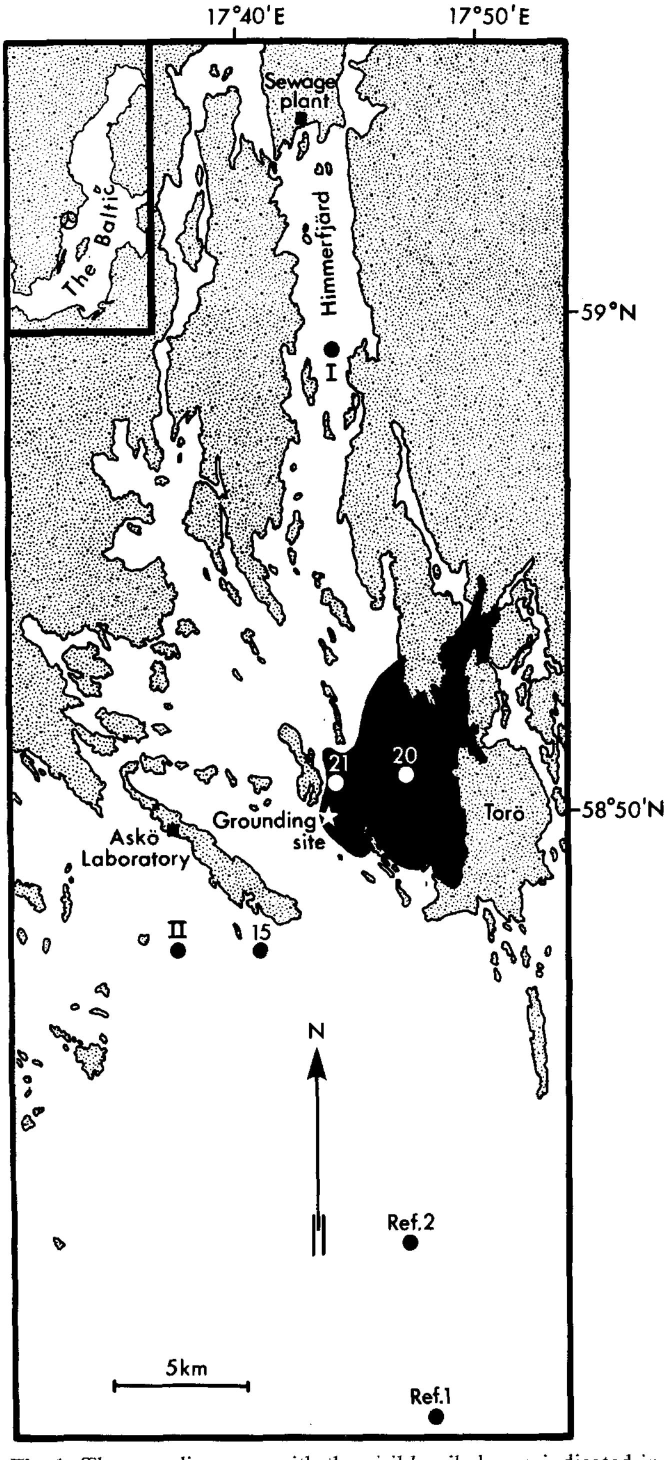

Fig. 1. The sampling area with the visibly oiled area indicated in black

were still visibly oiled (Fig. 1). The spill became the subject of an international ecological study, centered at the nearby Askö Laboratory of the University of Stockholm, Sweden. An extensive report covering the first year of study is already available (Kineman *et al.*, 1980), and has been summarized by Lindén *et al.* (1979). The results of the pelagial study have been published by Johansson *et al.* (1980). We report here detailed results from the benthos study, covering the effects on both macro- and meiofauna during the first years after the spill (November 1977 to March 1981, for meiofauna only to November 1979). Results from oil analyses of macrofauna and fish are also presented.

Spill Area

The affected archipelago area (Fig. 1) has a mean depth of about 20–25 m and a low, stable average salinity of about 6.5‰ S, varying hardly more than ± 1‰ S over the year. Temperature at the time of the spill was about +8 °C in the whole water column. The annual range is about −0.5° – +20 °C above the seasonal thermocline at 10–20 m depth, and 0° – +10 °C at 30 m. There is no perceptible tide in the area.

The benthos of the Askö-Landsort area has been treated in detail in several papers (Ankar and Elmgren, 1976; Ankar, 1977; Cederwall, 1977, 1978; Elmgren, 1976, 1978). Benthos data have been collected in the oil polluted area since 1972, initially as part of a study of the effects of a large new sewage treatment plant, situated at the head of the bay "Himmerfjärden". Before the spill, Stations 20 and 21 (see map, Fig. 1) were generally sampled once a year in October–November, and after the spill more frequently.

The depth of the stations were: Station 15: 44–45 m, Station 20: 32–33 m, Station 21: 28–29 m, and the bottom substrate, mud at all the stations. Stations 20 and 21 are located in an area which is cut off from exchange of deep water with the open Baltic by a sill of about 20 m depth between Askö and Torö. Station 15 is situated outside this sill.

Station 20 is situated in the middle of the area most affected by oil slicks (Fig. 1), near a station where considerable sedimentation of oil was recorded (Johansson *et al.*, 1980), and was identified early as heavily impacted. Station 21 is situated on the borderline of the visibly affected area (Fig. 1) and was first thought to be little influenced by the oil. Later oil analyses of biota and material from sediment traps showed oil to have been more widely spread than initially thought, and "Tsesis" oil was also found in *Macoma balthica* from Station 21, but in lower quantities than at Station 20 (Fig. 4c). No oil of "Tsesis" origin was identified in *M. balthica* from Station 15 (Table 5).

Material and Methods

Macrofauna Sampling

The macrofauna sampling followed the recommendations of the Baltic Marine Biologists (BMB, Dybern *et al.*, 1976). A 0.1-m² van Veen grab was used and samples were sieved live through 1×1-mm metal mesh sieves. The animals and sieve residues were preserved in 4% formaldehyde solution, buffered with hexamine and stained with rose bengal to facilitate sorting. Biomass was determined as formalin wet weight, after at least three months of preservation and careful blotting with filter paper. Each taxon and sample was weighed separately. The number of sampling units taken on each occasion is shown in Table 1 a–b.

Bivalves for oil analyses were collected using either a van Veen grab or a dredge and stored in hexane-cleaned glass bottles or aluminum foil and kept deep-frozen until analyzed.

The spill occurred just before the normal copulation period for the amphipods *Pontoporeia affinis* and *P. femorata* Kröyer. Egg-bearing females of the dominant species, *P. affinis,* were collected at the most strongly impacted station (No. 20) and at an unaffected reference site (No. 15) on 17 February and 9 March 1978, using an Ockelmann dredge (Ockelmann, 1964). The total number of eggs and the frequency of eggs showing either abnormal development or no differentiation at all were noted.

Meiofauna Sampling

Meiofauna was sampled using an Askö core sampler (Ankar and Elmgren, 1976: Appendix 1) with which core samples of 3.9 cm^2 and at least 7 cm length were obtained.

Each sampling unit was either a single core sample, or 3–4 pooled core samples. For details and number of sampling units, see Table 3 a–c. Treatment followed BMB recommendations (Dybern *et al.,* 1976). Sediment cores were preserved whole in 4% formaldehyde solution, buffered with hexamine and with rose bengal added to stain the animals. Meiofauna was delimited by a 1×1-mm metal mesh sieve as the upper limit (to exclude macrofauna), and by a 40×40-μm metal mesh sieve as the lower limit, with intermediate 500-, 200- and 100-μm sieves used to facilitate sorting and sub-sampling. Ciliates were not included, since it is uncertain to what extent they are destroyed by the preservative.

Each sampling unit was first sieved through 1- and 0.5-mm sieves, and then split into light and heavy fractions by repeated decantation (as in Elmgren, 1973). Before sorting, the light fractions were sieved through a 200-μm sieve and then subsampled as follows (in a sample splitter according to Elmgren, 1973): 100-μm fraction 1/8, 40-μm fraction 1/64. The finest light fraction (40 μm) was sonified (Thiel *et al.,* 1975) for 25–30 s before sorting. The heavier fractions were sieved through a 100-μm sieve (generally after sonification) and the retained fraction sorted in its entirety. The finest heavy fraction was discarded since earlier checks have shown it to be virtually devoid of animals (Elmgren *et al.,* in press). Treatment of samples from Station 15 from May, 1975 and earlier differed slightly (see Elmgren, 1975), but not in ways likely to affect results materially.

Samples for counts of dead and live ostracods were collected on 17 February and 9 March, 1978, at Stations 15 and 20, using the Ockelmann dredge with a mesh size of 450 μm, and subsequently sieved through a 500-μm sieve before sorting and counting.

Sediment Sampling

Cores for oil analysis of surface sediments were collected using either a modified Kajak core sampler (Kajak *et al.,* 1965) or the Askö corer also used for meiofauna sampling. The top 2 cm of the sediment were extruded into hexane-washed glass bottles and kept deep-frozen until analyzed. On 4 December 1978, further cores were taken at Station 20 using an experimental sampler, similar in principle to that of Craib (1965). This sampler rests on a tripod. It slowly lowers the core tube into the bottom sediment only after the tripod has come to rest on the sediment, thus decreasing the risk of surface loss due to a pressure wave. These cores were sliced into layers of 0–0.5 and 0.5–1 cm.

The oxygen content of the water above the sediment was measured (Winkler titration) using the Kajak core sampler or a bottom water sampler. Reference values for oxygen content were taken from Stations I and II (Fig. 1).

Fish Sampling

Flounder, herring (*Clupea harengus membras* L.) and cod (*Gadus morhua* L.) for oil analyses were caught in gill nets at Station 20 and kept deep frozen, wrapped in hexane-washed aluminum foil, until analyzed.

Oil Analyses

Oil analyses were performed by gas chromatography (GC) and combined gas chromatography and mass spectrometry (GC/MS) as described by Boehm *et al.* (1982). Concentrations are expressed as μg hydrocarbons per g dry weight, excluding shells.

Results

Macrofauna

Two stations were followed in detail (Stations 20 and 21, shown in map, Fig. 1). Results are given in Table 1, and Figs. 2 and 3. The effects of the oil spill have to be evaluated against a background of gradual change during 1972–1977 due to local eutrophication. The most important component of this change is a gradual increase in abundance and biomass of *Macoma balthica* at both stations, most clearly marked at Station 20 (see Fig. 3 d–e). This trend is even stronger farther up the "Himmerfjärd", closer to the sewage plant (U. Larsson, unpublished data).

The November 1977 sampling, carried out 16 d after the start of the spill, showed a drastic and statistically significant reduction in total macrofauna abundance at Station 20. On this occasion a smell of oil was noticed from several of the grab samples. At Station 21 also, the abundance was lower than during any of the four preceding years. This difference was, however, difficult to test

Table 1a. Macrofauna biomass (g m^{-2}) and abundance (no. m^{-2}) ±SE (standard error of mean) at Station 20, n = number of samples, + = biomass less than 0.05 g m^{-2}. The significance levels at the bottom of the table represents the results from comparisons between pre- and postspill means, using the two tailed rank-sum test according to Dixon and Massey, 1969, p 344

Date	n	Total		*Pontoporeia affinis*		*P. femorata*	
		biomass	abundance	biomass	abundance	biomass	abundance
72 11 23	3	32±11	1 546±191	5.0±1.1	1 364±125	1.3±0.5	204± 76
73 10 03	10	57± 5	4 490± 99	20.5±0.5	3 545± 79	5.7±0.4	519± 27
75 10 21	10	61± 3	4 105±168	10.4±0.8	2 174±140	6.9±0.5	1 521± 34
76 10 12	8	105± 8	3 340±173	9.0±1.0	1 831±144	6.2±0.5	1 017± 69
Spill							
77 11 11	8	107±10	410± 40	0.1± +	15± 2	0.2±0.1	13± 3
78 02 17	8	84±15	525±115	1.9±0.5	234± 71	0.5±0.2	54± 9
78 08 23	8	148± 9	527± 46	0.1± +	39± 4	+	9± 4
78 11 15	8	199±10	491± 23	0.1± +	9± 2	0.1±0.1	12± 7
79 04 26	5	206±21	376± 39	0.1± +	10± 5	0.3±0.1	24± 5
79 07 24	5	165±21	4 650±282	12.3±2.5	2 086±324	2.7±0.4	278± 55
79 11 05	8	248±20	5 843±251	8.4±0.5	841± 56	2.6±0.5	124± 21
80 04 17	5	144±34	2 604±659	3.7±1.3	550±217	0.3±0.1	22± 7
80 11 04	8	177±16	1 376±210	0.5±0.1	35± 5	0.7±0.1	49± 4
81 03 30	5	330±17	2 126±118	0.2±0.1	14± 8	0.3±0.1	34± 3
Pre-spill average	4	64±15	3 370±653	11.2±3.3	2 229±469	5.0±1.3	815±289
Post-spill average	10	181±22	1 893±617	2.7±1.4	383±209	0.8±0.3	62± 26
Significance level, P=		0.004	>0.05	0.024	0.008	0.008	0.004

(1) *Terebellides stroemi*, (2) Hydrobiidae, (3) *Idothea* sp., (4) *Mytilus edulis*, (5) *Gammarus* sp., (6) Chironomidae

Table 1b. Macrofauna biomass (g m^{-2}) and abundance (no. m^{-2}) ±SE at Station 21, n = number of samples, + = biomass less than 0.05 g m^{-2}. The significance levels at the bottom of the table represents the results from comparisons between pre- and postspill means, using the two tailed rank-sum test according to Dixon and Massey, 1969, p 344

Date	n	Total		*Pontoporeia affinis*		*P. femorata*	
		biomass	abundance	biomass	abundance	biomass	abundance
72 11 08	3	35± 5	3 355±157	8.1±0.3	2 274±155	3.7±1.0	895±196
73 10 03	3	59± 9	2 950±148	8.4±0.4	1 598±100	5.4±1.3	911±228
75 10 21	3	91± 6	3 297±402	7.0±0.9	1 638± 81	4.1±1.5	828±230
76 10 12	2	77±12	2 224±114	5.8± +	1 283±105	1.8±0.5	434± 50
Spill							
77 11 11	3	73± 1	1 175± 43	7.4±0.4	682± 40	0.5±0.2	34± 11
78 06 07	5	93± 8	3 681±324	6.7±0.3	2 300±222	1.5±0.2	585±114
78 11 14	5	143±13	2 620± 65	8.6±0.8	1 246± 35	4.6±0.7	662± 29
79 04 27	7	163± 9	2 310±109	4.5±0.2	811± 37	4.3±0.5	571± 44
79 07 24	6	164±14	2 970±346	9.4±1.3	1 847± 23	7.0±0.9	994±116
79 11 06	8	165±13	2 250± 58	6.7±0.2	745± 29	10.1±0.8	805± 45
80 04 17	5	135±13	1 846±175	2.7±0.3	532±135	3.7±0.5	426±101
80 11 03	8	136± 8	1 964± 48	4.5±0.2	665± 33	6.4±0.3	801± 38
81 03 30	5	129± 5	1 858± 76	4.2±0.3	576± 99	4.0±0.2	496± 15
Pre-spill average	4	65±13	2 957±260	7.3±0.6	1 698±208	3.8±0.7	767±112
Post-spill average	9	133±11	2 297±243	6.1±0.7	1 045±210	4.7±1.0	597± 91
Significance level, P=		0.012	>0.05	>0.05	>0.05	>0.05	>0.05

(1) *Terebellides stroemi*, (2) *Pygospio elegans*, (3) Chironomidae, (4) *Mytilus edulis*, (5) Hydrobiidae, (6) *Nereis diversicolor*, (7) *Cardium* sp.

Table 1a (continued)

Harmothoe sarsi		*Macoma balthica*		*Halicryptus spinulosus*		Others	
biomass	abundance	biomass	abundance	biomass	abundance	biomass	abundance
1.1±0.5	82±24	25±10	79± 32	0	0	0	0
1.0±0.1	242±10	29± 5	181± 16	0.6±0.4	5± 2	0	0
2.0±0.3	141±12	41± 3	260± 17	0.6±0.4	6± 4	+	2± 1 (1)
1.9±0.3	120±11	88± 8	328± 24	0	0	0.1±0.1	44±38 (2, 3)
+	1± 1	106±10	370± 39	0.9±0.5	10± 4	0	0
1.5±0.5	53±15	79±14	177± 33	1.2±1.3	3± 3	+	4± 4 (1)
0.1±0.1	2± 1	145± 9	515± 44	3.0±1.1	10± 2	+	3± 2 (3)
0.2±0.1	4± 2	196±10	468± 19	2.1±1.0	9± 4	+	1± 1 (4)
+	2± 2	201±21	324± 38	4.3±1.2	16± 5	0	0
6.8±1.4	350±60	141±24	1 912±162	2.4±1.2	20± 6	+	4± 2 (2)
5.3±0.8	131±16	229±21	4 724±242	1.2±0.6	5± 3	1.2±0.7	18± 8 (3, 5, 6)
0.6±0.2	136±43	136±30	1 870±393	2.9±2.9	26±17	0	0
1.8±0.4	55±10	173±16	1 231±207	0.6±0.4	6± 3	0	0
1.4±0.3	46±10	325±17	1 998±114	2.3±1.0	20± 6	1.0±1.0	14±14 (3, 4, 5)
1.5±0.3	146±34	46±14	212± 54	0.3±0.2	3± 2	0.1±0.1	12±11
1.8±0.8	78±34	173±22	1 359±438	2.1±0.4	13± 2	0.2±0.1	4± 2
>0.05	>0.05	0.004	0.024	0.004	0.024		

Table 1b (continued)

Harmothoe sarsi		*Macoma balthica*		*Halicryptus spinulosus*		Others	
biomass	abundance	biomass	abundance	biomass	abundance	biomass	abundance
0.7±0.5	64±19	19± 5	107±15	0.7±0.5	15± 3	0	0
0.5±0.1	88± 6	44± 8	320±60	1.1±0.7	34±12	0	0
0.6±0.2	286±58	77± 8	478±74	3.1±1.3	58±11	0.1±0.1	10±10 (1)
0.4±0.2	59± 5	68±11	406±41	1.3±1.0	23± 5	0.1±+	20± 0 (2, 3)
0.2±+	82±19	65± 1	341±58	0.4±0.4	6±11	0.5±0.2	30± 6 (1, 2)
0.8±0.1	336±30	81± 8	380±17	2.8±0.6	58± 9	0.5±0.1	22± 7 (1)
3.2±1.0	146±31	123±10	528±22	1.8±0.6	20± 6	1.8±1.7	18± 9 (1, 3, 4)
0.5±0.2	256±49	149±22	599±19	5.0±1.0	69± 7	0.1±0.1	4± 2 (1, 3)
4.9±0.8	523±37	137±29	525±30	5.1±1.6	68±11	0.2±+	13± 3 (1)
5.9±0.7	201± 7	136±11	444±39	4.1±0.9	28± 6	2.5±2.5	26± 7 (1, 4)
1.7±0.3	340±19	125±13	462±29	1.6±0.6	30± 5	0.2±0.1	56±24 (1, 3–7)
1.7±0.4	68± 9	120± 8	381±17	2.5±0.8	15± 4	0.5±0.2	34± 9 (1, 4)
0.6±0.1	320±19	117± 5	384±32	2.5±0.6	46±13	0.3±0.1	36± 9 (1, 4, 5)
0.6±0.1	124±54	52±13	328±80	1.6±0.5	33± 9	0.1±+	8± 5
2.2±0.7	252±49	117± 9	449±29	2.9±0.5	38± 8	0.8±0.3	27± 5
>0.05	>0.05	0.012	>0.05	>0.05	>0.05		

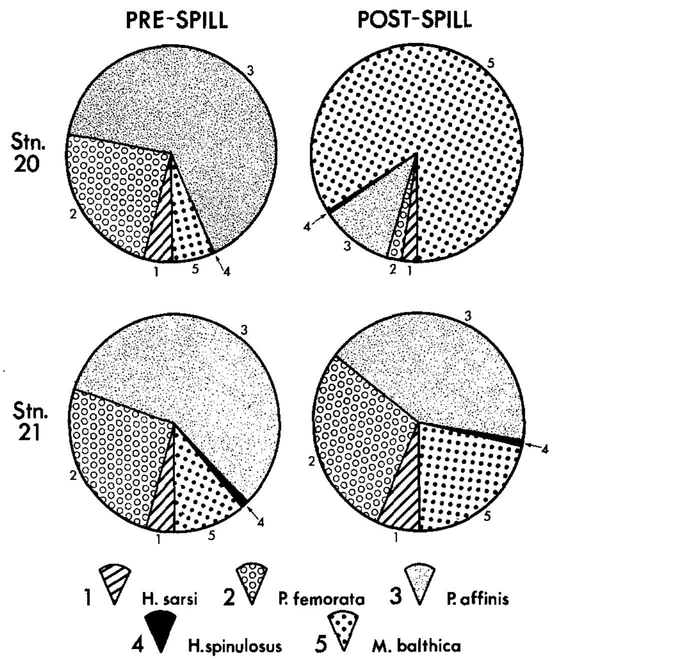

Fig. 2. Macrofauna abundance composition at two soft bottom stations before and after the spill. Station 20 was strongly influenced by the spill, Station 21 less impacted. Proportions calculated as means for four autumns before and four autumns after the spill

statistically, due to the lower number of samples taken at this station. The reduction at Station 20 was mostly due to an almost total disappearance of *Pontoporeia affinis* and *P. femorata* and the polychaete *Harmothoe sarsi* (Fig. 3a–c). All these decreases are statistically significant (for all three species $P < 0.001$ when the samples from November 1976 and November 1977 are compared, two tailed rank-sum test according to Dixon and Massey, 1969, p 344). The amphipods (but not the polychaete) were also reduced at Station 21, but far less drastically. The total macrofauna biomass at both stations was dominated by the bivalve *Macoma balthica,* which showed no decline (Fig. 3d–e). The same was true of the priapulid *Halicryptus spinulosus* v. Siebold (Table 1), which is the least abundant of the five macrofauna species normally found at these stations.

At Station 20, the *Pontoporeia* spp. (Fig. 3a–b) and *Harmothoe sarsi* (Fig. 3c) populations remained greatly depressed until July and November 1979, when pre-spill levels were once again attained. In 1980 and 1981 the *Pontoporeia* spp. biomasses were, however, very low again. The biomasses of both *Pontoporeia* species were statistically significantly lower after the spill than before (Table 1a). *Macoma balthica* biomass (Fig. 3d) increased considerably in the first years after the spill, presumably due to growth of established individuals, since abundance showed no corresponding increase (Fig. 3e). In July 1979, *M. balthica* abundance at Station 20 increased considerably, and by November peaked near 5 000 individuals per square meter (Fig. 3e). This peak was due to large numbers of small clams, 1.5–2 mm in July 1979, and thus did not show up in the biomass graph (Fig. 3d). In 1980–1981 the abundance remained high and in spring 1981 the individuals had grown considerably, resulting in a biomass higher than observed before at this station (Fig. 3d). Both the mean biomasses and abundances of *M. balthica* were significantly higher after than before the spill (Table 1a). The fifth species, *Halicryptus spinulosus* also increased in both biomass and abundance following the spill (Table 1a). The increase is, however, not as striking as that of *M. balthica.*

At Station 21 only *Pontoporeia femorata* was initially clearly reduced in biomass (Fig. 3b), but recovered to prespill values by mid-1978. *P. affinis* (Fig. 3a), *Halicryptus spinulosus:* (Table 1a) and *Harmothoe sarsi* (Fig. 3c) were not significantly affected. *Macoma balthica* showed a gradual increase in biomass (Table 1b), presumably due largely to individual growth, as at Station 20, since abundance did not change significantly (Fig. 3e).

In spite of the drastic reduction in *Pontoporeia affinis* population density at Station 20, it was possible to collect a small number of gravid females for determination of egg number and frequency of abnormal (including undifferentiated) embryos. The total percentage of abnormal embryos was about 7% at Station 20, but less than 1% at reference Station 15, far from the oil spill (Table 2). This difference is statistically significant ($P < 0.05$) using a normal approximation to a rank-sum test that combines

Table 2. *Pontoporeia affinis.* The frequency of abnormal egg development (malformed embryos and undifferentiated eggs) in gravid females from the oil polluted area (Station 20) and from a reference area (Station 15) (For raw data, see Elmgren *et al.,* 1980: Table 6.1)

Area	Polluted		Reference	
Date	78 02 17	78 03 09	78 02 17	78 03 09
Eggs/female, total $X \pm SD$	53.8 ± 16.0	45.5 ± 13.0	37.1 ± 10.6	44.8 ± 6.4
Abnormal eggs/female $X \pm SD$	3.4 ± 5.3	3.6 ± 10.0	0.4 ± 0.5	0.2 ± 0.4
Abnormal eggs, % of total eggs	6.4	8.0	1.2	0.4
No. of females examined	12	19	7	5
No. of females with abnormal eggs	8	12	3	1

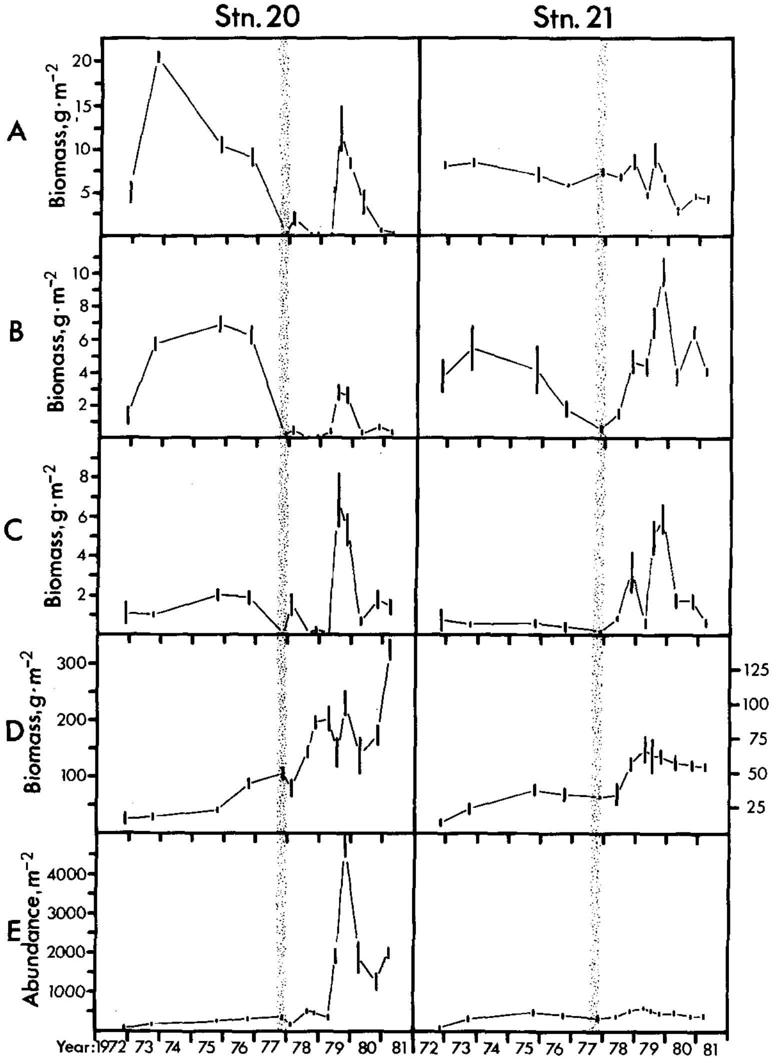

Fig. 3. The macrofauna ($\bar{X} \pm$ SE) at Stations 20 and 21. The shaded line indicates the spill (the duration of the spill was shorter than indicated by the line). A = *Pontoporeia affinis*, B = *Pontoporeia femorata*, C = *Harmothoe sarsi*, D = *Macoma balthica* (to the left biomass including shells, to the right excluding shells, assuming shellfree wet weight to be 41% of total weight, Ankar and Elmgren, 1976), E = *M. balthica*

the information from both sampling occasions (Lehman, 1975, pp 5–23 and 132–141).

Meiofauna

Since only a few prespill meiofauna samples were available from the oil affected area and the macrofauna at Station 21 seemed to show some influence from the spill, an additional reference station, No. 15, (Fig. 1) was selected. Meiofauna samples have been taken intermittently at this station since 1971, using essentially identical methods (Table 3 c).

Nematodes always constituted more than 90% of the meiofauna abundance at all stations and sampling occasions. The nematode abundance was generally 5 to 8 million per square meter (Table 3, Fig. 4 a), as is normal on fine sediments below 25 m in the area (Ankar and Elmgren, 1976). Stations 15 and 21, and Station 20 before the spill, seem representative, compared to an earlier survey of the area (Ankar and Elmgren, 1976, see also Fig. 5). After the spill, most nematode abundance values at Station 20 were somewhat lower than normal, but only one (February 1978) was low enough to be exceptional (below 1 million, Table 3 a, Fig. 5).

The other components of the meiofauna seemed more susceptible to the oil, and may be exemplified by the ostracods (Table 3, Fig. 4 b), which were quickly reduced in abundance at the most heavily impacted station (No. 20). All other meiofauna, as an aggregate, as well as individual groups, such as Turbellaria, harpacticoids and kinorhynchs, showed essentially the same picture as the ostracods (Table 3). Not until July and November 1979 were normal densities of non-nematode meiofauna attained again at Station 20, but this increase was due largely to high densities of harpacticoids, whereas Turbellaria, ostracods and kinorhynchs remained relatively rare.

The Ockelmann dredge samples collected in February and March 1978 showed a much higher proportion of live ostracods in relation to total ostracods (live + "recently" dead) at control Station 15 than at oiled Station 20, where only few live individuals were found. The difference between the stations was highly significant on both occasions (Table 4).

Table 3a. Meiofauna abundance (as 10^3 ind. · m^{-2} ± standard error of mean) at Station 20 (oiled). *n* = number of sampling units counted

Date	*n*	Total	Nematoda	(Total excluding nematoda)	Turbellaria	Kinorhyncha	Harpacticoida	Ostracoda	Temporary meiofauna	Others
74 08 05	4	7 439 ± 524	6 914 ± 531	(434 ± 32)	172 ± 16	55 ± 16	85 ± 18	82 ± 17	16 ± 5	24 ± 8
Spill										
77 11 11	3	4 962 ± 638	4 906 ± 638	(56 ± 8)	16 ± 9	1 ± 1	7 ± 7	13 ± 6	5 ± 2	14 ± 14
78 02 17	3	6'648 ± 953	6 493 ± 922	(155 ± 36)	56 ± 36	11 ± 9	52 ± 3	32 ± 4	3 ± 2	0
78 03 08	4	855 ± 180	845 ± 178	(10 ± 2)	4 ± 2	0	0	5 ± 2	1 ± 1	0
78 08 17	5	6 927 ± 1 266	6 782 ± 1 247	(145 ± 29)	6 ± 5	32 ± 14	13 ± 8	52 ± 12	5 ± 1	37 ± 11
78 09 06	3	3 124 ± 670	3 050 ± 659	(74 ± 12)	10 ± 6	20 ± 10	8 ± 7	8 ± 3	3 ± 2	25 ± 14
78 11 15	5	3 147 ± 535	3 066 ± 534	(81 ± 36)	3 ± 2	10 ± 5	36 ± 20	10 ± 4	1 ± 1	22 ± 16
79 04 26	3	2 899 ± 140	2 849 ± 127	(50 ± 17)	1 ± 1	0	28 ± 14	18 ± 6	0	3 ± 3
79 07 24	3[a]	4 483 ± 1 071	4 127 ± 972	(355 ± 114)	27 ± 13	30 ± 17	197 ± 82	69 ± 37	24 ± 7	9 ± 5
79 11 05	4[a]	3 909 ± 410	3 558 ± 373	(352 ± 45)	25 ± 8	10 ± 4	255 ± 16	13 ± 2	11 ± 1	38 ± 9
Post-spill average	9	4 106 ± 638	3 964 ± 624	(142 ± 43)	16 ± 6	13 ± 4	66 ± 31	24 ± 8	6 ± 3	16 ± 5

[a] One unit = half of 3 pooled cores

Table 3b. Meiofauna abundance (as 10^3 ind. · m^{-2} ± standard error of mean) at Station 21 (slightly oiled). *n* = number of sampling units counted

Date	*n*	Total	Nematoda	(Total excluding nematoda)	Turbellaria	Kinorhyncha	Harpacticoida	Ostracoda	Temporary meiofauna	Others
74 08 05	3	8 840 ± 3 080	8 146 ± 2 949	(694 ± 147)	120 ± 44	42 ± 12	101 ± 6	147 ± 23	7 ± 1	277 ± 136
76 11 23	3	7 171 ± 442	6 738 ± 426	(433 ± 25)	172 ± 47	23 ± 11	100 ± 20	133 ± 14	3 ± 1	3 ± 2
Spill										
78 06 06	3	5 228 ± 681	4 799 ± 654	(447 ± 55)	158 ± 11	71 ± 28	121 ± 36	78 ± 7	9 ± 2	9 ± 6
78 11 14	4	7 531 ± 805	6 915 ± 815	(616 ± 67)	258 ± 27	67 ± 15	170 ± 59	85 ± 10	20 ± 6	20 ± 20
79 07 24	4[a]	6 004 ± 222	5 496 ± 218	(508 ± 8)	131 ± 12	39 ± 16	157 ± 31	135 ± 7	35 ± 6	11 ± 4
79 11 06	4[a]	5 258 ± 424	4 974 ± 417	(284 ± 26)	49 ± 16	49 ± 23	61 ± 23	112 ± 17	6 ± 2	6 ± 5
Pre-spill average	2	8 005 ± 835	7 442 ± 704	(563 ± 131)	146 ± 26	33 ± 10	101 ± 1	140 ± 7	5 ± 2	140 ± 137
Post-spill average	4	6 005 ± 540	5 546 ± 480	(464 ± 70)	149 ± 43	57 ± 8	127 ± 25	102 ± 13	17 ± 7	12 ± 3

[a] One unit = half of 3 pooled cores

Table 3c. Meiofauna abundance (as 10^3 ind. · m^{-2} ± standard error of mean) at Station 15 (reference). *n* = number of sampling units counted. The significance levels refer to a comparison of pre- and post-spill means, using the two-tailed rank-sum test according to Dixon and Massey, 1969, p 344

Date	*n*	Total	Nematoda	(Total excluding nematoda)	Turbellaria	Kinorhyncha	Harpacticoida	Ostracoda	Temporary meiofauna	Others
71 05 25	1/4[a]	7 878	7 375	(503)	57 ± 28	89	284	49 ± 29	16 ± 9	8 ± 8
71 11 12	1/5[a]	5 678	5 374	(304)	25 ± 8	129	94	52 ± 17	1 ± 1	4 ± 4
72 05 09	3	3 296 ± 609	2 972 ± 549	(324 ± 70)	35 ± 9	99 ± 27	92 ± 48	53 ± 20	7 ± 4	41 ± 6
73 10 31	3[b]	7 721 ± 760	7 435 ± 736	(290 ± 26)	65 ± 15	80 ± 17	39 ± 11	73 ± 5	11 ± 5	32 ± 8
75 05 23	3[b]	6 930 ± 871	6 433 ± 823	(498 ± 51)	86 ± 17	110 ± 37	78 ± 43	110 ± 11	10 ± 5	104 ± 43
75 11 06	3[c]	7 023 ± 251	6 456 ± 259	(567 ± 75)	201 ± 31	52 ± 9	169 ± 42	127 ± 7	4 ± 1	14 ± 6
Spill										
78 03 09	3	7 851 ± 1 071	7 244 ± 1 015	(608 ± 66)	223 ± 17	159 ± 23	41 ± 8	165 ± 44	7 ± 1	14 ± 7
78 06 20	3	6 168 ± 1 091	5 735 ± 1 114	(433 ± 37)	195 ± 14	58 ± 25	49 ± 11	77 ± 19	14 ± 8	40 ± 19
78 08 23	3	5 718 ± 2 411	5 318 ± 2 338	(400 ± 82)	190 ± 55	58 ± 38	69 ± 8	46 ± 16	25 ± 2	12 ± 8
78 11 15	4	5 763 ± 583	5 279 ± 572	(484 ± 41)	194 ± 20	76 ± 13	107 ± 31	94 ± 20	10 ± 3	4 ± 2
79 11 05	4[c]	4 264 ± 402	3 756 ± 326	(508 ± 111)	74 ± 22	107 ± 21	208 ± 55	99 ± 17	8 ± 2	12 ± 11
Pre-spill average	6	6 421 ± 702	6 008 ± 681	(414 ± 50)	78 ± 27	93 ± 11	126 ± 36	77 ± 14	8 ± 3	34 ± 16
Post-spill average	5	5 952 ± 574	5 394 ± 554	(487 ± 36)	175 ± 26	92 ± 19	95 ± 31	96 ± 20	13 ± 4	16 ± 7
Significance level P =		> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	

[a] Higher *n* valid for groups where ±SE is given (sub 100 μm fraction examined only for one sampling unit)
[b] One unit = 4 pooled cores
[c] One unit = half of three pooled cores

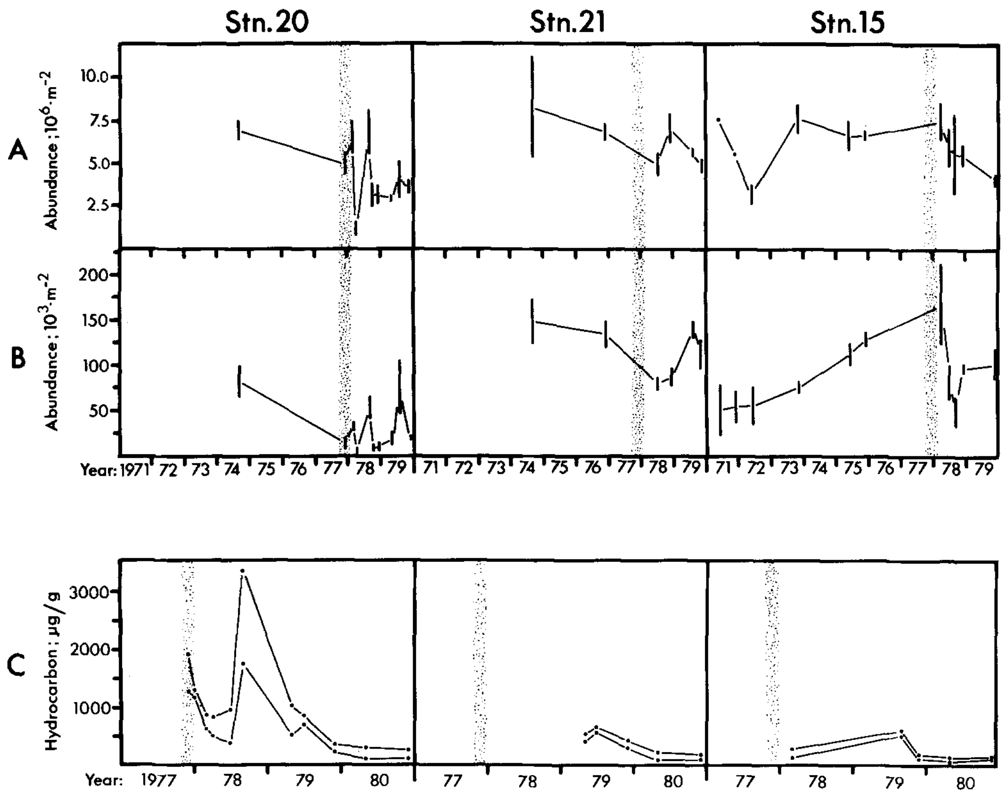

Fig. 4. Nematode (A) and ostracode (B) abundances ($\bar{X} \pm$ SE) before and after the spill (indicated by the shaded line). Hydrocarbon concentration in *Macoma balthica* (C). Upper line total concentrations, lower line aromatic hydrocarbons only

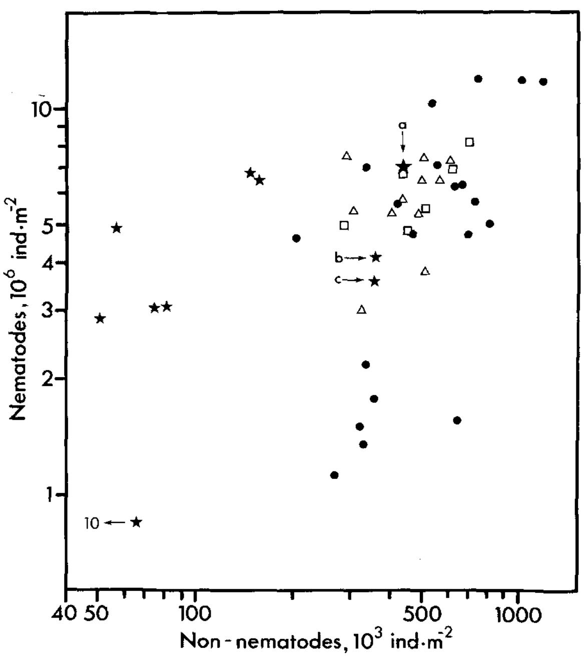

Fig. 5. Nematodes versus other metazoan meiofauna at oiled Station 20 = ★, slightly oiled Station 21 = □ and reference Station 15 = △ (from Table 3); and from 20 mud stations below 24 m depth in the Askö-Landsort area = ●, single core samples from July 1971 (Ankar and Elmgren, 1976). Letters at arrows pointing to Station 20 symbols give sampling dates: a = 74 08 05; b = 79 07 24; c = 79 11 05. Note logarithmic scales

Oil Contamination of Sediment and Biota

The sediment samples generally contained low levels of hydrocarbons, probably partly of weathered petroleum origin, but none, not even a few samples with higher levels, could be positively identified as of "Tsesis" origin (Boehm *et al.*, 1982).

"Tsesis" oil could, however, be identified in considerable quantities in benthic organisms (Table 5). Initial levels in *Macoma balthica* within the first month after the spill were near 2 000 $\mu g\ g^{-1}$ (total saturated + aromatic hydrocarbons) at Station 20, and gradually decreased in the next half year, while the composition showed progres-

Table 4. The numbers of dead and live ostracods in dredge samples from oil polluted Station 20 and reference Station 15 on two occasions in the spring following the spill

Date	February 17, 1978		March 9, 1978	
Station	15	20	15	20
No. of dead ostracods	5	848	18	312
No. of live ostracods	150	43	130	12
	$X^2 = 736$, df = 1 $P < 0.001$		$X^2 = 338$, df = 1 $P < 0.001$	

Table 5. Hydrocarbon concentrations in biota. UCM = unresolved complex mixture. Saturated, aromatic and total stand for: total saturated hydrocarbons (resolved + UCM); total aromatic hydrocarbons (resolved + UCM); and total hydrocarbons respectively. The hydrocarbons are further classified as probably being of "Tsesis" origin or resembling weathered "Tsesis" oil (+ + +), as originating from petroleum sources (+ +), or as biogenic compounds only (+). Concentrations in Ref. 1 and Ref. 2 represent offshore background values (Fig. 1). Ref. 3 is an area west of the Askö Laboratory where herring were caught. litt. 1 and litt. 2 are flounder caught at littoral stations in the polluted and unpolluted areas respectively. f = flesh, l = liver, g = gills, s = stomachs

Species	Station	Date	Saturated (1)	Aromatic (1)	Total (1)	Classification
Macoma balthica	15	Feb. 78	150	120	270	+ +
	15	Aug. 79	80	500	580	+ +
	15	Nov. 79	70	80	150	+ +
	15	Apr. 80	70	30	100	+ +
	15	Nov. 80	40	90	130	+ +
	20	Nov. 77	620	1 300	1 920	+ + +
	20	Dec. 77	100	1 200	1 300	+ + +
	20	Feb. 78	250	610	860	+ + +
	20	Mar. 78	320	490	810	+ + +
	20	Jun. 78	580	380	960	+ + +
	20	Aug. 78	1 630 ± 170	1 770 ± 120	3 400 ± 60 (3)	+ + +
	20	Apr. 79	510	510	1 020	+ + +
	20	Jul. 79	150	700	850	+ + +
	20	Nov. 79	130	210	340	+ + +
	20	Apr. 80	190	90	280	+ + +
	20	Nov. 80	150	100	250	+ +
	21	Apr. 79	140	400	540	+ + +
	21	Jul. 79	80	570	650	+ + +
	21	Nov. 79	130	310	440	+ + +
	21	Apr. 80	130	70	200	+ + +
	21	Nov. 80	90	80	170	+ + +
	Ref. 1	Aug. 80	70	30	100	+ + / + + +
	Ref. 2	Nov. 80	50	30	80	+ + / + + +
Flounder (*Platichthys flesus*)	20	Nov. 78 f	390 ± 20	60 ± 10	440 ± 20 (4)	+ + +
	20	Nov. 78 l	1 140 ± 630	120 ± 30	1 280 ± 620 (4)	+ / + + + (6)
	20	May 79 f	10	50	60	+ +
	20	Jul. 79 f	20 ± 10	90 ± 10	110 ± 10 (3)	+ / + + + (7)
	20	Nov. 79 f	30	40	70	+ + +
	20	Nov. 80 f	20 ± 3	20 ± 5	40 ± 7 (5)	+ + / + + + (8)
	litt. 1	Aug. 79 f	10 ± 1	30 ± 10	40 ± 10 (2)	+ +
	litt. 2	Aug. 79 f	20 ± 1	40 ± 7	60 ± 10 (2)	+ +
Cod (*Gadus morhua*)	20	Aug. 79 f	10	60	70	+
Herring (*Clupea harengus membras*)	20	Nov. 77 g	220	590	810	+
	20	Nov. 77 s	300	150	450	+ / + + (9)
	Ref. 3	Nov. 77 g	110	80	190	+
	Ref. 3	Nov. 77 s	320	80	400	+ / + + (9)

(1) rounded to nearest 10 $\mu g \cdot g^{-1}$
(2) mean of two analyses ± standard error
(3) mean of three analyses ± standard error
(4) mean of four analyses ± standard error
(5) mean of five analyses ± standard error
(6) + + + in one and + in three specimens
(7) + + + in two and + in one specimen
(8) + + + in one and + + in four specimens
(9) biogenic hydrocarbons dominated

sive weathering (Fig. 4c). In summer 1978 the samples showed increased levels, of a composition very like that found in the early samples, and the highest levels found in *M. balthica* at Station 20, over 3 000 $\mu g\ g^{-1}$ total hydrocarbons, were recorded. After this peak, oil levels decreased gradually, and the oil successively lost its characteristic "fingerprint". By 1980 total hydrocarbon levels (Table 5) were only about twice those at reference Station 15 (assumed to represent coastal background; offshore background values, from Stations Ref. 1 and Ref. 2 in Fig. 1, are only about half those at Station 15). The composition, while still resembling weathered "Tsesis" oil by virtue of the present quantities of alkylated phenanthrenes and dibenzothiophene compounds, was no longer distinctive enough to allow positive identification, even using GC/MS analysis.

Four flounder caught at Station 20 in November 1978 contained considerable quantities of hydrocarbons of "Tsesis" origin in both flesh and liver. The concentration in the flesh was about 440 $\mu g\ g^{-1}$. Five flounder caught in 1979 had lower levels (about 100 $\mu g\ g^{-1}$) and by 1980 levels were low (about 40 $\mu g\ g^{-1}$), and only one out of five analyzed specimens showed a "fingerprint" reminiscent of "Tsesis" saturated hydrocarbons. Two "reference" flounder caught in shallow water near Station 15 had about 60 $\mu g\ g^{-1}$ of hydrocarbons. A few analyses of herring in 1977 and one of cod in 1979 failed to show clear evidence of "Tsesis" hydrocarbons (Table 5).

Discussion

Macrofaunal Community Response

The oil spilled from the "Tsesis" rapidly spread into the area east of the grounding site (Fig. 1). Sediment traps deployed in this area demonstrated rapid sedimentation of at least 20 tons of oil (Johansson *et al.*, 1980). This means over 0.5 $g\ m^{-2}$ on average, but probably several times that figure in the most heavily affected parts (including Station 20). Already the first sampling at Station 20 showed a greatly altered macrofauna community, compared to several years of pre-spill data (Fig. 3). This might conceivably be explained by emigration from the affected area, since few dead animals were found. That amphipods actively avoid oil-contaminated sediments has been shown experimentally by Percy (1977) for *Onisimus affinis* and the same is true for *Pontoporeia affinis* (unpublished experiments by M. Notini, personal communication) and probably also for *P. femorata* (Atlas *et al.*, 1978). But that such avoidance could transport the bulk of the population kilometres away, to unaffected sediments, in one or two weeks, seems unlikely. Aquarium experiments (B. Sundelin, unpublished data) have shown that *Pontoporeia* spp. specimens will decompose almost totally in 2 wk at 7 °C, slightly lower than the spill temperature of 8 °C. Thus it seems more likely that the decreased abundance of *Pontoporeia* spp. and *Harmothoe sarsi* was a consequence of direct mortality in the 16 d between the spill and the first macrofauna sampling. That benthic amphipods as a group are exceedingly sensitive to oil pollution has been demonstrated repeatedly (e.g. Sanders *et al.*, 1980; Cabioch *et al.*, 1981; Elmgren and Frithsen, 1982).

The natural variability of the benthic community is always an uncertain factor in evaluating benthos data. From the Baltic, Andersin *et al.* (1978) described a seven-year cycle in abundance of *Pontoporeia affinis* in the Gulf of Bothnia. Such *Pontoporeia* spp. cycles are, however, not evident in benthos data from the Askö-Landsort area going back to 1970 (Cederwall, 1978, 1979 and unpublished data). There is perhaps a tendency towards a cycle, with a minimum around the time of the spill, in the *P. femorata* data (Fig. 3 b), but not in the *P. affinis* data (Fig. 3 a). The short-term *P. femorata* decline at Station 21 in 1977 thus can not be confidently identified as an effect of the oil spill. The simultaneous, drastic decline of both *Pontoporeia* species and *Harmothoe sarsi* at Station 20 is another matter, and must be considered a clear effect of the spill.

The only natural environmental perturbation that could have been expected to cause a reduction of the macrofauna as drastic as that found at Station 20 would have been a period of oxygen deficiency during the late summer or autumn preceding the spill. A partly reduced sediment surface and fairly low oxygen values were found at Station 20 in summer 1978 (postspill; see Elmgren *et al.*, 1980, Fig. 6.2), and could be taken as indicating that even lower oxygen values might have occurred the year before. However, several lines of evidence contradict this hypothesis. First, bottom water oxygen concentrations at three permanent stations in the "Himmerfjärd" were unusually high during 1977 (U. Larsson, unpublished data), even in the heavily eutrophicated innermost parts of the "Himmerfjärd", where low oxygen concentrations are normal in late summer and early autumn. Second, oxygen deficiency would not have resulted in such a drastic decrease of *Harmothoe sarsi,* which normally is the macrofauna species most common in areas of oxygen deficiency in the northern Baltic proper (e.g. Cederwall, 1978). Finally, since there is no question of any oxygen deficiency occurring after the breakdown of the thermocline in early October 1977 or before late summer 1978, one would have expected some re-invasion by *Pontoporeia* spp. and *H. sarsi* from the surrounding areas during the 9–10 months of high oxygen concentrations. There is little evidence of such an immigration to Station 20, the variations noted being more likely due to the natural patchiness of the benthos (since *Macoma balthica,* which is sedentary, also varied). The continued presence of repellent oil hydrocarbons in the sediment indicated by continued high hydrocarbon levels in *M. balthica* from Station 20 (Fig. 4 c) could, on the other hand, easily explain the absence of immigration during the first year and a half following the spill. The partly reduced sediment surface, noted at Station 20 in 1978, is more likely a result of the absence of *Pontoporeia* spp. bioturbation than a cause of the absence of amphipods.

The initial impact of the oil spill on the macrobenthic community at Station 20 was thus well marked, but not a total extermination. While total abundance declined drastically, due to the reduction in abundance of *Pontoporeia* (both species) and *Harmothoe sarsi,* there was initially little change in total biomass, since this is dominated by *Macoma balthica,* which did not decrease. The abundance of the two macrofauna species without swimming ability, and with generally low mobility, *M. balthica* and *Halicryptus spinulosus,* seem to have been little influenced by the spill. In fact, both species increased after the spill (Table 1 a), even though *M. balthica* showed considerable contamination by oil hydrocarbons (Table 5).

In July and November 1979, both *Pontoporeia* species and *Harmothoe sarsi* were once again found in the area in normal or near normal biomasses (Fig. 3 a–c). During 1980–81 the *Pontoporeia* species again showed much decreased biomass values. It seems likely that this repeated reduction is still causally connected to the spill, but the mechanism of action is obscure. Oil levels in the sediment, as indicated by levels in *Macoma balthica,* were much reduced by 1980 (Fig. 4 c, Table 5). It is still conceivable that *Pontoporeia* spp. might burrow into deeper sediment layers, not sampled by *M. balthica,* where toxic hydrocarbon fractions have been preserved. Equally likely is the possibility that oil effects show a small-scale patchiness on the bottom, depending on local sedimentation conditions, which might confuse the picture of the temporal development. A third possibility is that the increased *M. balthica* biomass might have outcompeted the amphipods for food.

The dramatic increase in *Macoma balthica* abundance at Station 20 during 1979 can be satisfactorily explained by the so-called *Pontoporeia-Macoma*-theory of Hessle (1924) and Segerstråle (1962, 1973). They noted a generally negative correlation in field abundance between these two genera, and suggest that the explanation is that high abundance of the deposit-feeding pontoporeias increases the mortality of newly settled *M. balthica* juveniles. This hypothesis has now been tested and upheld in aquarium experiments (R. Elmgren, S. Ankar and B. Marteleur, unpublished data). The oil induced disappearance of *Pontoporeia* spp. in 1978 could thus have resulted in unusually high survival of the *M. balthica* spat settled in 1978, and first recorded in the 1979 macrofauna samples (Fig. 3 e).

The successful *Macoma balthica* recruitment may have changed the competitive balance at Station 20 for many years to come, since *M. balthica* is a very long-lived species (about 25 yr, Segerstråle, 1960). This may lead to continued low biomass and production of the benthic species (*Pontoporeia* spp. and *Harmothoe sarsi*), generally preferred as food by commercially important fish in the area , e.g. herring (Aneer, 1975), and high biomass of less preferred species (*Halicryptus spinulosus* and, notably, *M. balthica*). This is at least the picture during the first 3 yr after the spill (as shown in Fig. 6).

Reproduction of *Pontoporeia affinis*

An increased frequency of abnormal development or non-differentiating eggs in *Pontoporeia affinis* seems to be a very sensitive indicator of toxic substances in the aquatic environment, since Sundelin (1981) also found effects of low levels of cadmium in the water (5 ppb). Nevertheless, this effect is likely to have only minor ecological influence, unless the area affected by oil is very large, since nearly all pontoporeias seem to have left or died at the most heavily impacted station. This is interesting as an example of so-called "effect monitoring" (ICES, 1978). In this case it seems that when the sub-lethal effect had reached a level that could be statistically demonstrated (increase of non-normal eggs from less than 1 to about 7%), the macrofauna community had already changed so drastically, that the impact was immediately obvious and beyond the need for confirmation by statistical testing.

Meiofauna Community Response

The meiofauna was also first sampled 16 d after the spill at Station 20, and then showed a drastic reduction in virtually all common meiofaunal groups (Table 3 a), excluding only the nematodes (Fig. 4 a). The dredge samples of large ostracods, taken in February and March 1978, show a much higher proportion of live ostracods at reference Station 15 than at spill Station 20, where only a few live ostracods were found (Table 4). There is thus clear evidence of a high mortality of ostracods, and population declines also in other non-nematode meiofauna at Station 20 following the spill (Table 3). The ostracod species concerned, and most of the other meiofauna, lack swimming ability and could not have emigrated from the area.

The continued relatively low abundance of all meiofauna, except nematodes at Station 20, for a year and a half following the spill also indicates the low post-spill populations to be an oil effect, since otherwise a rapid development of the meiofauna would have been expected, especially after the reduction of the competing macrofauna. For most of this period oxygen concentrations were adequate, and contribute no alternative explanation for the low non-nematode meiofauna at Station 20.

The harpacticoids were the only non-nematode meiofauna group to show a clear recovery at Station 20 during the 2 yr of monitoring. This agrees with results from microcosms (Grassle *et al.,* 1981) where recovery took only about 2 months, but at higher temperatures. Apparently, some harpacticoids are quite opportunistic, with high potential rates of increase, as shown by rapid increases following caging of salt marsh sediments (Bell, 1980), by early colonization of azoic Baltic sediment (Scheibel and Rumohr, 1979) and by high harpacticoid densities among intertidal algae after the "Amoco Cadiz" spill (Chasse, 1978). They seem to be a meiofauna equivalent to the groups of small, opportunistic benthic polychaetes, described by Gray (1979) as typical of the first stages of benthic macrofauna succession following disturbances, and prominent after the "Florida" spill (Sanders *et al.*, 1980).

Two years after the spill, Turbellaria, ostracods and kinorhynchs were still present in unusually low numbers at Station 20, as compared with pre-spill values (Table 3 a), and with the reference stations (Table 3 b–c).

The clear direct oil effects on the meiofauna community at Station 20 greatly resemble the results of the long-term oil addition experiments in experimental ecosystems, reported by Grassle *et al.* (1981), a similarity already discussed by Elmgren and Frithsen (1982).

Oil Analyses

Even though no "Tsesis" oil hydrocarbons could be identified with certainty in any of the sediment samples, we can state without doubt that oil must have reached the sediment surface, since (1) the sedimenting material in the water column contained large concentrations (up to 0.7%)

of oil, especially in the first week after the spill (Johansson *et al.*, 1980); (2) large *Macoma balthica* collected not only at Station 20, but also at other stations in the area contained considerable quantities of petroleum hydrocarbons of "Tsesis" origin within about a month after the spill, when the first *M. balthica* samples for oil analysis were collected (Boehm *et al.*, 1982); and (3) a smell of oil was detected from several grab samples at Station 20 in November 1977.

The failure to find oil in the sediment samples can probably be explained by several interacting factors. Newly sedimented oil will be concentrated in the uppermost flocculent surface layer of the sediment (Gearing *et al.*, 1980). This layer is not well sampled by gravity corers, such as those used in the present investigation (McIntyre, 1971; Elmgren, 1973; Gearing *et al.*, 1980). The sampling efficiency of the Askö corer for meiofauna has been tested by Ankar and Elmgren (1976). For the non-nematode meiofauna, which tend to live in the floccular top sediment, the efficiency was only 38–61%. The Kajak corer has been shown to be even less efficient (R. Hallberg, L.-E. Bågander and R. Elmgren, unpublished data). After the sampler had been brought to the surface, it is likely that there was an even further loss, as the water, with its suspended load of probably oil-contaminated surface floc, was poured off from above the sediment, prior to extrusion and sectioning of the cores. Finally, the sediment contained fairly high concentrations of biogenic hydrocarbons and in some cases unidentified petroleum hydrocarbons as well, and this would tend to swamp the signal from newly sedimented "Tsesis" oil. This is especially likely since sections as thick as 2 cm were used for all early sediment cores.

The oil analyses of *Macoma balthica* showed maximum oil contamination at Station 20 as late as the summer after the spill (August 1978). Whether this is due to the suspected patchiness of the oil impact (Elmgren *et al.*, 1980) or to re-introduction of relatively non-weathered oil from elsewhere, e.g. shallower sediments (Boehm *et al.*, 1982), cannot be determined with certainty. Both macro- and meiofauna population data from Station 20 indicate larger oscillations after the spill (Figs. 3, 4a–b), as after the West Falmouth oil spill (Sanders *et al.*, 1980), but this may be partly an artifact, caused by patchiness in the impact of the oil.

The relatively low sensitivity of *Macoma balthica* to oil pollution, coupled with its ability to take up hydrocarbons from the sediment, makes it an excellent indicator of the level of oil pollution to which a soft bottom area has been subjected. This supports the value of *M. balthica* as an indicator of oil pollution, as suggested by Shaw *et al.* (1977) and Taylor and Karinen (1977).

Duration of Impact

The most persistent biological effects following the "Tsesis" spill were recorded in the benthos (cf. Lindén *et al.*, 1979). The oil analyses clearly show the persistence of oil for longer periods in the sublittoral soft bottoms (> 3 yr), than in the littoral zone (~ 1 yr, Boehm *et al.*, 1982) and the pelagic zone (~ 3 wk, Johansson *et al.*, 1980). It is interesting to note that while recovery of the gross taxonomic composition of the meiofauna community seemed well underway by November 1979 at Station 20 (last sampling occasion), the macrofauna community remained disturbed even after over 3 yr, at a time when oil analyses indicated that continued direct oil toxicity was unlikely. We seem to be dealing here with delayed ecosystem effects, which persist even after the direct toxic effects of the oil have disappeared, and similar in principle to the intertidal secondary succession described by Southward and Southward (1978), following the "Torrey Canyon" spill. The total benthic community thus seems to have been a better integrator of environmental impact than a particular physiological parameter of a single species – even a highly sensitive one (such as embryonic development in *Pontoporeia* spp.). This agrees with the suggestion by Mann and Clark (1978) that whole systems are better indicators of oil pollution than single species.

Potential Loss of Fish Production

Since the macrofauna species reduced in abundance and biomass are the most productive (highest P/B ratios, Cederwall, 1977), and are the most preferred food for the local fish fauna (Aneer, 1975), the change in energy flow patterns must have been drastic at the most heavily impacted station (see Fig. 2). Based on Fig. 6 and some

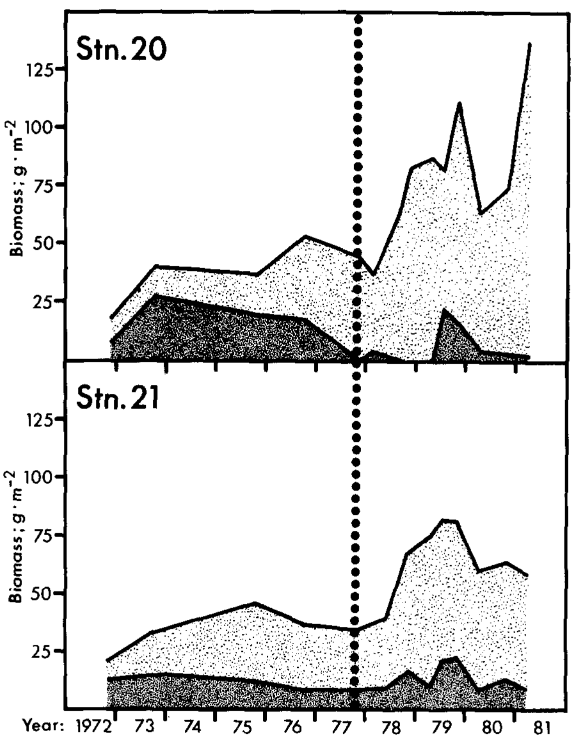

Fig. 6. Prime fish food organisms (*Pontoporeia affinis*, *P. femorata* and *Harmothoe sarsi*, heavily shaded) and other benthic macrofauna (*Macoma balthica* and *Halicryptus spinulosus*, lightly shaded) at Stations 20 and 21, shell-free wet weight. Dotted line indicates spill

unpublished benthos surveys, it is possible to estimate roughly the lost fish food production as follows: $15 \text{ g} \cdot \text{m}^{-2}$ (wet weight) of *Pontoporeia* spp. biomass, lost for 3 yr over 17 km^2 (half the visibly oiled area), and assuming an annual P/B of 2 for *Pontoporeia* spp. (Cederwall, 1977), gives a loss of 1 500 tons of *Pontoporeia* spp. Even though not all *Pontoporeia* spp. are eaten by fish, this could mean a loss of about 100 tons of fish production. Assuming further that half of this could be caught as a commercially interesting fish (herring), it is clear that on this occasion the cost of the direct loss of fish production (less than US$ 50 000 for the first 3 yr) was much less than the costs for the cleanup of the shores (US$ 1 600 000), and "Tsesis" repair and salvage costs (US$ 1 400 000). Total direct costs for the spill thus approximated $ 3 000 per ton of oil spilled. Indirect costs, hard to evaluate in monetary terms, include possible effects on the spawning of herring (discussed by Aneer and Nellbring, in press) and on the location of herring winter schools (such as found in the impacted area before the spill by Aneer *et al.,* 1978), as well as loss of amenity value to local sports-fishermen, due to known or suspected oil contamination of the catch.

Acknowledgements. This investigation could be carried out only due to wholehearted support from the Askö Laboratory staff, and especially its Director, B.-O. Jansson. L. Westin was project leader after the initial year. H. Cederwall carried out some of the sampling. We thank J. Gray, S. Blomquist, E. Bonsdorff and several other colleagues for comments on the manuscript. This investigation was partly funded by the following institutions in Sweden: The Swedish Environmental Protection Board, Sven and Dagmar Saléns stiftelse, The Swedish Coast Guard, Swedish National Food Administration, Ostkustfisk centralförening u.p.a., Stockholms läns Fiskförsäljning ek. för. and in the USA by Bureau of Land Management funds administrated by NOAA-OCSEAP during the first year.

Literature Cited

Addy, J. M., D. Levell and J. P. Hartley: Biological monitoring of sediments in ekofisk oilfield. *In:* Proc. Conf. "Assessment of ecological impacts of oil spills", Keystone Colorado, June 1978. Am. Inst. Biol. Sci. pp 514–539 1978

Aneer, G.: A two year study of the Baltic herring in the Askö-Landsort area, 1970–1972. Contrib. Askö Lab. Univ. Stockholm *8,* 1–36 (1975)

Aneer, G. and S. Nellbring: A SCUBA diving investigation of Baltic herring (*Clupea harengus membras* L.) spawning grounds in the Askö-Landsort area, northern Baltic proper. J. Fish Biol. *21,* 433–442 (1982)

Aneer, G., A. Lindquist and L. Westin: Winter concentrations of Baltic herring (*Clupea harengus* var. *membras* L.). Contrib. Askö Lab. Univ. Stockholm *21,* 1–19 (1978)

Andersin, A.-B., J. Lassig, L. Parkkonen and H. Sandler: Long-term fluctuations of the soft bottom macrofauna in the deep areas of the Gulf of Bothnia 1954–1974; with special reference to *Pontoporeia affinis* Lindström (Amphipoda). Finn. mar. Res. *244,* 137–144 (1978)

Ankar, S.: The soft bottom ecosystem of the northern Baltic proper with special reference to the macrofauna. Contrib. Askö Lab. Univ. Stockholm *19,* 1–62 (1977)

Ankar, S. and R. Elmgren: The benthic macro- and meiofauna of the Askö-Landsort area (northern Baltic proper). A stratified random sampling survey. Contrib. Askö Lab. Univ. Stockholm *11,* 1–115 (1976)

Atlas, R. M., A. Horowitz and M. Busdosh: Prudhoe crude oil in Arctic marine ice, water and sediment ecosystems: degradation and interactions with microbial and benthic communities. J. Fish. Res. Bd Can. *35,* 565–580 (1978)

Bell, S. S.: Meiofauna-macrofauna interactions in a high salt marsh habitat. Ecol. Monogr. *50,* 487–505 (1980)

Boehm, P. D., J. E. Barak, D. L. Fiest and A. A. Elskus: A Chemical investigation of the transport and fate of petroleum hydrocarbons in littoral and benthic environments: the "Tsesis" oil spill. Mar. environ. Res. *6,* 157–188 (1982)

Boucher, G.: Effets a long terme des hydrocarbures de l'"Amoco Cadiz" sur la structure des communautés de nématodes libres des sables fins sublittoraux. *In:* "Amoco Cadiz". Conséquences d'une pollution accidentelle par les hydrocarbures. Coll. Intern. Centre Océanologique de Bretagne, Brest (France) 19–22 novembre 1979, pp 539–549. (ISBN 2-90272-09-9). Paris: CNEXO 1981

Cabioch, L., J. C. Dauvin, F. Gentil, C. Retière et V. Rivain: Perturbations induites dans la composition et le fonctionnement des peuplementes benthiques sublittoraux, sous l'effet des hydrocarbures de l'"Amoco Cadiz". *In:* "Amoco Cadiz". Conséquences d'une pollution accidentelle par les hydrocarbures. Coll. Intern. Centre Océanologique de Bretagne, Brest (France) 19–22 novembre 1979, pp 513–525 (ISBN 2-90272-09-9). Paris: CNEXO 1981

Cederwall, H.: Annual macrofauna production of a soft bottom in the northern Baltic proper. *In:* Biology of benthic organisms. Eleventh Europ. Symp. Mar. Biol., Galway, Oct. 1976, pp 155–164. Ed. by B. F. Keegan, P. O'Ceidigh and P. J. S. Boaden. Oxford: Pergamon Press 1977

Cederwall, H.: Long term fluctuations in the macrofauna of northern Baltic soft bottoms. I. 1970–73. Contrib. Askö Lab. Univ. Stockholm *22,* 1–83 (1978)

Cederwall, H.: Energy flow and fluctuations of deeper soft bottom communities in the Baltic sea. Thesis summary, Askö Lab. and Dept. of Zool., Univ. of Stockholm. 23 pp. Stockholm 1979

Chasse, C.: The ecological impact on and near shores by the "Amoco Cadiz" oil spill. Mar. Pollut. Bull. *9,* 298–301 (1978)

Connell, D. W. and G. J. Miller: Petroleum hydrocarbons in aquatic ecosystems – behavior and effects of sublethal concentrations. Pt 1. Crit. Rev. environ. Control *11,* 37–104 (1980)

Connell, D. W. and G. J. Miller: Petroleum hydrocarbons in aquatic ecosystems – behavior and effects of sublethal concentrations. Pt. 2 Crit. Rev. environ. Control *11,* 105–162 (1981)

Cowell, E. B.: Oil pollution of the sea. *In:* Marine pollution, pp 353–401. Ed. by R. Johnston. New York: Academic Press 1977

Craib, J. S.: A sampler for taking short undisturbed cores. J. Cons. Perm. int. Explor. Mer *30,* 34–39 (1965)

Dixon, W. J. and F. J. Massey, Jr.: Introduction to statistical analysis, 3rd Ed., 638 pp. Tokyo: McGraw-Hill Kogakusha, 1969

Dybern, B. I., H. Ackefors and R. Elmgren (Eds.): Recommendations on methods for marine biological studies in the Baltic Sea, 98 pp. The Baltic Marine Biologists Publ. No. *1,* 1–98 (1976)

Elmgren, R.: Methods of sampling sublittoral soft bottom meiofauna. Oikos, Suppl. *15,* 112–120 (1973)

Elmgren, R.: Benthic meiofauna as indicator of oxygen conditions in the northern Baltic proper. Merentutkimuslait. Julk. *239,* 265–271 (1975)

Elmgren, R.: Baltic benthos communities and the role of the meiofauna. Contrib. Askö Lab., Univ. Stockholm *14,* 1–31 (1976)

Elmgren, R.: Structure and dynamics of Baltic benthos communities, with particular reference to the relationship between macro- and meiofauna. Kieler Meeresforsch. Sonderheft *4,* 1–22 (1978)

Elmgren, R., S. Hansson, U. Larsson and B. Sundelin: Impact of oil on deep soft bottoms. *In:* The "Tsesis" oil spill. Report of the first year scientific study (October 26, 1977 to December 1978), pp 97–126. Ed. by J. J. Kineman, R. Elmgren and S. Hansson. Boulder, Colorado: U.S. Dep. of Commerce. Office of Mar. Pollut. Assessment. NOAA, 1980

Elmgren, R. and J. B. Frithsen: The use of experimental ecosystems for evaluating the environmental impact of pollutants: a comparison of an oil spill in the Baltic Sea and two long term, low level oil addition experiments in mesocosms. *In:* Marine mesocosms. Biological and chemical research in experimental ecosystems, pp 153–169. Ed. by G. D. Grice and M. R. Reeve. Berlin: Springer Verlag 1982

Elmgren, R., R. Rosenberg, A. B. Andersin, S. Evans, P. Kangas, J. Lassig, E. Leppäkoski and R. Varmo: Benthic macro- and meiofauna in the Gulf of Bothnia (Northern Baltic). Finn. mar. Res. (In press)

Gerlach, S. A.: Food-chain relationships in subtidal silty sand marine sediments and the role of the meiofauna in stimulating bacterial productivity. Oecologia *33,* 55–69 (1978)

Gearing, P. J., J. N. Gearing, R. J. Pruell, T. L. Wade and J. G. Quinn: Partitioning of No. 2 fuel oil in controlled estuarine ecosystems: Sediments and suspended particulate matter. Environ. Sci. Technol. *14,* 1129–1136 (1980)

GESAMP: IMCO/FAO/UNESCO/WMO/WHO/IAEA/UN, Joint Group of Experts on the Scientific Aspects of Marine Pollution (GESAMP): Impact of oil on the marine environment. Rep. Stud. GESAMP *6,* 1–250 (1977)

Grassle, J. F., R. Elmgren and J. P. Grassle: Response of benthic communities in MERL experimental ecosystems to low level, chronic additions of No. 2 fuel oil. Mar. environ. Res. *4,* 279–297 (1981)

Gray, J. S.: Pollution-induced changes in populations. Phil. Trans. R. Soc. Lond. B *286,* 545–561 (1979)

Hessle, C.: Bottenboniteringar i inre Östersjön. Medd. Kung. Lantbruksstyrelsen. *250,* 51 pp. (1924)

ICES: International Council for the Exploration of the Sea. On the feasibility of effect monitoring. Coop. Res. Rep. *75,* 1–42 (1978)

Johansson, S., U. Larsson and P. D. Boehm: The "Tsesis" oil spill. Impact on the pelagic ecosystem. Mar. Pollut. Bull. *11,* 284–293 (1980)

Kajak, Z., K. Kasprzak and R. Polkowski: Chwytacz rurowy do pobierania prob mikro- i makrobentosu, oraz probo niezaburzonej strukturze mulu dla celow eksperymentalnych. Ekol. Pol. (B) *11,* 441–451 (1965)

Kineman, J. J., R. Elmgren and S. Hansson (Eds.): The "Tsesis" oil spill. Report of the first year scientific study (October 26, 1977 to December 1978), 296 pp. Boulder, Colorado: U.S. Dep. of Commerce. Office of Mar. Pollut. Assessment. NOAA. 1980

Lehman, E. L.: Nonparametrics. Statistical methods based on rank, 457 pp. San Francisco: Holden Inc. 1975

Lindén, O., R. Elmgren and P. D. Boehm: The "Tsesis" oil spill – its impact on the coastal ecosystem of the Baltic Sea. Ambio *8,* 244–253 (1979)

Mann, K. H. and R. B. Clark: Long-term effects of oil spills on marine intertidal communities. J. Fish. Res. Bd Can. *35,* 791–795 (1978)

McIntyre, A. D.: Deficiency of gravity corers for sampling marine meiobenthos and sediments. Nature, Lond. *231,* 260 (1971)

McIntyre, A. D. and K. J. Whittle (Eds.): Petroleum hydrocarbons in the marine environment. Cons. Int. Explor. Mer Rapp. P. V. Reun. *171,* 230 pp. (1977)

Ockelmann, K. W.: An improved detritus-sledge for collecting meiobenthos. Ophelia *1,* 217–222 (1964)

Percy, J. A.: Responses of Arctic marine benthic crustaceans to sediments contaminated with crude oil. Environ. Pollut. *13,* 1–10 (1977)

Renaud-Mornant, J., N. Gourbault, J.-B. de Panafieu et M. N. Helleouet: Effets de la pollution par hydrocarbures sur la méiofaune de la Baie de Morlaix. *In:* "Amoco Cadiz". Conséquences d'une pollution accidentelle par les hydrocarbures. Coll. Intern., Centre Océanologique de Bretagne, Brest (France) 19–22 novembre 1979, pp 551–561 (ISBN 2-90272-09-9). Paris: CNEXO 1981

Sanders, H. L., J. F. Grassel, G. R. Hampson, L. S. Morse, S. Garner-Price and C. C. Jones: Anatomy of an oil spill: long-term effects from the grounding of the barge "Florida" off West Falmouth, Massachusetts. J. mar. Res. *38,* 265–380 (1980)

Scheibel, W. and H. Rumohr: Meiofaunaentwicklung auf künstlichen Weichböden in der Kieler Bucht. Helgol. wiss. Meeresunters. *32,* 305–312 (1979)

Segerstråle, S. G.: Investigations on Baltic populations of the bivalve *Macoma baltica* (L.) Part I Introduction. Studies on recruitment and its relation to depth in Finnish coastal waters during the period 1922–1959. Age and growth. Comm. Biol. Soc. Sci. Fenn. *23,* 1–72 (1960)

Segerstråle, S. G.: Investigations on Baltic populations of the bivalve *Macoma baltica* (L.) Part II. What are the reasons for the periodic failure of recruitment in the deeper waters of the inner Baltic. Comm. Biol. Soc. Sci. Fenn. *25,* 1–26 (1962)

Segerstråle, S. G.: Results of bottom fauna sampling in certain localities in the Tvärminne area (inner Baltic) with special reference to the so-called *Macoma-Pontoporeia* theory. Comm. Biol. Soc. Sci. Fenn. *67,* 3–12 (1973)

Shaw, D. G., A. J. Paul and E. R. Smith: Responses of the clam *Macoma balthica* to Prudhoe Bay crude oil. Proc. 1977 Oil Spill Conf. Am. Petroleum Inst. Publ. *4284,* 493–494 (1977)

Southward, A. J. and E. C. Southward: Recolonization of rocky shores in Cornwall after use of toxic dispersants to clean up the "Torrey Canyon" spill. J. Fish. Res. Bd Can. *35,* 682–706 (1978)

Sundelin, B.: Effects of cadmium on *Pontoporeia affinis* and the natural population of meiofauna in a soft bottom model ecosystem (In Swedish with summary in English). Swedish Environmental Protection Board, P M *1422,* 1–28 (1981)

Taylor, T. L. and J. F. Karinen: Response of the clam *Macoma balthica* (Linnaeus), exposed to Prudhoe Bay crude oil as unmixed oil, water soluble fraction and oil-contaminated sediment in the laboratory. *In:* Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms, pp 229–237. Ed. by D. A. Wolfe. Oxford: Pergamon Press 1977

Thiel, H., D. Thistle and G. Wilson: Ultrasonic treatment of sediment samples for more efficient sorting of meiofauna. Limnol. Oceanogr. *20,* 472–473 (1975)

Date of final manuscript acceptance: November 26, 1982.
Communicated by T. Fenchel, Aarhus