

Chronic effect of No. 2 fuel oil on population dynamics of harpacticoid copepods in experimental marine mesocosms

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ABSTRACT: Harpacticoid copepods in free-standing mesocosms were exposed to No. 2 fuel oil at a concentration of $190 \mu\text{g l}^{-1}$ for 168 d, and then allowed to recover for 64 d. The harpacticoid community was composed of 9 species. *Tisbe* sp., *Rhynchothalestris rufocincta*, *Dactylopodia vulgaris* and *Alteutha rara* were seldom present in the mesocosms, whereas *Longipedia americana*, *Microarthridion littorale*, *Ameiropsis brevicornis*, *Thompsonula hyaenae* and *Enhydrosoma baruchi* were present throughout the sampling period. Chronic effects of oil additions on the population dynamics of 2 of the 5 regularly occurring species, *A. brevicornis* and *T. hyaenae*, were not statistically discernible. *L. americana* and *M. littorale* were adversely affected by the oil additions and their populations did not recover. *E. baruchi* abundances remained fairly constant in the control and experimental tanks throughout the oil additions, but bloomed in the experimental tanks during the recovery period.

INTRODUCTION

Approximately 42 % of all anthropogenic sources of petroleum enter the ocean via runoff from urban and industrial development (Hoffman et al. 1983, NAS in press). The effects of petroleum on marine organisms have been widely examined, but the emphasis of research has been on post-spill effects (for a review of major spills see Teal & Howarth 1984). Little work has been done on the effects of chronic inputs of oil to estuarine ecosystems.

Petroleum is a complex structure that is classified by origin (crude), level of refinement and amount of weathering. All oil is composed of combinations of saturated (aliphatic) hydrocarbons, which predominate in most crude and refined oils, and aromatic hydrocarbons, i.e. compounds with alternate carbon atoms linked by double or triple bonds, typically forming a 6 carbon ring structure. Number 2 fuel oil is a common refined oil used widely in the northeastern United States and thus commonly found in estuaries such as Narragansett Bay (Wade & Quinn 1980). In the present study, the constituents of this oil were operationally divided into 2 fractions: F₁ contained both aliphatic and alicyclic compounds, and F₂ contained aromatic and polyolefinic hydrocarbons.

Meiobenthos is an important link for the transfer of energy from benthic to pelagic food webs (e.g. Coull 1973, Marcotte 1980, Hicks & Coull 1983). In particular, harpacticoid copepods are often the second most numerically abundant organisms in soft sediments (Hicks & Coull 1983). They are also thought to be the most important component in the transfer of energy from the benthos to the pelagic environment via predation by larval and juvenile fish (Hicks & Coull 1983).

Recent studies at the Marine Ecology Research Laboratory (MERL) of the University of Rhode Island, USA, have shown that the benthos is far more susceptible to chronic oil pollution than the pelagic environment (Grassle et al. 1981, Oviatt et al. 1982, Frithsen et al. 1985). In these studies, the majority of the meiobenthos was not sorted to the lowest taxonomic level. This was done to make the project more manageable (Frithsen et al. 1985), but in so doing, some important details on community structures may have been missed.

There have been few and varied reports on the effects of oil on harpacticoids under laboratory conditions. Results ranged from little or no effect, e.g. 42 mg l^{-1} of oil and Corexit 7664 (a dispersant) on *Tisbe bulbisetosa* (Dalla Venezia & Fossato 1977), to reduced production for *Nitocra affinis* with exposure to the

water-soluble fraction of crude oil at a concentration of $200 \mu\text{l l}^{-1}$ (Ustach 1979). In field studies of both real and simulated spills, varied responses also occurred, ranging from increased abundances (Naidu et al. 1978, Fleeger & Chandler 1983), to extreme reduction in abundance (Wormald 1976) and ultimate extinction (Giere 1979).

It is the purpose of this paper to examine the response of harpacticoid communities in a marine mesocosm to chronic exposure to low concentrations of No. 2 fuel oil, over a 7 mo period.

MATERIALS AND METHODS

Six fibreglass cylindrical tanks, each measuring 5.5 m high and 1.8 m in diameter and containing 13 m^3 of water from Narragansett Bay (USA), were used for the chronic oil experiment; 3 were control replicates and 3 were treatment replicates. Each tank contained 30 cm of sediment, a fine silty mud, collected from the north end of Conanicut Island, Narragansett Bay. The tanks were operated on a flow-through system that exchanged 432 l d^{-1} , providing a turnover time of 27 d, approximating that of the bay (Nixon et al. 1980). For a more complete description of the system see Gearing et al. (1979) or Oviatt et al. (1982).

An oil-water dispersion (OWD) of No. 2 fuel oil was added twice weekly to the 3 treatment replicates, from 14 Feb 1977 to 1 Aug 1977, with a 2 mo recovery period. The concentration of oil in the tanks ranged from 300 to $500 \mu\text{g l}^{-1}$ (ppb) immediately after addition, to 30 to $70 \mu\text{g l}^{-1}$ just before the next addition. This gave a geometric average concentration of $190 \mu\text{g l}^{-1}$. For a more detailed description of the methods used for the examination of oil see Gearing & Gearing (1982), and for determination of oil concentration in sediments and particulate matter see Gearing et al. (1980) and Wade & Quinn (1980).

Ten cores of 4.155 cm^2 were collected monthly from each of the 6 tanks. Only the 0 to 2 cm layer of the cores was sampled consistently for meiofauna. All 10 cores were pooled per tank, to reduce sorting time (Grassle et al. 1981, Frithsen et al. 1985). Previous studies had shown that no statistically significant patterns exist in within-tank variance (centre vs margin) (Rudnick et al. 1979).

Samples were sieved through 297, 200, 100 and $44 \mu\text{m}$ sieves. These fractions were subsampled using the method described by Elmgren (1973), and with a micro-splitter similar to that described by Olsson (1975). This generated splits of 1/1 (297 μm), 1/8 and 1/4 (200 μm), 1/8 and 1/40 (100 μm), and 1/200 (44 μm). The samples were stained with rose bengal. The harpacticoid copepods were sorted according to species,

sex/age class, size, tank, replicate and abundance 10cm^{-2} .

The sample program was balanced and complete for each sample date (3 replicates of control and treatment). Within-replicate variance did not form a necessary part of the present sample design (cf. Rudnick et al. 1979). Data were tested for assumptions of a parametric analysis of variance, and after several transformations these assumptions were not met. Therefore, a 2-way (treatment-time) Kruskal-Wallis analysis of variance of the ranks was performed. Differences between rank means were tested using a nonparametric Tukey type test after Miller (1966) (see also Zar 1984). Differences between means were considered statistically discernible at $p < 0.05$ (i.e. the critical value for rejection of the null-hypothesis). The critical values actually calculated for comparisons with $p < 0.05$ are reported in the text.

Means were plotted to indicate quantitative changes in faunal abundances in control and experimental tanks with time. These data did not conform to assumptions of parametric tests of differences among means. Therefore standard deviations would be misleading indicators of differences and accordingly were not plotted. The statistical analysis was done using the Statistical Analysis System (SAS 1982a, b) version 82.4 and a hand calculator.

RESULTS

Behaviour of oil in water column and sediments

Removal of oil from the water column occurred in a number of ways; the majority of the F_1 fraction was removed by volatilisation and sorption to particulate matter (Gearing & Gearing 1982). Bio-degradation seemed to occur only in the n-alkanes (Gearing & Gearing 1982). The F_2 fraction was removed in the colder months by volatilisation, and in the warm months by bio-degradation. Of the aromatic fraction (F_2), 80 to 90 % was in true solution, with the remainder associated with particulate matter (Gearing & Gearing 1982). The F_1 was distributed evenly between micellar form and forms associated with particulate matter (Gearing & Gearing 1982). Of the saturated hydrocarbons (F_1), 70 % was associated with the 0.3 to $45 \mu\text{m}$ size fraction of particulate matter, and 30 % with particles $>45 \mu\text{m}$ (Wade & Quinn 1980).

An unconsolidated layer of floccules was present at the sediment-water interface in the oil tanks throughout the experiment (Gearing et al. 1980, Wade & Quinn 1980), and ranged in depth from 1 mm to 1 cm as the dosing progressed (Gearing et al. 1980). This layer was seldom present in the control tanks and, if present, was

never deeper than 1 or 2 mm (Gearing et al. 1980). The concentration of oil in the sediment, averaged over the top 3 cm, was $151 \mu\text{g g}^{-1}$ dry sediment, or about 12 % of the total amount of F_1 hydrocarbons added (Wade & Quinn 1980). The highest concentration was recorded in the surface flock ($527 \mu\text{g g}^{-1}$ dry sediment), and decreased with depth (Gearing et al. 1980, Wade & Quinn 1980). In a similar experiment in 1978, using the same system but with only $90 \mu\text{g l}^{-1}$ of oil, and a new corer with a much lower bow wave effect, Gearing et al. (1980) found 10 times more of the F_1 fraction in the surface sediments than in the 1977 experiment. The difference was accounted for by the better collection of the surface flock. Using the value measured by Olsen et al. (1982) for the concentration of oil in the surface flock for the 1978 experiment, $900 \mu\text{g l}^{-1}$, an estimate of the concentration for the 1977 experiment, $1800 \mu\text{g l}^{-1}$, was obtained.

After oil addition had stopped, the oil disappeared from the water column within 2 wk, whereas it took a year to be removed from the sediments (Gearing et al. 1980).

Harpacticoids

Nine different species occurred in the tanks; however, *Tisbe* sp., *Rhynchothalestris rufocincta* (Brady 1880), *Dactylopodia vulgaris* (Sars 1905) and *Alteutha rara* (Brady 1910) were seldom present. The 5 regularly occurring species were *Longipedia americana*, *Microarthridion littorale*, *Ameiropsis brevicornis*, *Enhydrosoma baruchi* and *Thompsonula hyaenae*. The total abundances of these taxa in both control and experimental tanks rose from February until March (experimental), or April (control) (Fig. 1). Their abundances fell thereafter in the experimental tanks, but remained high in the control tanks until August (Fig. 1). There was a statistically discernible difference in abundance between control and experimental tanks for the months of June ($p = 0.001$) and July ($p = 0.005$). The abundances in the controls were higher than those in the oiled tanks. In September, after 2 mo of recovery, the abundances in the experimental tanks were statistically greater than those of the controls ($p = 0.001$).

Ameiropsis brevicornis (Sars 1907) populations fluctuated throughout the experiment in both the control and experimental tanks (Fig. 2). No statistical differences in population abundances were detected between the control and oil tanks. A few juveniles were present in the oil tanks in July and September.

Thompsonula hyaenae (I. C. Thompson 1889) reached its population maximum in June in the control tanks (Fig. 3). It usually had a higher abundance in the control than in the oil tanks, but no statistically discern-

ible differences were detected. Juveniles were present in June, but only in the control tanks.

Longipedia americana (Wells 1980) (Fig. 4 A to C) was not detectable in the experimental tanks after May, whereas the population maximum was reached in the control tanks during July. In the July bloom, both sexes and all age classes, except nauplii, were well represented. The population abundances in the control

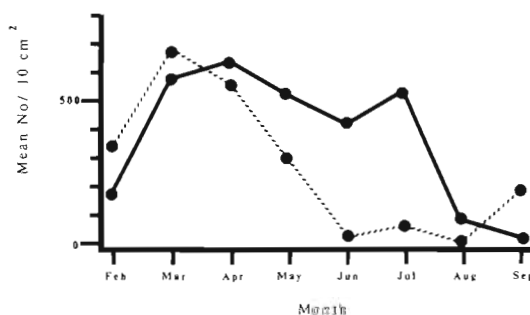


Fig. 1. Relation between mean abundance of total harpacticoid copepods and time for control (solid line) and experimental tanks (broken line). Differences between tanks statistically discernible for June ($p = 0.001$), July ($p = 0.005$) and September ($p = 0.001$).

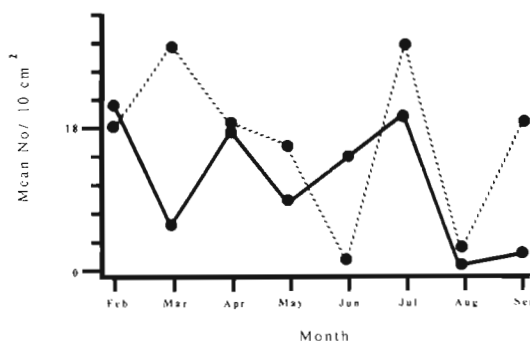


Fig. 2. *Ameiropsis brevicornis*. Relation between mean abundance and time for control (solid line) and experimental tanks (broken line). Differences between tanks statistically not discernible.

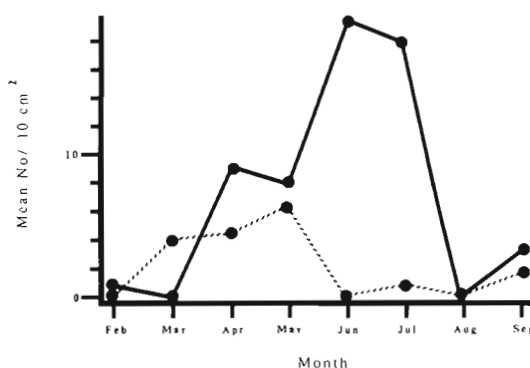


Fig. 3. *Thompsonula hyaenae*. Relation between mean abundance and time for control (solid line) and experimental tanks (broken line). Differences between tanks statistically not discernible.

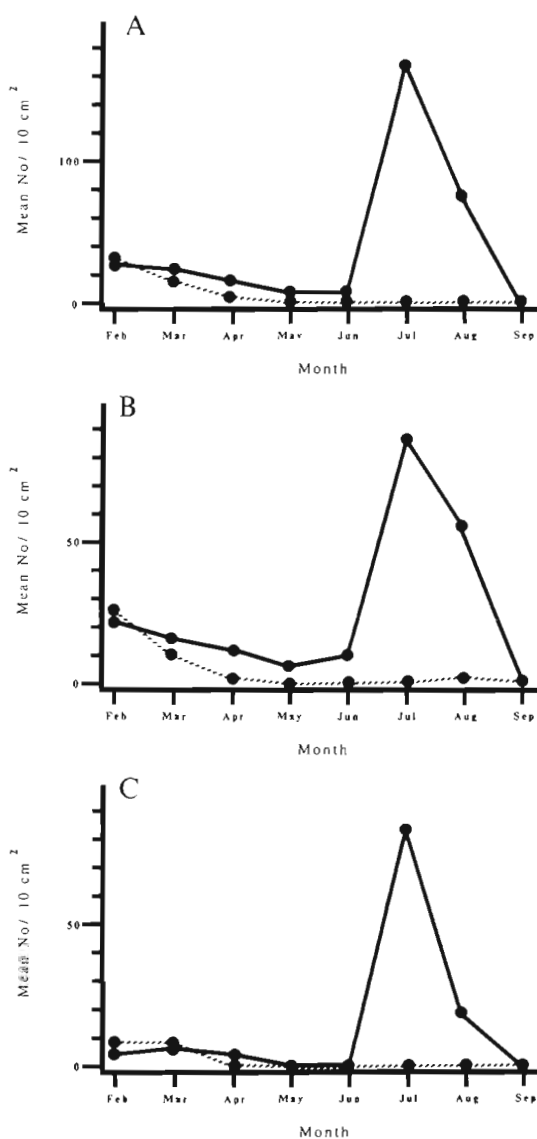


Fig. 4. *Longipedia americana*. Relation between mean abundance and time for control (solid line) and experimental tanks (broken line). (A) Total population; differences statistically discernible for April ($p = 0.025$), May ($p = 0.01$) and July ($p = 0.01$). (B) Adults; differences between tanks statistically not discernible. (C) Juveniles; differences between tanks statistically not discernible

tanks fell precipitously before September. There was a statistically discernible difference in abundance between control and oil tanks for April ($p = 0.025$), May ($p = 0.01$) and July ($p = 0.01$). The abundances in the control were higher than those in the oil tanks.

Microarthridion littorale (Poppe 1881) was the numerically dominant species in the tanks, and reached its population maximum during March–April in both control and experimental tanks (Fig. 5 A to C). No juveniles were present in the oil tanks after May (Fig. 5C). However, juveniles were detected as late as July in the control tanks (Fig. 5C). There was a statistically

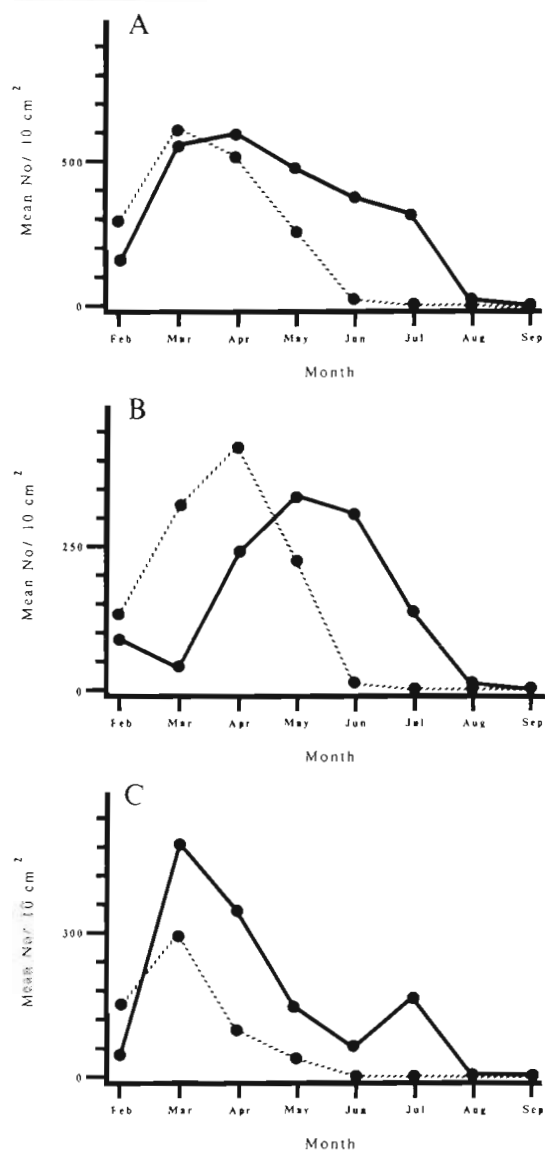


Fig. 5. *Microarthridion littorale*. Relation between mean abundance and time for control (solid line) and experimental tanks (broken line). (A) Total population; differences between tanks statistically discernible for June ($p = 0.001$) and July ($p = 0.01$). (B) Adults; differences between tanks statistically not discernible. (C) Juveniles; differences between tanks statistically discernible for April ($p = 0.001$)

discernible difference in abundances between the control and oil tanks for June ($p = 0.001$) and July ($p = 0.01$), with higher abundances in the control tanks. There were statistically more juveniles present in the control tanks than in the oil tanks for April ($p = 0.001$).

Enhydrosoma baruchi (Coull 1975) reached its population maximum in the experimental tanks during September, 2 mo after the last oil addition (Fig. 6A). No such bloom occurred in the control tanks. There was a statistically discernible difference in abundance between control and oil tanks for September ($p = 0.001$), with the oil tanks containing higher abun-

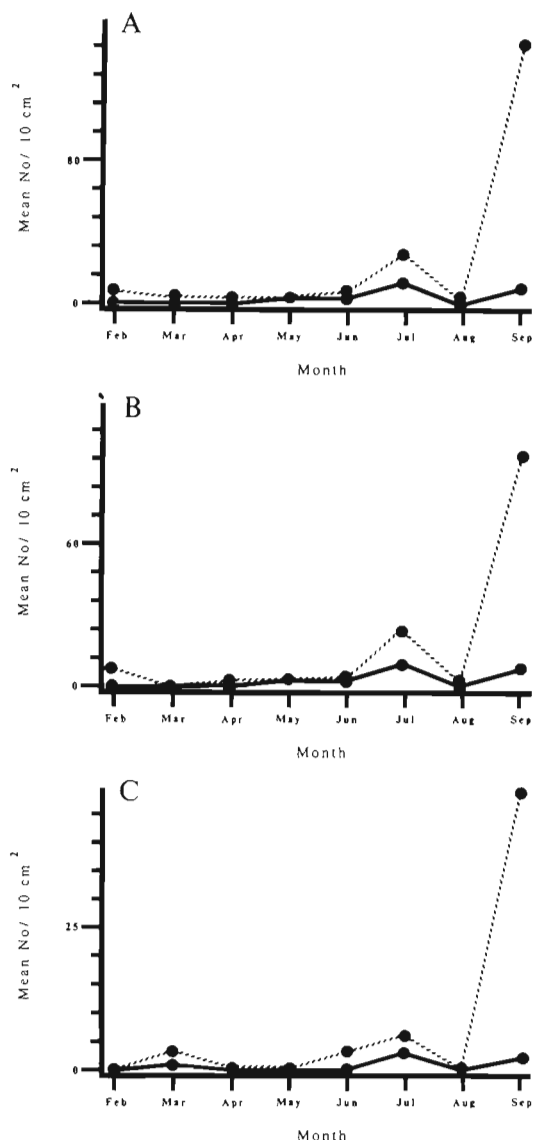


Fig. 6. *Enhydrosoma baruchi*. Relation between mean abundance and time for control (solid line) and experimental tanks (broken line). (A) Total population; differences statistically discernible for September ($p = 0.001$). (B) Adults; differences between tanks statistically not discernible. (C) Juveniles; differences between tanks statistically not discernible

ces. Both sexes and all age classes, except nauplii, were well represented in the bloom (Fig. 6B, C).

DISCUSSION

Pelagic input of oil contaminated the surface flocculent layer of the benthos. This effect was persistent and had statistically identifiable results on the meiobenthic community inhabiting this layer. A similar concentration of oil at the sediment-seawater interface followed the Tsesis oil spill (Boehm et al. 1982).

The presence of oil in this layer was deleterious to

the abundances of 2 species of harpacticoids, *Longipedia americana* and *Microarthridion littorale*. No acute or chronic LC_{50} tests have been conducted on either of these 2 species. Available evidence indicates that the present results may not apply to all other harpacticoid species. Dalla Venezia & Fossato (1977) found no short or long term effects to *Tisbe bulbisetosa* when exposed to concentrations of oil and Corexit 7664 (dispersant) in the 40 mg l^{-1} range. Ustach (1979), on the other hand, reports a reduction in egg production for *Nitocra affinis* after exposure to a water-soluble fraction of oil. Although little is known about the responses of benthic harpacticoids to oil pollution, extensive research has focussed on the effects of oil on planktonic copepods (National Academy of Science 1985), and the range of LC_{50} is between 1 and 100 ppm (Vargo 1981). Oil concentrations experienced by the harpacticoids in the present study were about 1.8 ppm.

A habitat difference exists between *Longipedia americana* and *Microarthridion littorale*. Species of *Longipedia* are well known to be demersally planktonic (Wells 1980). *L. americana* was present in both planktonic and benthic samples (Vargo 1981, present study). It was the second most abundant species in the plankton in the control tanks, during the spring-early summer sampling period, and was less abundant in summer samples (Vargo 1981). Its abundance was severely limited in oil tanks (Vargo 1981). The large increase in abundance in July (Fig. 4A) in the control tanks was probably caused by an influx of this species from the bay as a result of the flow-through feature of these mesocosms. This influx did not appear in the oil tanks, indicating the potentially toxic effects of oil to this species. The OWD of No. 2 fuel oil has been demonstrated to adversely affect the respiration and excretion rates of the planktonic calanoid copepods *Acartia clausi* and *A. tonsa* (Vargo 1981). Vargo (1981) speculates that chronic exposure to this concentration affected the respiratory membranes, thus inhibiting oxygen uptake. *L. americana* has a significantly higher respiration rate than epibenthic or inbenthic harpacticoids (Coull & Vernberg 1970), and thus may be more susceptible to damage to its respiratory membranes. This could account for its low tolerance to oil.

Microarthridion littorale is found in fine flocculent sediments at the sediment-seawater interface; it feeds by sorting bacteria and diatoms from clay floccules (Marcotte 1977, 1983). Its epibenthic habitat was directly affected by the oil. As a result, *M. littorale* was exposed to the highest concentration of oil. As the accumulation of oil progressed, the abundance of *M. littorale* fell precipitously. A decrease in abundance was also observed in the controls, but this occurred 2 mo after the population crash in the oil tanks. Autumn declines in the abundance of *M. littorale* in

natural habitats off shore from MERL were also observed by Marcotte (unpubl.).

Microarthridion littorale did not appear to be as susceptible to the OWD as did *Longipedia americana*, even though it was subjected to much higher concentrations in the sediments. Perhaps this difference could be accounted for in the fractionalization of the oil: F_1 in sediments, F_2 in the water column (Gearing & Gearing 1982). The aromatic fraction of hydrocarbons (F_2) is more toxic to crustaceans than the saturated hydrocarbons (F_1) (Lee 1975, Harris et al. 1977, Trucco et al. 1983).

The negative effect on population abundances of *Microarthridion littorale* may have been mediated by disruption of egg production. Decline in egg production with exposure to oil has been demonstrated in the harpacticoid copepod *Nitocra affinis* (Ustach 1979). Inhibition of egg production would account for the decrease (non-replacement) of juveniles in the oil tanks after the first 2 mo of exposure (Fig. 5C). In nature, however, such non-replacement might not figure largely in the population's response to oil. The nauplii of *M. littorale* are frequently advected by bottom currents/turbulence (Bell & Sherman 1980, Palmer & Brandt 1981). This advection paired with the ability of this species to delay naupliar development (Coull & Dudley 1976) may disperse *M. littorale* populations away from oil-contaminated areas. However this did not occur in these mesocosm experiments.

The only species to exhibit a statistically discernible increase in the oil tanks during the recovery period was *Enhydrosoma baruchi*. Its numbers remained nearly constant in both treatment and control tanks throughout the oil addition period. *E. baruchi* is like *Microarthridion littorale* in habitat and feeding behaviour but may have been able to avoid the toxic affects of the OWD by remaining deeper in the sediments than *M. littorale* and the other harpacticoid taxa (cf. Fleeger 1980). Further, if the metabolism of *E. baruchi* is like its congener *E. propinquum*, a not unreasonable assumption, it probably has a lower respiration rate than either *Longipedia americana* or *M. littorale* (Coull & Vernberg 1970) and may not experience the same degree of respiratory inhibition as postulated above. In accord with the present findings, Fleeger & Chandler (1983) found that *E. woodini* was not only able to withstand large quantities of oil ($13000 \mu\text{g g}^{-1}$ dry sediment) in a simulated spill, but also to increase its abundance. It appears that *E. baruchi* may be able to survive exposure to oil either by avoidance, resistance or both.

Enhydrosoma baruchi grew better during the recovery period in treatment tanks than in the controls. This phenomenon may have 2 causes. (1) There was more fine flocculated material at the sediment-sea-water interface in the treatment than in the control

tanks. Species of *Enhydrosoma* are known to select and thrive best in sediments of this texture and constituency (Marcotte 1983, own obs.). This fact may have predisposed the treatment tanks for a bloom of *E. baruchi*. (2) A second factor must have initiated the bloom. Abundances of *E. baruchi* and *Microarthridion littorale* were significantly negatively correlated in the present study (-0.526 , $p = 0.008$, $n = 24$) indicating that these copepods which have almost the same ecological requirements (living and feeding in similar habitats on similar foods), may have been competitors (but see Fleeger 1980). Release from competition with the autumn decline in abundance of *M. littorale* could have triggered the bloom of *E. baruchi*.

Previous papers published on MERL experiments revealed that the harpacticoids recovered from oil dosings (Elmgren et al. 1980, Grassle et al. 1981, Oviatt et al. 1982, Frithsen et al. 1985). We have demonstrated that the abundances of 2 species were negatively and significantly affected by exposure to oil: *Longipedia americana*, *Microarthridion littorale*. The population of *Enhydrosoma baruchi* increased in treatment tanks after the oil additions ended and the population abundance of *M. littorale* had declined. Although the rise in *E. baruchi* abundance was dramatic, it amounted to only 25 % of the highest abundance recorded for *M. littorale*. Thus an overall trend is that abundances of harpacticoids were reduced in the oil-containing tanks.

During periods of oil pollution and recovery, the present data indicate that harpacticoid assemblages may change from ones numerically dominated by epibenthic and demersally planktonic species (e.g. *Microarthridion littorale* and *Longipedia americana*) to ones dominated by inbenthic taxa (e.g. *Enhydrosoma baruchi*). This change could have important consequences on the transfer of energy to higher trophic levels. For example, harpacticoids are an important food source for estuarine/coastal larval and juvenile fish (Coull 1973, Kaczynski et al. 1973, Marcotte 1980, 1983, Hicks & Coull 1983). Since many benthos-feeding fish larvae are sighted predators, epibenthic/planktonic prey would be easier to capture than inbenthic ones (Marcotte 1983, Marcotte & Browman 1986).

Persistence of the F_1 fraction in sediment, and its effects on population abundances of harpacticoid copepods, demonstrate the vulnerability of meiobenthic systems to oil pollution. Oil concentrations in many of the world's estuaries already exceed the levels found in MERL experiments (Frithsen et al. 1985). One can predict, therefore, that important effects should already be measurable for taxa (e.g. fish larvae) which are tied ecologically to the type and abundance of meiobenthic taxa. Furthermore, even if harpacticoids do survive exposure to oil, they could potentially pose a threat to predators who feed upon them. Schwartz (1985)

showed that feeding behaviours and growth of juvenile pink salmon *Oncorhynchus garbuscha* were adversely affected when fed oil-contaminated prey.

The use of chemical dispersants should also be examined in productive estuarine environments. Wong et al. (1984) showed that in a simulated spill treated with dispersant, the oil formed micro-droplets which became associated with diatoms. As a result, the oil sank much faster. Therefore, while dispersants rid the water column of oil, making the pelagic system appear healthy and productive, benthic habitats and the harpacticoid copepods which inhabit them may become severely and persistently affected.

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