Oil Spill Studies: A Review of Ecological Effects

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ABSTRACT / We reviewed seven particularly well known and/or studied oil spills that have occurred since the National Academy of Sciences 1975 report, "Petroleum in the Marine Environment" or that occurred prior to that report but about which significant new information has since been acquired. The spills studied were from the barge *Florida*, and tankers *Arrow*, *Argo Merchant*, *Amoco Cadiz*, and *Tsesis* and blowouts from the Bravo and Ixtoc I platforms.

These "best" studies yield only limited insight into effects because they lack controls and have a high degree of natural variability. The *Tsesis*, *Florida*, and *Amoco Cadiz* cases are exceptional since they occurred in areas of ongoing research programs and had nearby areas suitable for controls. Oil spills have produced measurable effects on ecosystems that have not been readily predictable from laboratory studies on isolated organisms. However, ecosystem-level interactions are poorly understood even without the complications resulting from effects of pollution. These generalizations emerge: oil regularly reaches sediments after a spill; oil in anoxic sediments is persistent; oil regularly contaminates zooplankton and benthic invertebrates; fish are also contaminated, but to a lesser extent; oil contamination decreases the abundance and diversity of benthic communities.

Offshore spills are very poorly studied, especially with regard to the effects of oil slicks and dissolved oil. Fish eggs, fish larvae, and birds can be killed, but documentation on the extent of these effects is scanty.

Since the Torrey Canyon and Santa Barbara oil spills in 1967 and 1969, the effects of such accidents have been intensively studied. But in spite of all this study there is still a great deal of controversy about the effects of oil in the marine environment, particularly in the more open parts of the oceans. We chose here review studies of seven spills because they were either particularly well studied, very large and well publicized, or both (Table 1, Figure 1): *Florida*—a well studied inshore spill of a light refined oil; *Arrow*—a well studied inshore spill of a heavy refined oil; *Argo Merchant*—an offshore spill of a heavy refined oil thinned with light oil; Bravo—an offshore blowout above the water surface (crude oil); *Tsesis*—a well studied nearshore spill of heavy refined oil; *Amoco Cadiz*—a massive well studied offshore and inshore spill of crude oil; and Ixtoc I—an offshore blowout at the bottom (crude oil).

Our selection includes spills in the nearshore and offshore, of both crude and refined oils, but we do not address the consequences of chronic oil spills such as from refinery effluents. All of the spills reviewed either occurred after the US National Academy of Sciences report of 1975, "Petroleum in the Marine Environment," or if they occurred before that date, have produced significant new information since 1975. Thus it is not surprising that our review reaches several conclusions that are different from those in such early reviews as Moore and Dwyer (1974). For instance, they concluded that 1–2 days of weathering significantly reduces the toxic effects of oil spills. Our review does not support this conclusion.

Our review does not cover all of the information gathered in the studies of these spills, but instead concentrates on a few discrete questions. These are the following: 1) How long does spilled oil persist in various parts of the ocean system? 2) What is the expectation that oil spilled on the surface will reach the bottom, what are the transport mechanisms, and do they vary with distance from shore? 3) Are there generalities about the effects of oil upon benthic and littoral marine systems? 4) Can effects on planktonic organisms be demonstrated and are they important? 5) What effects on fish and fisheries have been found or can be inferred? 6) Is there a significant distinction between effects from spills of crude oil versus spills of refined products? 7) Can we use knowledge gained in experimental studies to infer what effects might occur in spills where we know the concentrations of oil in the environment? 8) Are there effects of potential importance to the ecosystem that emerge from interactions between populations, but that were not readily predictable from knowledge of effects of oil upon individual species?

We do not discuss the effects of floating oil slicks themselves. That slicks affect sea birds and some mammals is unquestioned, although not particularly well studied or documented. We do not discuss the areal extent of damage done by the spills. For most spills this is poorly known, so we prefer to emphasize the types of interactions between spilled oil and ecosystems

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Table 1. Date of spills, volumes of oil spilled, and percentage of spilled oil cleaned up.

	Date	Volume spilled (tons)	% Cleaned up
Florida	09/16/69	630	<1%
Arrow	02/04/70	15,000	<1%
Argo Merchant	12/15/76	28,000	0%
Platform Bravo	04/22/77	20,000	<1%
Tsesis	10/26/77	1,100	~65%
Amoco Cadiz	03/16/78	250,000	<8%
IXTOC 1	06/03/79	457,000– 1,400,000	<10%

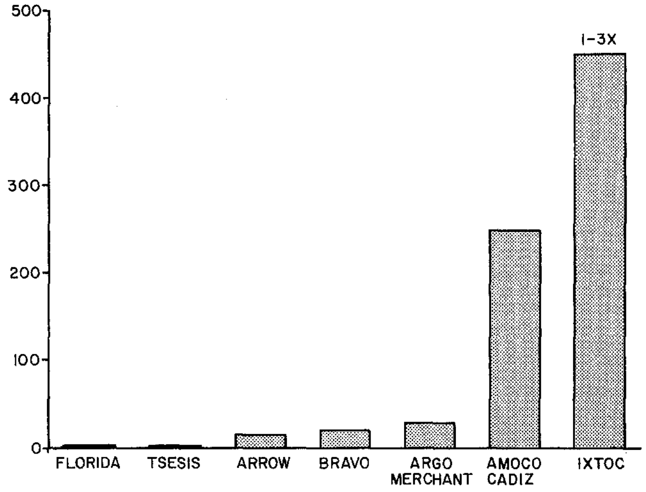

Figure 1. Volume of oil spilled from each of the seven spills. The estimates available for the Ixtoc I spill vary from the 454,000 tons illustrated to almost three times that much.

rather than the extent of these interactions. This field is so unstudied that even the types of effects that occur are often unclear.

Description of the Spills

On September 16, 1969, the barge *Florida* grounded on rocks off West Falmouth, Massachusetts and lost its entire cargo of 630 tons of No. 2 fuel oil, a light distillate. A storm the following day drove the oil ashore, mixing it into water and sediments, tending to maximize the effects. There were immediate kills of small fishes, benthic invertebrates, and marsh organisms. Some dispersants were used and booms were deployed in an attempt to keep the oil out of West Falmouth and Wild Harbors. While visible oil never appeared in West Falmouth, the booms were unable to keep oil out of Wild Harbor. The extent of the immediate kill was documented by timely sampling before the dead organisms decomposed. Oil and some of its effects have persisted in a fraction of the impacted area for at least 12 years after the spill.

On February 4, 1970, the tanker *Arrow* went aground in Chedabucto Bay, Nova Scotia, carrying 15 × 10^3 tons of bunker C fuel oil, of which about two thirds were released into the water. Oil driven by wind and water coated over 300 km of shoreline. Considerable amounts of sea ice prevented observations and sampling until the following spring. Concentrations of total oil in the water column were as high as 100 μg/l in May when first sampled. Dispersants were not used. The most recent studies, published in 1978, indicate that oil persisted in some areas for six years.

The *Argo Merchant* grounded on Nantucket shoals, December 15, 1976, and subsequently lost all 28 × 10^3 tons of its cargo, No. 6 fuel oil thinned with about 20% of its volume with cutting stock (equivalent to No. 2 fuel oil). Storms broke up the vessel and attempts both to prevent a spill by pumping oil into another vessel and to clean up the spill were total failures. Burning the oil was tried without success. No dispersants were used. Oil escaped from the wreck for one month, until January 15. Most of the oil formed into large, floating "pancakes" and disappeared into the ocean to the east. Parts of the cutting stock dissolved and could be found under the slick at concentrations up to 250 μg/l.

Platform Bravo in the Ekofisk field in the North Sea blew out from April 22–30, 1977. About 20 × 10^3 tons of oil, at a temperature of 75–90°C, shot 50 m into the air. Much of the material evaporated, but about 12 × 10^3 tons fell back onto the sea surface, resulting in a slick covering some 4000 km^2. Containment efforts were generally unsuccessful. Dispersants were used only in the immediate vicinity of the platform. Up to 300 μg/l of oil were detected within 18 km of the blowout, with no concentration gradient in the upper 5 m. The spill occurred before the spring bloom, so biomass of plankton was low.

On October 26, 1977, the tanker *Tsesis* went aground in the Baltic, within the Swedish archipelago, and lost 1100 tons of oil, mostly No. 5 fuel oil, but some bunker oil as well. Environmental temperatures were low and intertidal organisms were already inactive. Cleanup was relatively successful due to the unusually favorable circumstances, and only about 400 tons of oil were not recovered. No dispersants were used on the slick. In that part of the Baltic, low salinity, varying from 6.6 to 7.9‰, results in a relatively depauperate fauna. The sediment load in the water is low, but significant amounts of a wide variety of pollutants are present. This is typically a low energy environment. The site was well studied before the spill and investigations of the spill began within one day of the event.

The supertanker *Amoco Cadiz* went aground on March 16, 1978 on rocks off Portsall on the northwest coast of France resulting in what was then the world's largest oil spill. All of the cargo, about a quarter of a million tons of light Arabian and light Iranian crude, was lost over a period of 15 days. The oil formed a water-in-oil mousse of at least 50% water, came ashore, and heavily impacted 140 km of Brittany coast and affected less intensely another 260 km. Less than 20,000 tons was cleaned up, mostly by scraping it off beaches. Booming estuaries and skimming the oil was not effective. Dispersants were used to some extent offshore and in cleaning some shores and seawalls. There is a partial lack of data on biological recovery from this spill because just two years after *Amoco Cadiz,* the tanker *Tanio* broke up off the coast and reoiled 45% of the area affected by the first spill (Gundlach and others 1981).

On June 3 1979, Ixtoc I, an exploratory well, blew out in 48 m of water about 80 km from shore in Bahia de Campeche, Mexico. Fire broke out and destroyed the rig. Oil and gas then entered the water at the bottom. Gas rose to the surface and burned. Some portion of the oil was dispersed in the water; some formed a large slick, which in mid-June covered over 3000 km^2. The well was finally capped in March 23, 1980. Estimates of the volume of oil spilled varied from 454×10^3 to over 1.4×10^6 tons. Less than 10% was recovered. By all estimates this surpassed the *Amoco Cadiz* spill of the previous year, making it the world's largest oil spill. Large amounts of dispersants were used in the vicinity of the well and south of 25°N. Oil was found more than 1000 km from the blowout. It reached Mexican and Texas beaches. On the latter, it was estimated that 10,000 tons came ashore. Hurricanes from July onward hampered capping and clean-up operations, although Hurricane Frederick in mid-September cleaned off the Texas beaches. At present there is very little information about biological effects of the spill, especially in Mexican waters.

Persistence of Oil

Oil in the water column may persist for half a year, but is usually diluted and sedimented to background levels much more rapidly than this. The highest levels of hydrocarbons are found in chronically polluted waters, immediately under slicks or in areas where the oil is mixed into the water by wave action or as a result of being injected at the bottom. In the *Amoco Cadiz* case, immediately after the spill, there were 3–20 μg/l offshore, 2–200 μg/l nearshore, and up to 500 μg/l in the "Abers" (estuaries). These concentrations decreased to background levels (2 μg/l) by April, mid-May, and not until after September in these three areas, respectively (Marchand and others 1979). Immediately under the *Argo Merchant* slick, oil that matched the cutting stock in composition was found at concentrations of up to 250 μg/l (Gross and Mattson 1977). In February, two months after the spill, samples taken widely over Georges Bank at all depths, showed elevated hydrocarbon levels (10–100 μg/l) with the characteristics of *Argo Merchant* oil (Boehm and others 1978). Five months after the spill, concentrations had fallen to 1–50 μg/l and were low by the following winter: up to 8 but generally less than 1 μg/l (Hoffman and Quinn 1980). In the Ixtoc I blowout, the total particulate concentrations of the f-2 fraction (naphthalenes, phenanthrenes, and dibenzothiophenes), measured at a depth of 2 m, ranged from 2860 μg/l close to the well, 30–60 μg/l 16-km from the well, to approximately 5 μg/l 44-km away. The dissolved (filterable) fraction of the same compounds were about 50 μg/l near the well, 30 μg/l 16-km distant, and down to background levels 44-km away (Boehm and Fiest 1980).

Oil in sediments is more persistent. In anoxic sediments it can be very long-lasting, as witnessed by the fact that petroleum accumulates geologically under such conditions. There is relatively little data on persistence in sediments following spills, mostly because investigations have not continued for long enough periods. In the *Florida* spill, oil was measured in sediments 7 years after the spill (Teal and others 1978) and is still present 12 years after the spill in at least a small fraction of the initially oiled sediment (judging by appearance and a clearly recognizable smell of fuel oil). In the *Arrow* spill, a follow-up study done 6 years after the spill found 10–25,000 μg/g of oil in sediments measured by UV fluorescence (Thomas 1977). In these sediments newly dead clams averaged 650 μg/g of oil, while living specimens were found to have 150–350 μg/g of oil (Gilfillan and Vandermeulen 1978). Periwinkles were also found to still be contaminated with oil, but the average level of contamination was only 12–18 μg/g. The marsh grass, *Spartina alterniflora,* from six oiled sites still showed the surprisingly high contamination of about 15,000 μg/g, compared with less than 70 in controls (Thomas 1978). Recent estimates put residence time for the *Metula* oil spilled in the Strait of Magellan in 1974 at 15–30 years in low energy sand and gravel beaches, and over 100 years for sheltered tidal flats and marshes (Gundlach and others 1981). Since oil lasts much longer in sediments and has the potential for long-term effects there, we should address the likelihood of oil spilled on the surface reaching the bottom.

Oil Transport to the Bottom

In all 7 spills we reviewed, there is evidence either that oil was transported to the sediments (that is, it was detected in the sediments themselves or in the benthic animals) or that a mechanism for such transport was present (Table 2). In the

Table 2. Evidence for transport of oil to sediments.

	Direct chemical analysis of sediments	Chemical analysis of benthic fauna	Analysis of zooplankton guts and/or fecal pellets	Sediment traps
Florida	+	+	0	0
Arrow	0	+	+	0
Argo Merchant	–	–	+	0
Bravo	–	0	0	+
Tsesis	–	+	+	+
Amoco Cadiz	+	+	0	0
IXTOC 1	+	0	0	0

+ = observed.

– = not observed, or observed only occassionally.

0 = no pertinent observations; or data collected, but interpretation is ambiguous.

Florida, Amoco Cadiz, and Ixtoc I spills, oils attributable to the spills were found in the sediments by chemical analyses (Blumer and Sass 1972a, b, Marchland and Caprais 1981, Boehm and Fiest 1980). In addition in the *Arrow* (Scarratt and Zitko 1972) and *Tsesis* (Boehm and others 1980) spills, analyses of the benthic fauna detected oil similar to that spilled, indicating that oil had reached the bottom. There was no good evidence of oil from the spills in bottom sediments or animals in the *Argo Merchant* or Bravo spills. The sediments sampled after the Bravo spill were contaminated with oil, but it was believed to come from chronic pollution associated with the oil development (Audunson 1977), which would make it very difficult to detect small amounts of spilled oil.

Oil can reach the bottom by various mechanisms. One of these is direct mixing of oil with sediments by wave action in shallow water with transport to deeper water by density currents, as occurred in the *Florida* spill (Sanders and others 1980). Sorption onto particulate matter suspended in the water column with subsequent sinking can also occur in deeper water. Sediment traps set out the month following the Bravo spill collected from 1.0–21.8 mg/g (dry weight) crude oil content compared to 0.8 at a control site (Mackie and others 1978). Another mechanism for sedimentation of oil is uptake by zooplankton, packaging as fecal pellets, and subsequent sinking of the pellets, as measured in the *Arrow* spill (Conover 1971). When oil is detected in the guts of zooplankton, as in the *Argo Merchant* (Gross and Mattson 1977) and *Tsesis* (Johansson 1980) investigations, one can assume that some will be incorporated into fecal pellets and sink.

Oil from the *Tsesis* spill was never analytically detected in the sediment, even when efforts were made to recover the uppermost surface layers (Boehm and others 1980). However, oil from the *Tsesis* definitely sank through the water as indicated by its presence in benthic organisms, by the population changes in the benthos, and by large amounts of weathered *Tsesis* oil in sediment traps placed in the spill area. Both the trap and organism analyses detected oil over a larger area than exhibited any visible slick or sheen. Oil was even found upwind of the tanker. Extrapolations from the sediment trap results indicate that a minimum of 19 tons or 5% of the oil reached the level of the traps, which were not put in place until 6 days after the spill (Linden and others 1980). Clearly negative analytical evidence from sediment analyses does not prove oil has not reached the bottom.

Oil sedimentation processes have been further elucidated in mesocosms in which carefully controlled studies, not possible in the field, can be conducted. In the CEPEX enclosures, Lee and others (1978a) found the non-volatile aromatic hydrocarbons were taken up by phytoplankton and sedimented with them. Naphthalenes began to appear in the sedimenting particles in less than 2 days. Heavier molecular weight compounds took about one week, although more of the latter compounds eventually reached the bottom. Naphthalenes were being fairly rapidly degraded in the water column by day 3 after the addition of the oil, more than an order of magnitude more rapidly than anthracene. The net result was that compounds from benzene through phenanthrene were lost from the water by evaporation and degradation, while the heavier molecular weight compounds, chrysene through benzopyrene, were mostly sedimented and photochemically broken down. In the MERL mesocosms, experimenters added 190 μg/l of an oil-in-water dispersion of No. 2 fuel oil to their tanks for 25 weeks beginning in February. At 20 weeks there were 109 μg/g of oil in the upper 2-cm of sediments at the bottom of the 13-m deep tanks (Elmgren and others 1980a).

The lack of degradation and, therefore, the accumulation in sediments of the heavier molecular weight aromatic hydrocarbons are supported by field data from the *Amoco Cadiz* spill

(Atlas and others 1981). The larger molecules, which in this case included alkylated phenanthrenes and dibenzothiophenes, were relatively enriched in the sediments as time progressed. Methyl anthracene and benzanthracene were bio-degraded only by co-metabolism, not all the way to carbon dioxide. When the more readily degraded molecules were gone, the larger aromatic hydrocarbons and their partial metabolites remained in the sediments.

We now know that in even the deep parts of the oceans, particles reach the bottom rapidly enough to transmit seasonal effects, that is, there is bulk settling in less than 60 days to 3200 m (Deuser and others 1981). We may thus expect that the heavier molecular weight hydrocarbons will typically reach ocean sediments more or less in proportion to their supply to the surface waters.

Benthic and Littoral Effects

Massive kills can occur when oil reaches the benthos in sufficient quantity. The only indication of a massive kill may lie in the remains of the dead organisms, but if they lack hard parts there will be little evidence left. Within twelve hours after the *Florida* spill, there was nearly total eradication of the macrobenthos at the most heavily oiled sites containing over c.133 mg/l wet weight (reported as 400 mg/l dry wt). At sites with intermediate oil levels (9–100 mg/l), there were intermediate reductions compared to control sites. Soft bodied animals killed by the oil disappeared within one week. Their deaths would not have been detected by sampling initiated later than this (Sanders and others 1980). The Falmouth shellfish warden reported that 27 m^3 of soft-shell clams (*Mya arenaria*), and 40 m^3 of seed clams were killed in Wild Harbor by the *Florida* spill (Souza 1970). Marsh grass, *Spartina alterniflora*, was completely killed on the most heavily oiled parts of the intertidal area (over 2000 mg/l).

In the *Tsesis* spill there was a dramatic difference in effects on plants and animals of the littoral zone. The dominant littoral alga in the region is *Fucus vesiculosus*, which suffered no effect that could be measured. This may have been partly due to the fact that the plants were dormant when the spill occurred. On the other hand, "A drastic decrease of the total *Fucus* macrofauna took place along the shore that was first hit by the oil." Up to 100% of the crustacea found the day after the spill, before the oil had reached the shore, disappeared once the slick reached their habitat. Faunal density within the algal zone two weeks after the spill was 8–10% of the prespill level (Notini 1980).

Oil from the *Amoco Cadiz* reached the bottom over a large region. It penetrated to a depth of 7 cm, with the highest concentrations found in muddy sediments. Ampeliscid amphipods, which had accounted for c.40% of the biomass in fine sand sediments offshore, were virtually eliminated (Cabioch and others 1981). Inshore there was massive mortality of some species such as heart urchins, razor clams, and the amphipod *Bathyporeia,* while other species such as the clam *Tellina* and the polychaete *Owenia* survived (d'Ozouville and others 1979).

In the Abers, benthic populations were correlated with hydrocarbon levels in the sediments. At less than 50 mg/l in the sediments, population simply decreased with no evidence of change in structure. Between 100 and 1000 mg/l, species of small polychaetes, mostly Cirratulids and Spionids, appeared. At the highest levels of pollution, over 10,000 ppm, only the opportunistic Cirratulids and Capitellids were present (Glemarec and Hussenot 1981).

The most exposed rocky shores of the Brittany coast were protected from oil by reflected waves. On sheltered rocky shores, *Ascophyllum* was killed and replaced by *Fucus* as long as there were *Fucus* plants in the vicinity to serve as propagule sources (Gundlach and others 1981). *Fucus* sp. in general suffered little from the oil in either appearance or growth except where they were damaged by clean-up operations (Topinka and Tucker 1981). A variety of animals, particularly limpets and periwinkles, were also killed. Effects were due to oil alone since they were observed in areas where no detergents were used (Hess 1978).

Beaches were littered with dead animals immediately after the spill. Many species found dead occur both subtidally and intertidally. But sand hoppers, characteristic only of upper beach levels, were found dead by the thousands on at least one beach. Interstitial faunas were not examined (Hess 1978). The spilled oil came ashore during an erosional period and was subsequently covered during the depositional period. As a result, beaches retained oil in buried layers for 2 years after the spill (Hess 1978).

There is much less information on the impact of the Ixtoc I spill on benthos. The best studies were on the Texas coast 1000 km from the spill. The macro-infauna, dominated by polychaetes and haustoriid amphipods, decreased in population densities, but not in number of species after Ixtoc I. The changes were probably due to the Ixtoc oil, although the authors suggest that hurricanes, seasonal changes, and clean-up techniques could also have been responsible. However, other studies in the Gulf region did not show any effect of storms on numbers of individuals (Thebeau and others 1981).

There are organisms that are extremely sensitive to oil spills, such as ampeliscid amphipods, while other forms are relatively resistant. In the *Florida* spill, oiled sediments acted as traps for ampeliscids because they continued to move into contaminated sediments and subsequently died until the oil decreased in concentration or toxicity sufficiently to permit their survival (Sanders and others 1972).

There was a dramatic decrease in the abundances of two species of amphipods and one polychaete species within sixteen days after the *Tsesis* spill. The data do not permit distinction between death or emigration as the reason for the change. These affected animals exhibited a subsequent small increase in numbers followed by another fall to almost zero. This may indicate migration into the polluted area followed by death of the migrants (Elmgren and others 1980b). In spite of the reduction in numbers, it was possible to examine reproductive success in a few amphipods in the affected area. About 10% of eggs showed either abnormal or undifferentiated embryos, compared to 1% in the control area (Elmgren and others 1980b).

On the other hand, little or no response to the spill was observed in either numbers of individuals or biomass in some benthic species. After the *Tsesis* spill, good examples of this were *Macoma,* a small clam, and priapulid, a type of worm. Since *Macoma* dominates the benthic biomass, there was no decrease in overall biomass (Elmgren and others 1980b). However, *Macoma* did exhibit an effect of the oil. Individuals collected from the spill area about one week after the event burrowed into clean sand in the laboratory significantly more slowly than clams from a control area. This sublethal effect of the spill would have subjected them to more than normal predation when they were exposed by sediment movements (Linden 1980).

Six years after the *Arrow* spill, populations of the lug worm, *Arenicola,* were more abundant in the oiled sediments than anywhere else in Nova Scotia, despite elevated hydrocarbon concentrations, suggesting that they are relatively resistant to oil pollution (Gordon and others 1978). Although after the *Amoco Cadiz* spill almost the entire fauna of exposed intertidal mud flats was killed by oil, in more sheltered areas the lugworm *Arenicola* was very common after the spill (Gundlach and others 1981).

Within the meiofauna, nematodes tend to be resistant, while ostracods are sensitive to oil. Meiofauna were reduced in abundance after the *Tsesis* spill except for nematodes, which were considered as a group and not analyzed according to taxa. Most of the ostracods (a group of small crustacea) were killed, as indicated both by the low number of live individuals and the high ratio of dead to living individuals in samples from the affected area, compared with controls. Samples taken ten months after the spill still showed a reduction in numbers. This is almost certainly a direct result of the oil, since otherwise one would expect to see a bloom in the meiofauna as a result of the decrease in the macrofauna. The results are very similar to those found in the Marine Ecosystem Research Laboratory (University of Rhode Island) after several months of pollution in an experimental system with No. 2 fuel oil (Elmgren and Frithsen 1982).

In Morlaix channel, *Amoco Cadiz* oil caused a decrease in the abundance of harpacticoid copepods, which fell from 10–35% of the fauna to 2%. The total abundance of meiofauna was not affected due to high productivity of nematodes (Renaud-Mornant and others 1981). Analyses of species composition of the nematodes indicated changes due to the disappearance of dominant species and proliferation of opportunistic species characteristic of disturbed conditions (Boucher 1981).

Once in sediments, hydrocarbons are taken up by benthic organisms with greater uptake of the heavier relative to the lighter molecular weight aromatic compounds. In samples from New York Bight and Buzzards Bay, presumably under equilibrium conditions, annelids contained from 3–5% of the concentration per unit weight of aromatic hydrocarbons found in the sediments (Farrington and others 1981). Uptake from the water may occur more readily than from sediments in carnivores or filter feeders, while deposit feeders, in more intimate contact with porewaters could be expected to show a more rapid uptake from sediments (Anderson and others 1978, 1979). Although some mobile organisms such as fish may avoid contaminated areas, this is certainly not a universal type of behavior, as illustrated by results of Weber and others (1979) with juvenile English sole. The effects that the oil in the sediments may have on fish can depend on the overall amount, but also on the age (composition) of the pollutant and the season (activity level of the fish) (Fletcher and others 1981), with less effect during periods when the animals are less active, as one would expect. The greatest effects are found during reproductive periods when the stress resulting from diversion of energy to gametogenesis presumably enhances the sensitivity of the organisms to pollutants (Jackson and others 1981, Anderson and Anderson 1976), emphasizing reductions in scope-for-growth (Gilfillan and others 1977).

Macoma, which could be collected in abundance following the *Tsesis* spill, were analyzed for hydrocarbons and found to contain 500–900 μg/g dry weight aliphatics and 500–1700 μg/g aromatics one month after the spill. A year after the spill, the clams still contained hydrocarbons, characterized by branched alkanes, isoprenoids, and an unresolved complex mixture, as is typical of weathered oil. The trimethyl benzene series played a "prominent minor role" in the aromatic hydrocarbon chemistry of *Macoma* throughout the study "indicating an interesting resistance to degradation both within the animals and in particulate or sedimented material comprising their food" (Boehm and others 1980).

The edible mussel, *Mytilus edulis,* initially showed rapid uptake of spilled oil to levels of 5–30 mg/g dry weight. The character of the alkane fraction of the oil rapidly changed to that of weathered oil. One year later the animals had returned to their pre-spill conditions, except at the most heavily oiled stations. There was a generally similar story for the aromatic fraction of the oil, although at the one year sampling there were still elevated levels of substituted naphthalenes that had been completely absent in the pre-spill samples. The extent of contamination in *Mytilus* extended over at least 42 km^2, a much larger area than one would have thought was affected, based upon observations of slicks and/or sheens (Boehm and others 1980).

Nine months after the *Amoco Cadiz* spill, petroleum hydrocarbons identified on the basis of their UV fluorescence patterns were observed in limpets from rocky shores and *Mya* (clams) from mud flats. By that time the limpets showed no indication of heavier molecular weight aromatic compounds, although these were still apparent in the clams (Vandermeulen and others 1981).

Some effects of the oil persist as long as the oil persists, and since oil is most persistent in fine sediments, effects are also the most persistent there. Sanders and others (1980) summarized the effects of the *Florida* oil as "faunal changes matched in intensity and duration the gradient of pollution by #2 fuel oil from the *Florida.*" Faunal changes included decreases in diversity, in density, and in numbers of species. Species richness increased before evenness of distribution among species during the recovery process, that is, species returned to the community before the normal distribution of numbers between species was achieved (Sanders and others 1980).

Fiddler crabs (*Uca pugnax*) were reduced in density in the oiled marsh, which as in the case with the benthic amphipods, acted as a lethal trap for these territorial animals. Behavioral changes caused by the oil included slowing of movement and digging of burrows that were shallower than normal. The newly settled animals were more affected than the adults and their settling was reduced (Krebs and Burns 1977). Recovery was highly correlated with the disappearance of the naphthalene fraction of oil in the sediments. Their study areas were not yet comparable to controls after 7 years when their study ended (Krebs and Burns 1978). Fiddler crabs showed induction of mixed function oxygenases, but the levels of activity were too small to rid the animals of their body burdens of oil within their lifetimes (Burns 1976a).

Most of the studies in the *Arrow* spill were done in the rocky and sandy intertidal areas. The oil was concentrated in the upper two thirds of the intertidal areas. It was most persistent at about mean high tide, where in sheltered lagoons it was still present 7 years after the event. The rockweed, *Fucus vesiculosus,* was reduced in vertical distribution for 5 years. *Fucus spiralis,* which is confined in that region to the mean high tide level, was killed and had not reappeared in the oiled region by 1976, six years after the spill. In sheltered areas, the marsh grass, *Spartina alterniflora,* was killed one year after the spill, recovering 2 years later. Rocky shore animals including barnacles and periwinkles did not change in abundance or distribution except where their habitat was changed by changes in rockweed (Thomas 1978). The larvae of *Balanus balanoides,* a barnacle, settled and grew normally even in 1970 (Thomas 1977).

A detailed follow-up study was done in 1976, six years after the *Arrow* spill when the oiled sediments contained from 10–25,000 $\mu g/g$ of oil (measured by UV fluorescence). Species diversity (Shannon–Weiner index) was lower at oiled sites than at unoiled control sites. Macrofaunal biomass was c.1400 wet g m^{-2} at oiled sites, vs. approximately 4400 wet g m^{-2} at control stations. Six and seven years after the spill, populations of soft-shelled clams (*Mya arenaria*) from oiled sites were still stressed. Fewer mature adults were found than at control stations. Individuals showed lower shell growth rates, lower assimilation rates, and lags of 1 to 2 years in tissue growth (Gilfillan and Vandermeulen 1978).

After the *Tsesis* spill, recovery in the littoral zone began within two months, with normal densities reached within one year at some stations. Recovery varied depending on degree of exposure to oil and the species involved. For example, one station exposed less than one day to oil recovered rapidly except for a small species of isopod, *Iaera.* Because of its small size, this isopod did not have sufficient mobility to recolonize the area within the recovery period (about six weeks) of the more mobile species at that site (Notini 1980). At more heavily oiled sites, recovery was slower and populations that had recovered in numbers might still show effects of the oiling. Gammareid amphipods at one heavily affected station had recovered in abundance by June, but only 8% of the samples contained adults compared with 75% in control stations (Linden and others 1980).

After the *Amoco Cadiz* spill, benthic animals depurated at rates depending on period of exposure (Friocourt and others 1981), and on the species. Although Japanese and flat oysters both showed contamination 3 months after the spill, the flat oysters were almost clean 9 months later, while the Japanese oysters were still heavily contaminated (Laseter and others 1981).

Marshes were severely affected where *Amoco Cadiz* oil came ashore, with complete kill of higher plants and fauna. There was no recovery in two years at the most heavily oiled sites (Gundlach and others 1981). The edge of the marsh was especially oil retentive with concentrations of 6,600–245,000 mg/l, 5–10 times higher than in mud flats (Vandermeulen and others 1981). Ile Grande marshes were subject to a massive clean-up effort using manual labor and heavy machinery to remove oil and oiled sediment. The result was so large a modification of the morphology of the system that it may require a century for return to the prespill condition (Long and Vandermeulen 1979). Twelve years after the *Florida* spill, complete recovery of the salt marsh had not yet occurred although most areas were normal in gross appearance (personal observation of JMT).

Opportunistic species typically play a large role in the initial recolonization of an area defaunated by an oil spill. Following the *Florida* spill, *Capitella* increased greatly in abundance in the inshore low and subtidal stations, monopolizing the otherwise defaunated sediments for the first eleven months following the spill, and then crashed in population size. *Mediomastis* at offshore sites followed a similar course except that it persisted longer. A similar role for opportunists was described following the *Amoco Cadiz* spill by Glemarec and Hussenot (1981).

To summarize benthic effects: when fresh oil reaches the bottom, effects including massive deaths among sensitive species are to be expected; there are striking differences in sensitivities between species; opportunists are among the resistant groups and will dominate the benthos following a severe oil kill; oil in sediments is taken up by organisms selectively with relatively more of the higher molecular weight fraction seen in animals than in sediments; recovery begins rapidly on exposed rocky shores, but effects can persist for at least 6–12 years in protected soft sediments.

Planktonic Effects

Probably the best evidence of effects on plankton in the field comes from studies of the *Tsesis* oil spill. Little oil was detected dissolved or mixed into the water: only 50–60 μg/l at a depth of 0.5–1 m 5-km from the wreck after 2–5 days, although there were no data on oil in water closer to the wreck (Kineman and Clark 1980). Phytoplankton species composition was not changed by the oil, but microflagellates, which may be relatively insensitive to oil, already made up 75–90% of the individuals present at the time of the accident and remained dominant following the spill. The biomass of phytoplankton increased following the spill and productivity increased as a result. There was no change in production per unit biomass, however, which suggests that the reason for the increases was a decrease in zooplankton grazing pressure (Johansson 1980).

Planktonic bacterial biomass was unusually high following the *Tsesis* spill, although the rate of productivity calculated as the frequency of dividing cells showed no increase. The reasons for the changes could have been either more growth of or less grazing on the microbial populations. The abundance of hydrocarbon degraders was not examined. Nutrients to support bacterial growth were at high concentrations in the water at the time of the spill. No clearly discernable changes in populations of bacterial grazers, such as ciliates (which are not particularly sensitive to oil) and rotifers, were detected (Johansson and others 1980). The zooplankton populations were at their annual biomass minimum and no biomass changes were detected beyond 1 km from the spill in either ciliates or net-plankton. Changes in larger zooplankton abundance were seen close to the spill site for the first five days immediately following the accident, possibly due to either narcosis of the animals or their avoidance of the area. Control data from outside the spill area were sparse and highly variable, but showed no measurable species changes. Much of the zooplankton was contaminated with oil droplets, 50% during the first week after the grounding, with 20% of the animals still exhibiting oil after 3 weeks. Most of the oil was on the feeding appendages although it was also seen in the guts of the animals.

Data on plankton effects from other spills are generally less useful. In the Bravo spill, Rey and others (1977) examined phytoplankton and found diatoms dominating the phytoplankton both before and immediately after the spill. Two weeks later, although diatoms still predominated, they also found *Phaeocystis* (a colonial flagellate) at some stations. These authors, as well as Lännergren (1978), also examined primary production and found no conclusive effect of the spill, although Rey and others (1977) claimed a slight effect at stations where they found the highest levels of aromatic hydrocarbons (1 μg/l). Grahl-Nielsen and others (1977) found values for aromatic hydrocarbons of up to 8 μg/l during the blowout within a few kilometers of the platform.

There was a retardation of phytoplankton growth (determined from chlorophyll-a) for several weeks in the immediate vicinity of the *Amoco Cadiz* wreck and in the long narrow estuaries, Abers. Further away, phytoplankton production was apparently stimulated as a result of nutrient release from dead organisms (Cabioch and others 1981). There were apparently no observations on possible effects in the species composition of the phytoplankton. The spill resulted in considerable mortality of zooplankton. This did not show up immediately, but was apparent twenty days after the wreck in the heavily oiled areas. In Aber Benoit, there were large amounts of zooplankton debris, and the surviving *Temora longicornis,* a copepod, showed depressed levels of digestive enzymes. Seventy days later the biomass showed no signs of recovery (Samain and others 1979). In coastal areas, zooplankton were contaminated with oil in proportion to their distance from the wreck. The investigators did not distinguish between internal and external contamination.

Copepods at most stations within 10 km of the *Argo*

Merchant wreck were found with oil on their mandibles or in their guts. Polak and others (1978) found oil on copepods in 14 of 22 samples taken the following February. This oil was claimed to be from the *Argo Merchant* on the basis of analysis with synchronous-scanning UV fluorescence. Oil was found stuck to pollock eggs and to a lesser extent to cod eggs. Pollock were more developed and may have been higher in the water column. An average of 20% of cod and 46% of pollock eggs were damaged or dead at all stations sampled. This was contrasted to 4% dead or damaged laboratory spawned cod eggs, which were used as controls (Longwell 1978). It is certainly questionable as to whether laboratory spawned eggs are suitable controls, and in the field the highest egg mortalities (50–78%) were found at stations with little or no visible oil slick (Gross and Mattson 1977). Stations with obvious slicks had lower mortalities. We would argue that the oil was nevertheless responsible for the mortality and that the presence of a visible slick may be a poor indicator of oil in the water column. The greatest extent of zooplankton oiling was also found at stations with no visible slick, but the extent of zooplankton contamination was highly correlated with fish egg mortality (Figure 2). Such a correlation could be caused by contaminated sampling nets, but the absence of surface slicks and presence of oil in the guts of the zooplankton (Gross and Mattson 1977) suggests that the observations were real.

In the *Arrow* spill, Conover (1971) found incorporation of oil droplets, which were of the size of the natural food of the copepods, into their guts. Most passed through the animals without modification, as far as could be detected by fluorescence measurements, and were deposited on the bottom in fecal pellets. As much as 10% of the oil in the water was associated with copepods and their feces contained up to 7% oil. Conover says there were no apparent effects on the copepods, but did not substantiate his claim.

Fish and Fisheries

Contamination of fishes was found in the *Argo Merchant, Amoco Cadiz,* and Bravo spills, but only in very small amounts or a small portion of the fish examined (MacLeod and others 1978, Neff and Haensly 1981, Mackie and others 1978). This is in contrast to many invertebrates (including commercially important shellfish), which much more commonly showed contamination with high concentrations of oil. Although adult fish can be killed by oil spills, this probably poses less of a threat to commercial fisheries than does damage to eggs and larvae, or changes in the ecosystem supporting the fishery. These subtle effects are very poorly studied.

There was an immediate fish-kill in the *Florida* spill indicated by fish that washed ashore in windrows (Hampson and Sanders 1969) (Table 3). Induction of mixed function oxygenases occurred in *Fundulus heteroclitus* in Wild Harbor, compared with control marshes (Burns 1976b). Four years after the spill the fish showed a reduction of body burden of hydrocarbons to near background levels, presumably as a result of the enzyme activity (Burns and Teal 1979). These high enzyme levels were still present 8 years after the spill (Stegeman 1978), which correlated with the persistence of the oil (Teal and others 1978). On the other hand, fish gut analyses showed *Argo Merchant* type alkanes in only two cod and one flounder stomachs of 37 sampled in connection with that spill. The aromatic hydrocarbons matched in only one of the cods (MacLeod and others 1978).

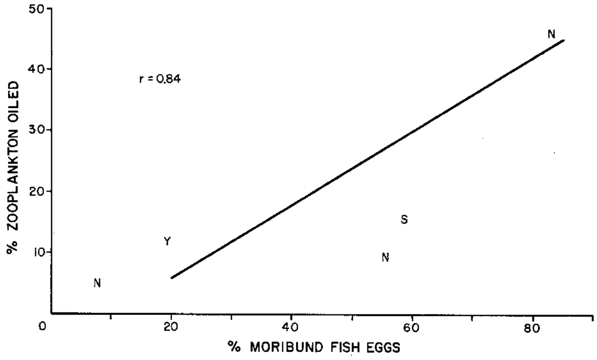

Figure 2. The percent of dead and dying fish eggs from stations sampled after the *Argo Merchant* spill compared with the percent of oil contaminated zooplankton at the same stations. Symbols indicate whether oil slicks were seen at the stations: *Y* = yes; *N* = no; and *S* = yes, but only a small amount. Data are from Gross and Mattson (1977).

Researchers did not detect any *Tsesis* oil in herring at the site of that tanker grounding (Nellbring and others 1980) (Figure 3). Spawning frequency of herring in the following spring was lower in the affected area than comparison areas, however, other differences between the areas confound any attempt to say how important the oil pollution was to inhibition of spawning. The hatching success of eggs in the affected area was about half of that in reference areas. This may have been partly due to direct effects of oil on the eggs, but was probably due largely to increased fungus infection of the eggs. Adult gammarids, normally important in keeping the degree of fungal growth on fish eggs low, were killed by the oil and almost absent in the polluted area. In spite of the lowered hatching success, there was no significant difference in the proportion of malformed larvae, which supports the notion that hatching success was a function of the effect of the oil on the benthic crustacea rather than directly on the fish eggs.

Near the wreck after the *Amoco Cadiz* spill, there was an

Table 3. Effects of oil spills on fish and fisheries.

	Death of fish eggs or larvae	Decrease in fish spawning	Death of adult fish	Decreased growth of fish or shellfish	Contamination of finfish	Contamination of shellfish	Decreased fishery recruitment	Decreased fishery catch
Florida	0	0	+	0	+	+	0	+
Arrow	0	0	0	+	0	+	0	0
Argo Merchant	+	0	0	0	–	–	0	0
Bravo	0	0	0	0	+	0	0	0
Tsesis	+	+	0	0	–	+	0	0
Amoco Cadiz	0	0	+	+	–(+)	+	+	+
IXTOC 1	0	0	0	0	0	0	0	0

+ = observed.

– = not observed, or observed only occasionally.

0 = no pertinent observations; or data collected, but interpretation is ambiguous.

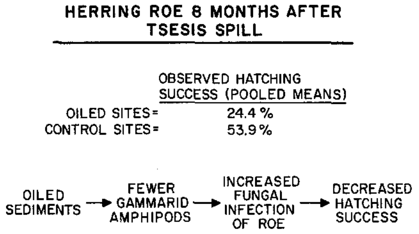

Figure 3. An indirect effect of oil on hatching success of herring eggs spawned after the *Tsesis* spill. See text for explanation.

immediate kill of a few tons of fishes, of species of slight commercial value. There was also a decline in fish catches in Brittany through the following year, even outside the contaminated zone (Maurin 1981). In the Bays there was reduced recruitment of flatfishes in 1978, which were apparent in that cohort in the fishery until 1981, but recruitment was back to normal by 1979 (Desaunay 1981). In the year after the *Amoco Cadiz* spill, growth of flatfish, plaice, and sole was reduced in Aber Benoit estuary. The effect was greater in young sole and in adult plaice. These grew less than 30% of the normal rate, while young plaice and adult sole grew at nearly 90% of their normal rate. The fishes were significantly slimmer than controls. Up to 80% of the individuals showed fin rot 9 months after the spill. This fraction dropped to about 10% over the next 11 months (Conan and Friha 1980). Eels caught from 2–8 months after the wreck near the heavily oiled area showed a variety of physiological and histopathological abnormalities in gills, ovaries, and kidneys, changes characteristic of many vertebrates subjected to long-term stress (Lopez and others 1981).

Experiments indicate that planktonic fish eggs and larvae can be affected by exposure to petroleum hydrocarbons in water at levels similar to those found in the more polluted marine areas discussed above (Kühnhold and others 1978). However, in the case of fishes, the interpretation of field results is probably more difficult than for any other group. Even in the case of the commercial species whose populations are best followed, there is very little information on the connection between the success of the larval and egg stages and the success of the year class when it eventually enters the fishery (Hennmuth and others 1980). If a pollution event were to severely damage what would otherwise have been a successful year class, it would simply not appear in the fishery. Without intensive well-designed study and considerable good fortune, no one would know or even be able to make a good guess as to whether there was a connection between the pollution damage and the failure of the year class, or whether this was simply another year in which recruitment into the fishery was unsuccessful.

Nature of Spilled Oil

That spills of refined products are significantly more damaging to marine environments than are those of crude oils is commonly stated (for example, Moore and Dwyer 1974). We question this assertion and ask whether there is a significant distinction between effects in spills of crude oil versus spills of refined products. We will here ignore the smothering and coating effects of slicks, especially heavy slicks that come ashore and be concerned only with the dissolved and dispersed oil in the water column and subtidal sediments. We believe our review indicates that the same sorts of effects can be found in spills of all types of oils. The major difference in results from spills of different oil types would probably come primarily from the dilution of the more toxic compounds. In a No. 2 fuel oil, most of the aromatic fraction consists of the more toxic two and three ring compounds. In crudes, these compounds can make up a much smaller part of the aromatic fraction. But in either type of spill, given similar environmental conditions, we are more impressed with the similarities in concentration and composition of those hydrocarbons dissolved and dispersed in the water than we are with the differences (Burns and Teal 1979, Boehm and others 1978, Kineman and Clark 1980, Grahl-Nielsen 1978, Fiest and Boehm 1981). It would appear that the size of the spill and environmental conditions at the time of the spill are more important in determining the nature and extent of effects than is the nature of the oil itself, at least in the seven spills reviewed here.

Inferences from Experimental Studies

Offshore spills such as the *Argo Merchant,* Bravo, and Ixtoc I accidents have proven very difficult to study and we know rather little about their effects. Although there is no doubt that spilled oil can cause damage nearshore, we may still ask whether or not there is evidence that the concentration of oil in the offshore oceanic environment reaches high enough levels and remains there long enough to have significant effects. This must be considered separately for water and for sediments since there is fairly clear evidence that the answer is "yes" for sediments. For example, although a result of chronic leakage rather than a spill in the Ekofisk field, Addy and others (1978) have found changes in populations of benthic animals correlated with hydrocarbon levels in the sediments. The oil apparently came from a central storage tank that flooded with sea water as the oil was pumped from the top of the tank. This water, which dissolved some hydrocarbons while in the tank, vented back over the bottom as the tank refilled with oil. The benthic fauna in the vicinity of this tank was reduced in numbers of species and density of individuals mainly due to a reduction in one species of polychaete. There was a concurrent, but not equivalent, increase in population of another, more opportunistic polychaete. The levels of aromatic hydrocarbons in the sediments close to the storage tank were in the 10–25 μg/g dry sediment range.

In the Ixtoc I spill, if the speed with which the slick or water containing oil moved was about 0.5 knots (Ross and others 1980), then plankters moving with the contaminated water would have been exposed to concentrations of 50–100 μg/l of aromatics for a little less than a day. Following the *Argo Merchant* spill, plankters could have been exposed to concentrations of between 10 and 100 μg/l for two months (Boehm and others 1978).

To consider whether or not these concentrations could affect planktonic organisms, we can look at results of Ott and others (1978) who found that exposure to about 10 μg/l of various naphthalenes in water resulted in a significant reduction in egg production in *Eurytemora,* a copepod, during a 10–14 day experiment. Ten times this concentration killed the animals in 24 hours. We may conclude that in severe pollution incidents, offshore hydrocarbons get into the water column in sufficient quantities and remain there long enough that they could have an effect. Saying that there could be effects is very different from saying that significant effects in the water column have been demonstrated.

Experimental studies have shown that there can be effects of oil on phytoplankton. Growth inhibition of single-species algal cultures in laboratory experiments has usually required concentrations of over 10,000 μg/l of a variety of the more toxic aromatic hydrocarbons: benzene, toluene, xylene (Dunstan and others 1975); or heterocompounds, cresols (Thomas and others 1981). In the latter study, dinoflagellates were more sensitive than diatoms, and in mixed species experiments that included dinoflagellates, microflagellates, and diatoms, only the latter grew in the presence of cresols. In contrast in the CEPEX studies, Lee and others (1977) found that low concentrations of c.40 μg/l of water extract of No.2 fuel oil, which decreased to zero by day 15 of the experiment, significantly reduced populations of a large centric diatom (*Ceratualina*) from 50–90% of phytoplankton carbon in control enclosures to less than 8% in the experimental enclosures. Their place was taken by microflagellates (*Chrysochromulina*), which increased to 60–80% of phytoplankton carbon in the oiled enclosure. Pennate diatoms and dinoflagellates were not affected. The total standing stock of phytoplankton initially declined to a little over 10% of the control and then increased as a result of the microplankton bloom so that by the third day the production in the oiled enclosure exceeded that in the control. There was an increase in microzooplankton in the experiment as their food source increased. Bacterial plankton increased (especially in response to naphthalene additions) and incorporated increased nitrogen as a result of their metabolism of the hydrocarbons, to the extent that, if nutrients had been limiting, they would have competed with phytoplankton for this often limiting nutrient. Among the larger zooplankton, ctenophores (comb jellies) decreased in abundance, but copepod nauplei showed no change in abundance. In another experiment the addition of 75 μg/l of naphthalenes produced no change in the phytoplankton, increased bacterial plankton and tintinnids (planktonic protozoans) which feed on bacteria, and decreased copepod nauplei (Lee and others 1978).

Reduction in grazing pressure that releases plankton can also cause a bloom. We have seen above that it has often been impossible to distinguish between this effect and a direct stimulation of production, though the consequences for the rest of the system could be quite different. The changes in the food web could conceivably either stimulate or depress the productivity at any other specific point in the system. A reduction in the number of links could, for example, increase the energy flow to the benthos, but the increase might be available to a different set of consumers than would have normally have consumed the production available at the bottom.

In the MERL experimental system, Elmgren and others (1980a) found that phytoplankton production was stimulated during a 5-month chronic pollution with about 180 μg/l of water accommodated fraction of No. 2 fuel oil (which we calculate was equivalent to about 75 μg/l total aromatics based on Gearing and others 1979). The dominant phytoplankters were little affected by the oil directly, but exhibited a marked increase in biomass and a change in species composition, which included a bloom of nanoflagellates. The changes were caused by ten-fold reduction in grazing pressure in the oiled tanks. Zooplankton biomass was reduced about one-half, but the largest change was in populations of benthic filter-feeders, which accounted for most of the difference in grazing.

If the results of the above experiments seem highly variable, it must be recognized that the natural variations in plankton populations with which experimenters were working are great. Certainly the variations and patchiness in offshore areas are not less. This points up the difficulty of ever being able to determine the effect of oil pollution upon planktonic populations, especially in the case of a spill where there is almost never any information on the distribution of the plankton before the event. Even in a chronically pollution situation, the spatial and temporal variability in plankton often makes the detection of subtle effects in the field extremely difficult, if not impossible. Nonetheless, such changes could be significant. It is conceivable that a spill could cause a significant reduction in an age class of a commercial species. Yet because of the natural and presently not understood variability, we would probably not detect the change and certainly not be able to relate it to the spill.

Ecosystem Level Effects

In the MERL experimental tanks, researchers added 190 μg/l of an oil-in-water dispersion of No. 2 fuel oil to their tanks for 25 weeks beginning in February. At 20 weeks there were 109 μg/g of oil in the upper 2-cm of sediments at the bottom of the tanks. During the experimental period, the macrofauna decreased drastically. There was an average of 325 individuals weighing 845 g in the control tanks compared with 95 individuals at 78 g in the oiled tanks. There was also a significant decrease in metazoan meiofaunal populations (especially harpacticoids and ostracods, with a smaller reduction in nematodes), although benthic diatoms, ciliates, and foraminifera increased significantly. These increases were believed due to decreased bioturbation, predation, and grazing, as a result of the reductions in the larger animals, a result that would not have been predicted on the basis of knowledge of the effects of oil on the individual populations involved (Grassle and others 1981, Elmgren and others 1980a).

Another effect that may emerge at the ecosystem level of organization was found in the studies of the *Tsesis* spill. Herring reproduction was significantly reduced in the oiled area not as a result of the effects of oil on the fish eggs themselves, but as a consequence of the decrease in amphipod populations that ordinarily grazed on the fungi growing on the fish eggs and prevented fungal damage (Nellbring and others 1980).

Finally we must note that all of the studies refered to above draw conclusions when there is data on the hydrocarbons, on the presence of the parent compounds, the unmodified petroleum hydrocarbons. There is growing evidence that the first (intermediate) products of petroleum hydrocarbon metabolism, quinones, phenols, and other oxygenated compounds, are not only often the most biologically active compounds, but are much more persistent in both organisms and sediments than had previously been suspected. Varanasi and Gmur (1981) found that while uptake of naphthalene was more rapid than that of benzo(a)pyrene, the former was more rapidly eliminated from the tissues of English sole than the latter. One day after exposure, 98% of the benzo(a)pyrene was present as intermediate metabolites, while only 15% of naphthalene was so present. Since most studies have not examined tissues for metabolites, considerable doubt is cast upon many studies of correlations between hydrocarbons and biological effects. In a MERL experiment with labeled benz(a)anthracene, 230 days after the addition of the compound, 29% had been completely degraded to carbon dioxide and lost to the atmosphere, but over 40% was still present, equally divided between the parent compound and intermediate metabolic products (Hinga and others 1980).

Summary

There is no doubt that petroleum hydrocarbons can get to subtidal marine sediments in sufficient concentrations to affect the benthic community. Concentrations in the water column can also reach levels high enough for periods long enough to affect the plankton. There is no information about possible long-term effects in the plankton. It seems likely that many of the possible effects upon planktonic systems will never be detected, in fact, could not be detected without a massive research program. This is not to say that they may not exist, but that a large degree of variability is an integral part of such systems and that detection of effects of external influences is extremely difficult. In the case of eggs and larvae of commercially valuable fishes, the need is especially important. Because of the importance of the fishing industry in the United States' economy, we hope this is a research area likely to get sufficient support for research to contribute significantly to understanding the problems.

There are only limited data on long-term effects in benthic systems, but they illustrate that long-lasting effects occur under some conditions. Since benthic organisms stay in place, there is much better opportunity to study the effects of hydrocarbon input upon these systems. In spite of this, there is little good well-controlled data. There are excellent opportunities at the present to begin long-term studies in frontier areas of the outer continental shelf that could be carried through a long period of oil and gas exploration and production to fill the gap apparent in our present information. There should also be a new effort to look for subtle effects in areas that have been in production over a long time, such as the Gulf of Mexico.

Field research is especially important for answering questions about the effects of hydrocarbons on ecosystems. It is only in the oceanic ecosystems themselves, that all of the potential interactions are present to affect the outcome of the perturbations represented by petroleum related activities. The field research must be treated in an experimental context, using oil activities as the treatment, and setting up suitable controls. It is, of course, necessary to use laboratory experiments to aid in understanding of the field results. Macrocosm experiments such as MERL and CEPEX are exceedingly useful in isolating parts of the systems for detailed experimentation. But none of the latter can substitute for work in the oceans with complete oceanic ecosystems.

Finally, most of the above discussion of the effects of oil and oil spills on marine systems emphasizes what can occur and the unexpected interactions that have been found. Looking at the effects from the opposite point of view—how much area is affected in most spills and what the rates of recovery are—one could arrive at a more optimistic view (Gunkel and Gassman 1980). In most spills, even those that have some effects over huge areas such as *Amoco Cadiz* or Ixtoc I, there have been few demonstrated effects in the water column and the oil has been present there for only limited periods. Rocky headlands are also quickly cleansed and recovery usually occurs within a few years, as far as achieving a complete recolonizing of the substrate is concerned. But where the initial recolonization is not the normal dominant species, time for return to the initial conditions may be much greater, for example, in the case of the rockweeds in the *Amoco Cadiz* and *Arrow* spills. Also, as Vendermeulen (1982) has noted, most long-term studies of oil spills have been quite selective and limited in scope, and it is likely that the presently known effects are representative of a wider range that has occurred but which has not been detected.

The longest effects have been found in soft sediments in shallow protected waters. In the *Florida* spill, while there are still obvious indications of spill damage 12 years later, probably over 95% of the area initially damaged is now apparently fully recovered. Although we would argue that full recovery can only be claimed when an area has returned more or less to its prespill condition, including being occupied by its prespill fauna and flora, it may much more rapidly recover to the extent that it is fully occupied by organisms and may possess a productivity similar to that found before the spill.

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